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We're now turning to how advancements in surgical robotics are shaping the future of surgery. Emerging robotics companies, like Microbot Medical, maker of a single-use robotic system, are harnessing these technologies to address market needs while challenging the capital-intensive models of established players.

Investors are also sensing the opportunity; funding for robotics surgery companies, like Vicarious Surgical, drove record-setting healthcare investments in 2020. The future of robotic surgery is moving towards more usable, intelligent robotic systems that can perform a greater range of procedures.

In this peace of Research we study the Da Vinci Robot and we discovered the functionality of this Surgical Robotic and we examined the efficiency and highlighted the future of these Robotics through Robotics invention manuals and Robotic Surgery Technology Innovation Assembly and we tested the background for the Da Vinci robot in different Surgeries. The future of this robot is the next revolution in Surgeries work.

Part 1 Introduction

1 Pancreatic Cancers and Cystic Neoplasms

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1.1 Introduction

Most pancreatic cancers are ductal adenocarcinomas arising from the exocrine pancreas. Pancreatic ductal adenocarcinoma (PDAC) has a poor prognosis and age, male gender, tobacco consumption, chronic pancreatitis, and some hereditary syndromes are risk factors. Most patients are diagnosed with advanced disease usually by cross-sectional imaging. Currently endoscopic ultrasound-guided fine-needle aspiration (EUS-FNA) is the standard approach for tissue sampling of a mass lesion. Surgery is the only curative therapy. In contrast, pancreatic neuroendocrine tumors (pNETs) are less common and have a better prognosis.

Pancreatic cystic lesions (PCLs) are increasingly recognized as premalignant precursor lesions and offer the opportunity to intervene early in pancreatic cancer. Computed tomography/magnetic resonance imaging (CT/MRI) is frequently used for the initial

Table 44.1 2010 WHO classification of primary pancreatic malignant tumors

Epithelial tumors	
Ductal adeno CA	Adenosquamous CA
Mucinous adeno CA	Hepatoid CA
Medullary CA	Signet-ring cell CA
Undifferentiated CA	Undifferentiated CA with osteoclast-like cells
Acinar cell CA	Acinar cell cystadeno CA
IPMN with an associated invasive CA	Mixed acinar-ductal CA
Mixed acinar-neuroendocrine CA	Mixed acinar-neuroendocrine-ductal CA
Mixed ductal-neuroendocrine CA	MCN with an associated invasive CA
Pancreatoblastoma	Serous cystadeno CA
Solid pseudopapillary neoplasm	
Mesenchymal tumors	
Lymphangioma	Lipoma
Solitary fibrous tumor	Ewing's sarcoma
Desmoplastic small round cell tumor	Perivascular epithelioid cell neoplasm
Neuroendocrine neoplasms	
Pancreatic neuroendocrine microadenoma	NET G1/carcinoid
NET G2	Neuroendocrine CA
Large-cell neuroendocrine CA	Small-cell neuroendocrine CA
Enterochromaffin cell, serotonin-producing NET	Gastrinoma, malignant
Glucagonoma, malignant	Insulin-producing CA (insulinoma)
Somatostatinoma, malignant	VIPoma, malignant
Lymphomas	
Diffuse large B-cell lymphoma	

CA, carcinoma; MCN, mucinous cystic neoplasm; NET, neuroendocrine tumor.

evaluation; however, EUS-FNA is the preferred imaging tool for tissue sampling and clinical guidance. Biochemical, cytological, and DNA analysis of aspirated cyst fluid aids in the differentiation between benign, premalignant, and malignant lesions. Options for treatment include surgery and endoscopic ablation therapies. Some lesions should also be followed up conservatively.

Although pancreatic malignancies may arise from exocrine and endocrine pancreas, most cancers originate from the ductal epithelium and are termed PDACs)¹ (Table 44.1). Because of its aggressive behavior, PDAC is one of the most common cancer-related deaths in United States. Screening, early diagnosis, and treatment strategies are challenging.

pNETs were formerly named islet cell tumors and are mostly indolent, with a small percentage demonstrating malignant behavior.² pNETs are usually an incidental finding on cross-sectional imaging.

PCLs are mostly recognized coincidentally^{3,4} with a prevalence of 1.2 to 19% in different studies.^{3,4,5,6} Nowadays the term, pancreatic cystic neoplasms (PCNs), is more preferred instead of PCL and these lesions are usually classified as either neoplastic or nonneoplastic (Table 44.2). Most PCLs are nonneoplastic and account for 80% of the pancreatic cysts.^{3,4,7} PCNs are composed of cysts with either a mucinous or serous epithelial lining. Mucinous cysts have a malignant potential whereas serous cystic neoplasm (SCN) are typically benign.

This chapter reviews the major advances in the diagnosis and management of pancreatic cancers and PCNs.

Table 44.2 Cystic lesions of pancreas		
Feature	Cyst type	Related cysts
Nonneoplastic cysts	<i>Epithelial Mucin</i>	Nonneoplastic cysts
		Endometrial cyst
		Lymphoepithelial cyst
		Enterogenous cysts
		Squamoid cysts
		Para-ampullary duodenal wall cyst
	<i>Nonepithelial Ps</i>	Pseudocyst
		Simple cyst
		Retention cyst
Neoplastic cysts (pancreatic cystic neoplasms)	<i>Mucinous cystic lesions</i>	Intraductal papillary mucinous neoplasm
		Mucinous cystic neoplasm
	<i>Nonmucinous cystic lesions</i>	Serous cystic neoplasm
		Solid pseudopapillary neoplasm
		Cystic pancreatic endocrine neoplasm
	<i>Other neoplastic</i>	Acinar-cell cystic neoplasm
		Ductal adenocarcinoma with

	<i>plastic cystic lesions</i>	cystic degeneration

1.2 Pancreatic Cancers

1.2.1 Ductal Adenocarcinoma of the Pancreas

PDAC risk increases with age (age at median diagnosis is 71)⁸ and men are slightly more affected.⁹ About 80% of cases have advanced disease at diagnosis and the 5-year survival rate is only 4% in these patients.¹⁰ The risk factors for PDAC include advanced age, male gender, “non-O” blood group, and obesity. External risk factors include exposure to high-fat diets, smoking, occupational exposure to nickel, petroleum, and wood pulp. Medical risk factors include a history of partial gastrectomy and chronic pancreatitis, or diabetes. Inherited genetic predispositions to PDAC include familial adenomatous polyposis syndrome, Lynch’s syndrome, Peutz–Jeghers syndrome, hereditary pancreatitis, hereditary breast–ovarian cancer syndromes, ataxia telangiectasia, Li–Fraumeni syndrome, familial atypical multiple mole melanoma syndrome (FAMMMS).^{1,11,12,13}

PDAC has a progressive cancer development pathway, which is similar to the adenoma–carcinoma sequence. Pancreatic intraepithelial neoplasias (PanIn) are the initiating precursor lesions and the degree of dysplasia increases from PanIn 1 to 3. Most of these lesions contain *KRAS* mutations, moreover PanIn 2 and 3 lesions are found to contain *p53*, *SMAD4*, and *CDKN2A* mutations.¹⁴ Intraductal papillary mucinous neoplasms (IPMNs) and mucinous cystic neoplasm (MCN) may also initiate the tumorigenesis process, and almost half of IPMN cases contain a *KRAS* mutation (40–65% of cases).¹³

Two-thirds of PDACs are located in the head of the pancreas and present at an earlier stage than malignancies located in the body or tail. Jaundice due to biliary obstruction is the most common presenting symptom and in one-third of patients, Courvoisier’s sign (a palpable gallbladder) is present. Pancreatic body and tail lesions remain asymptomatic until advanced disease progresses. Abdominal (predominantly epigastric) or midback pain, pruritus, asthenia, weight loss, and depression are the most common symptoms.¹⁵ Pancreatic exocrine insufficiency present with

steatorrhea and malabsorption, and new-onset diabetes exists in about half of the patients.¹⁶ Migratory thrombophlebitis is another common presentation.¹⁷

Genetic predisposition is present in 5% of patients with PDAC and 95% are sporadic. Although screening programs in high-risk patients are not widely established in the United States, candidates listed in Table 44.3 could be candidates for screening as recommended by the International Cancer of the Pancreas Screening Consortium.^{18,19}

Blood tests usually reveal a mild anemia. Cholestatic enzymes and bilirubin levels are elevated in cases with biliary obstruction. Although having a poor sensitivity in diagnosis, CA 19–9 levels are predictive for recurrent malignancy after surgery.²⁰

Patients with jaundice are initially evaluated with ultrasonography (US), which has limited access to the pancreas. A hypoechoic mass in the pancreas is typical for PDAC and a “double duct sign” (dilation of both common bile duct and pancreatic duct) is also a common feature. Computed tomography (CT) and magnetic resonance imaging (MRI) are commonly used tools for the diagnosis of PDAC (Fig. 44.1). A pancreatic-protocol triphasic CT is one of the best tools for staging. Unnecessary staging laparoscopies and laparotomies are 80% avoided with this protocol.²¹ MRI does not usually add extra information over CT.²² Fluorodeoxyglucose–positron emission tomography (FDG-PET) has a similar accuracy with CT/MRI; on the other hand, it may demonstrate small local and distant metastasis.²³ Nowadays, EUS-FNA is one of the best method for tissue sampling and staging (**Video 44.1**). Having a low complication rate,²⁴ EUS is better at detecting small lesions compared to CT/MRI^{25,26} (Fig. 44.2). Along with its usage in cyst fluid sampling, it has a therapeutic role in advanced PDAC (celiac ganglion blockage in cancer pain relief and biliary drainage when endoscopic retrograde cholangiopancreatography [ERCP] is not possible).

Preoperatively, PDAC is staged based on American Joint Committee on Cancer tumor, node, metastasis (TNM) system.²⁷ Both T1 and T2 lesions are limited to the pancreas, with a tumor dimension less than or equal to 2 cm in T1 and greater than 2 cm in T2. Superior mesenteric vein, portal vein, and splenic vein invasion is considered T3, and superior mesenteric

Table 44.3 Screening candidates for PDAC suggested by International Cancer of the Pancreas Screening Consortium

Screening candidates for PDAC	↑ Risk of PDAC
Two FDR with PDAC, with at least one affected FDR	Sixfold
Three or more blood relatives with PDAC and at least one FDR	14- to 32-fold
Peutz–Jeghers syndrome regardless of family history of PDAC	132-fold
Hereditary breast and ovarian cancer syndrome (BRCA2 mutation carriers) with either one FDR with PDAC or at least two affected family members	3.5- to 10-fold
PALB2 mutation carriers with at least one FDR with PDAC	N/A
FAMMMS (p16 mutation) carriers with at least one FDR with PDAC	9- to 47-fold
Lynch’s syndrome (mismatch repair gene mutation carriers) and one FDR with PDAC	N/A

FDR, first-degree relatives; FAMMMS, familial atypical multiple mole melanoma syndrome; PDAC, pancreatic ductal adenocarcinoma.



Fig. 44.1A heterogeneous 45 × 27 mm malignant mass in the body of pancreas on computed tomography (CT).

artery and celiac axis invasion are considered T4 tumors. N1 staging describes lymph node metastasis and M1 staging indicates metastatic disease. Potentially resectable tumors are T1, T2, and T3, and T4 lesions are unresectable. Furthermore, National Comprehensive Cancer Network (NCCN) classified PDAC clinically²⁸ (▶Table 44.4).

A multidisciplinary approach is needed for the treatment of PDAC patients. Radical R0 resection is the only curative treatment and this takes place in less than 20% of patients. In cases with unresectable tumor or when neoadjuvant chemotherapy is planned, a histologic or cytological diagnosis is necessary. **Surgically resectable PDAC (stages I–II)** patients should undergo a Whipple procedure or distal pancreatectomy depending on the localization of PDAC. Today, laparoscopic distal pancreatectomy is the preferred technique for distal tumors.¹³ The recommended therapy for **borderline resectable PDAC** is neoadjuvant chemoradiation.¹³ As an adjuvant therapy, both gemcitabine and 5-fluorouracil (5-FU) were found to improve survival after R0/R1 resection.^{29,30,31} On the other hand, adjuvant radiotherapy is not routinely advised.^{29,30} Neoadjuvant chemotherapy has a limited efficacy and although no definite

optimal treatment is present, nab-paclitaxel (gemcitabine plus albumin-bound paclitaxel particles) and 5-FU, irinotecan, oxaliplatin, and leucovorin combination are commonly used. **Locally advanced, unresectable PDAC (stage III)** patients should receive folfinirnox or gemcitabine–nab-paclitaxel as studies report similar response rates with metastatic tumors.³² **Metastatic PDAC (stage IV)** patients should also receive the same regimen as in stage III, resulting in 10% 2-year survival rate.^{33,34} Endoscopic biliary drainage, expandable metallic stent placement for duodenal obstruction, opioids, and EUS-guided celiac plexus blocks are palliative treatments for advanced PDAC (▶ Fig. 44.3).

1.2.2 Pancreatic Neuroendocrine Tumors

pNETs are indolent tumors arising from cells of the endocrine and nervous system with variable malignant potential. About 1 to 2% of pancreatic tumors are pNETs³⁵ and their incidence increases with age. Two-thirds of pNETs are nonfunctional but secrete chromogranin, neuron-specific enolase, neuroten- sin, ghrelin, and human chorionic gonadotropin subunits. The symptomatic pNETs include insulinomas, gastrinomas, glu- cagon can be such as multiple endocrine neoplasia type 1, is type 1, and tuber- ous sclerosis. A cor tests, imaging, endoscopic techniques, and biopsi hormonally inactive hypervascular pancreatic mass e of a nonfunctional



Fig. 44.2 A heterogeneous, irregular 27-mm malignant mass on endoscopic ultrasound (EUS).

Comprehensive Cancer Network (NCCN)

Stage	Involvement
Local or resectable	Absence of extrapancreatic disease, no invasion of superior mesenteric artery and celiac axis, SMA and splenic vein are patent
Borderline resectable	Absence of extrapancreatic disease. SMA encasement < 180°, celiac encasement < 180° (tail), short-segment SMV occlusion, SMV/portal impingement, abutment/encasement of hepatic artery
Locally advanced or unresectable	Absence of extrapancreatic disease. SMA encasement > 180°, any celiac abutment (head) or celiac encasement > 180° (body/tail), unreconstructable SMV/portal vein occlusion; aortic invasion or encasement, lymph node metastases beyond field of resection
Metastatic disease	Extrapancreatic disease

PDAC, pancreatic ductal adenocarcinoma; SMA, superior mesenteric artery; SMV, superior mesenteric vein.



Fig. 44.3 An 82-year-old man with a history of pancreatic cancer and a metal stent placement presented with hemobilia. A 10 × 8 cm covered metal stent was placed through the previously placed 4-cm metal stent by endoscopic retrograde cholangiopancreatography (ERCP).

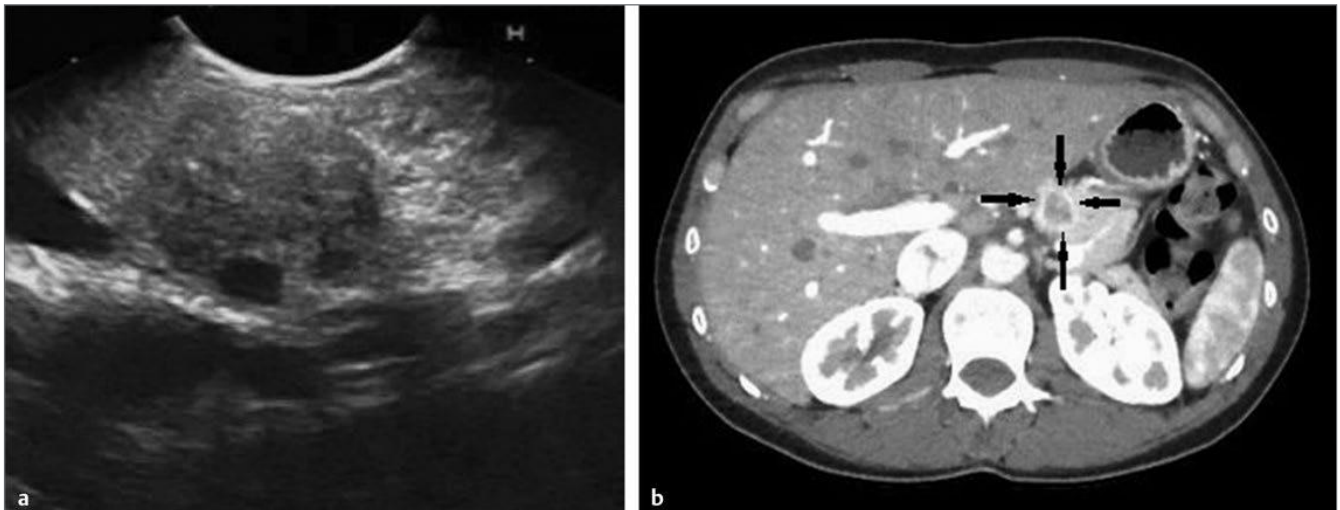


Fig. 44.4 (a) A hypoechoic, 20 × 22 mm round homogenous mass on EUS in pancreatic body consistent with pancreatic neuroendocrine tumors (pNET). (b) CT showing the same lesion.

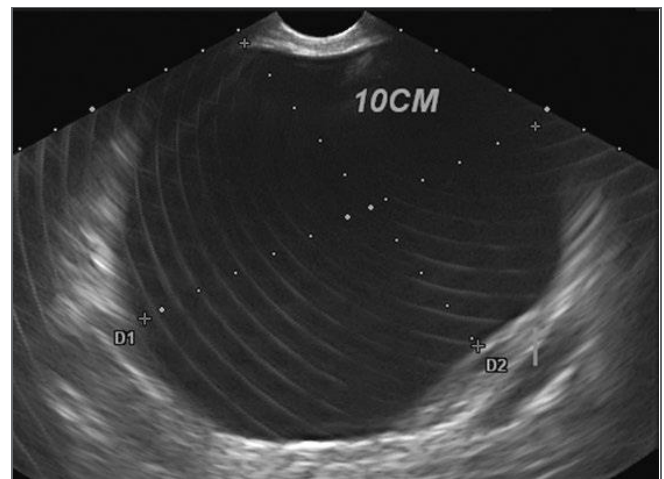


Fig. 44.6 A 10 × 10 cm thick-walled pseudocyst on EUS.

pNET, which are commonly large lesions at diagnosis with high metastasis rates.^{39,40} Today, scintigraphy and EUS-guided FNA are the mostly used imaging tools to discriminate a pNET from PDAC (► Fig. 44.4).

The only curative treatment for pNETs is surgery. Locoregional therapy for liver metastasis, systemic chemotherapy for residual disease, and somatostatin analogs for functional pNETs are recommended.⁴¹ The prognosis of pNETs is better, compared to PDAC, and is dependent on surgical outcomes.⁴²

1.3 Cystic Lesions of Pancreas

1.3.1 Nonneoplastic Cysts

Pancreatic Pseudocysts

The most common PCLs are pancreatic pseudocysts (PPs) which are inflammatory fluid

collections in the course of acute or chronic pancreatitis.⁴³ Pseudocysts occur in 10 to 20% of patients with acute pancreatitis with a slight male predominance.⁴⁴ After



Fig. 44.5 CT showing an 11.1 × 9.1 × 17.8 cm bilobed pseudocyst.

4 weeks of acute pancreatitis, an enhancing capsule forms and may delineate a local fluid collection, or a pseudocyst. The capsule does not contain an “epithelial lining.”⁴⁵ The fluid within PPs is usually dark, opaque, and low viscosity, but may contain necrotic tissue. PPs are usually single (90%), unilocular lesions containing fluid with high amylase and lipase activity in a size ranging from 2 to 20 cm.^{43,45,46}

Symptoms of PPs are abdominal pain, early satiety, and weight loss. Usually there are no specific findings on physical examination.⁴⁷ Medical history of pancreatitis, continuous abdominal pain, and consistently elevated amylase levels after clinical resolution of pancreatitis may be clues for a PP.

Initial imaging for a pseudocyst is transabdominal US, which shows an anechoic cystic lesion arising from the pancreas. Abdominal CT, which is usually superior to US, shows a well-circumscribed, thick-walled, round, or oval cystic lesion⁴³ (▶ Fig. 44.5). CT reveals additional information about pancreatic tissue, where there could be signs of acute or chronic pancreatitis. MRI, magnetic resonance cholangiopancreatography (MRCP), and ERCP do not contribute much to the diagnosis. With FNA capability, EUS is one of the best imaging modality to detect a PP (▶ Fig. 44.6), demonstrating an anechoic cystic lesion that is surrounded by

a thick rim. Cystic fluid analysis reveals high amylase and low carcinoembryonic antigen (CEA) levels.⁴⁸ Cytology shows inflammatory cells and histiocytes; on the other hand, epithelial cells are highly suspicious for PCN and granulocytes indicate an active infection.⁴⁹

PPs, smaller than 4 cm, frequently resolve without any treatment.^{50,51,52} Either percutaneous or endoscopic drainage is the choice of treatment for large and symptomatic PPs. EUS-guided transduodenal and transgastric drainage, with a 90% success and low complication rate, is the preferred technique today.⁴⁸ In some cases, necrotic material should also be removed via a cystogastrostomy or cystoduodenostomy (**Video 44.2**). Surgical drainage is generally reserved for cases, when endoscopic drainage has failed.⁵³

1.3.2 Pancreatic Cystic Neoplasms

PCNs are mainly classified as IPMN, MCN, SCN, or solid pseudopapillary neoplasm (SPN) (▶Table 44.1). Although different frequencies are reported in the literature, in a Korean study, IPMN accounts for 41%, MCN for 25.2%, SPN for 18.3%, SCN for 15.2%.³ General features of PCL are summarized in

▶Table 44.5.

IPMN is defined by intraductal proliferation of neoplastic mucin-producing columnar epithelium originating from the pancreatic duct. Papillary projections of this epithelium may rise from main duct, branch ducts, or both. It is commonly seen in older men (at 60–80s) and is classically a solitary lesion in the head of pancreas, but is multifocal sometimes (up to 30%). Approximately 20 to 50% of PCNs are believed to be IPMN.^{3,54,55} When the main duct is diffusely or segmentally involved, it is termed main duct IPMN (MD-IPMN) and has a high premalignant potential.^{56,57,58,59} In cases when side branches are involved, it is termed branch duct IPMN (BD-IPMN) and the annual malignancy rate is reported to be only 2 to 3%.^{60,61,62} Mixed IPMN is classified when both main and side branch ducts are affected with a malignancy rate reported to be between those of MD-IPMN and BD-IPMN.

Histologically, dysplasia in IPMNs is classified as low, moderate, or high grade.^{63,64} Further histologic assessments determine the subtypes of IPMN: gastric foveolar type (predominant in BD-IPMN) usually represents low-grade dysplasia.^{65,66,67} Intestinal type (predominant in MD-IPMN) represents intermediate- to high-grade dysplasia and colloid type adenocarcinoma frequently develops in association with it.⁶⁸ Invasive cancers are frequently tubular-type adenocarcinomas, which have a worse

Table 44.5 General features of some pancreatic cystic lesions

Parameters	Pseudocyst	IPMN	MCN	SCN
Demographics Age, sex, history, panc	Chronic pancreatitis history, alcohol consumption	o 60–70 years old o 40–50 years old	o 60–80 years old o 40–50 years old	o 60–80 years old
Descriptions Location, size, wall, capsule	Mostly head localization, solitary, small to very large size, fibrous-thick capsule	Mostly head localization, incidental and solitary Rarely multifocal and multilocular	Mostly pancreatic body and tail localization, incidental, solitary and large, thick wall	Entire pancreas localization oligo/macrocystic or many small cysts
Cross-sectional imaging (CT/MRI)	Mostly unilocular cyst, inflammatory parenchymal findings of pancreatitis	MD: MPD is diffusely or partially involved, BD: pancreatic duct communicated solitary or cluster of cysts, sometimes multifocal	Thickly septated macrocysts, thickened wall, peripheral “eggshell calcification”	Multiple microcysts, central fibrous scar with calcification, rarely oligocystic
Endoscopic ultrasonography	Unilocular, anechoic, thick-walled cyst, chronic pancreatitis features	MD: MPD dilation, hyperechoic nodules arising from ductal wall, BD: small, “cluster of grape-like” dilations of BD, mural nodules	Few septated big cyst, not dilated pancreatic duct, peripheral calcifications, sometimes atypical papillary projections	Multiple-anechoic, small cystic areas, “honeycomb appearance,” occasionally central calcification or fibrosis

CytologyNo epithelial lining	, inflam- matory cells and histiocytes, degenerative debris	Papillary mucin- producing epithelium, ± atypia in vari- ous degree, staining positive with mucin, colloid- like mucin	Mucin- producing tall columnar epithelium, ± atypia in various degree, staining positive with mucin, “ovarian- like mu- cosa,” colloid-like mucin	Mostly acellular and nondiagnostic, cluster of small cells in bland cuboi- dal morphology, staining positive with glycogen and negative with mucin
EUS-FNA fluid analysis	↓ Viscosity, nonmucinous, clear (brown-green in color sometimes), may be hemor- rhagic, amylase ↑, lipase ↑, CEA↓↓	↑ Viscosity, viscous mucus, amylase ↑ (60%) CEA usually ↑ <i>KRAS</i> mutation (+) (60–80%)	↑ Viscosity, viscous mucus, amylase ↓, CEA usually ↑, <i>KRAS</i> muta- tion (+) (14%), <i>GNAS</i> mutation (–)	↓ viscosi ty, Clear fluid, May be hemorrhagic Amylase ↓↓ CEA ↓↓

BD, branch duct; CEA, carcinoembryonic antigen; CT, computed tomography; EUS-FNA, endoscopic ultrasound–guided fine-needle aspiration; IPMN, intraductal papillary mucinous neoplasm; MCN, mucinous cystic neoplasm; MD, main duct; MPD, main pancreatic duct; MRI, magnetic resonance imaging; SCN, serous cystic neoplasm; ♂ : Men; ♀ : Women; ↓: Low; ↑: High; ↓↓: Very Low.

prognosis compared to the colloid type. Intraductal oncocytic papillary cancers are infrequent and have a prognosis similar to ductal adenocarcinoma.^{69,70} Gastric-type IPMN demonstrates the best prognosis, on the other hand, pancreatobiliary and intestinal type demonstrate the worse prognosis.⁷¹

Although abdominal pain, malaise, nausea, and vomiting may be seen in patients with IPMN, it is usually diagnosed unintentionally.⁵⁴ Serum laboratory analysis and tumor markers are generally not of diagnostic value.³ Imaging tools not only help to diagnose an IPMN, but also help for the differential diagnosis and the evaluation for resectability. Today, upper gastrointestinal (GI) endoscopy and ERCP are not commonly used for the diagnosis.⁷² Although most cystic lesions are detected by conventional imaging (US, CT, and MRI) incidentally (►Fig. 44.7), multidetector CT (MDCT) is currently the preferred method for evaluation. Additionally, the combination of MDCT with MRI is reported to be superior to each imaging alone.⁷³ Nowadays, EUS is the favored procedure, especially in patients who are prior to surgery. Papillary projections, cyst wall thickening, internal septations, mural nodule, and debris in the cyst can be visualized.^{3,51,54,74} EUS can differentiate a benign cyst from malignant IPMN with an accuracy of 40 to 90%, which is superior to US, ERCP, CT, and MRI.⁷⁵

Highly viscous cystic fluid with high CEA levels indicates a mucinous cyst (IPMN or MCN), which reflects a mucinous epithelium. A CEA cutoff value of 192 ng/mL is found to be the best predictor for a mucinous cyst, in contrast to amylase activity that does not discriminate a mucinous from nonmucinous cyst.⁷⁶ Malignant

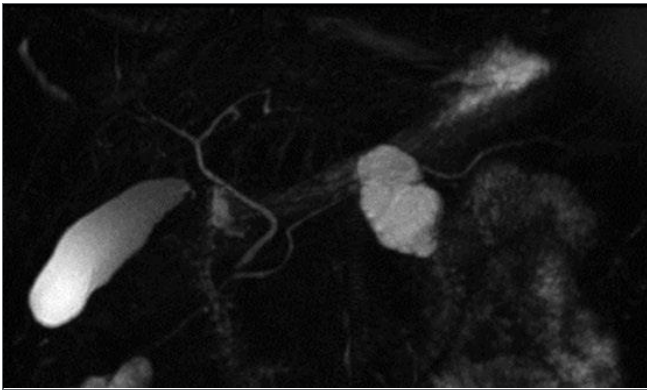


Fig. 44.7 A multilobulated, 45 × 27 mm hyperintense lesion adjacent to the body of the pancreas on magnetic resonance cholangiopancreatography (MRCP) without connection to main pancreatic duct, representing a side branch intraductal papillary mucinous neoplasm (IPMN).

cells by FNA are highly predictive of a malignant IPMN.⁷⁷ Although a *KRAS* mutation is highly specific for mucinous neoplasms,⁷⁸ it is ineffective in discriminating malignant cyst from benign cysts. Moreover, *GNAS* mutations cannot predict malignancy but may be specific for IPMN.⁷⁹

Having a high malignancy potential, international consensus guidelines recommend a surgical resection in patients with MD-IPMN.^{56,57,58,59} Given a low-risk potential, asymptomatic BD-IPMN patients without risk factors should be monitored with MRCP. Potential indications for surgical resection include the presence of a mural nodule, increase in size, and high-grade dysplasia in cytology. EUS-guided cyst ablation with alcohol or alcohol combination with paclitaxel is an alternative choice of treatment^{80,81} (**Video 44.3**).

Mucinous Cystic Neoplasms

The second type of mucinous cyst is MCN, which is reported to account for 23% of resected PCN.⁸² Common features of MCN include a solitary cyst in body or tail of the pancreas affecting mostly females at an age of less than 50. Commonly, it does not communicate with the pancreatic duct. An ovarian-type stroma underlies the mucin-producing columnar ductal epithelium in MCN, which stain positively for human chorionic gonadotropin, estrogen and progesterone receptors. There are three types of MCN: mucinous cystadenoma exhibiting benign features, mucinous cystic tumor with borderline features, and mucinous cystadenocarcinoma demonstrating malignant features.^{83,84}

The symptoms of MCN include abdominal pain, weight loss, and fatigue in 70% of patients. Jaundice and a palpable mass could be the findings on physical examination. Laboratory tests are commonly in normal limits.⁸⁵

A thinly septated, large solitary cyst with peripheral calcification are typical findings in CT.⁸⁶ The calcifications are lamellated and these contrast the central stellate calcifications of SCN. On MRI, peripheral calcifications, thickened wall, and septations were found to predict a malignancy in 95% of patients. Similar findings can be shown in EUS (**Fig. 44.8**), but the FNA material provides powerful diagnostic tools. MCNs contain a thick mucin in the aspirated fluid (**Video 44.4**), which is rich in CEA, but low in amylase. The cyst fluid is often positive for *KRAS*, however, negative for *GNAS*.^{87,88,89}

Because of having a high premalignant potential, current consensus guidelines recommend surgery for MCN.⁶⁰ Laparoscopic distal pancreatectomy with splenic preservation is the preferred surgery for lesions in the pancreatic tail. EUS-guided



Fig. 44.8 (a)CT showing an 18-mm cystic lesion in the pancreatic tail (white arrows). (b)The appearance of the same lesion on EUS. Surgical histology revealed a benign mucinous cystic neoplasm (MCN).

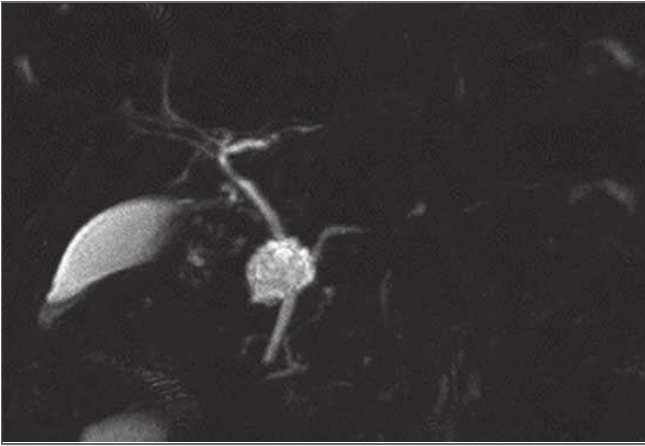


Fig. 44.9 A 28-mm, multiseptated, microcystic serous cystadenoma within the head of the pancreas on MRCP.

cyst ablation should be a choice in patients who refuse or cannot tolerate surgery.

Serous Cystic Neoplasms

SCNs are typically benign cysts in women at age less than 60, which can be located anywhere in the pancreas. These are most commonly classified as benign and serous cystadenocarcinomas are very rare. SCN contains a thin, bloody fluid, surrounded by a thin wall consisting of cuboidal epithelial cells, which stain periodic acid–Schiff (PAS) positive. These grow slowly and take a long time to reach large dimensions.⁹⁰ About 90% of von Hippel–Lindau patients develop SCN.⁹¹

Patients with SCN are frequently asymptomatic and CT/MRI reveals the common findings of a microcystic morphology. In the center of the lesion is a stellate-shaped central scar surrounded by multiple tiny cysts. Having similar morphology, CT/MRI sometimes fails to differentiate unilocular (oligocystic) SCN from MCN or BD-IPMN. Unilocular lesions are lobulated, thin-walled cysts usually in the pancreas (▶Fig. 44.9). The EUS findings include multiple small, anechoic thinly septated cysts. EUS-guided FNA aspiration reveals low amylase and CEA levels and infrequently PAS-positive cuboidal cells.⁹²

SCN has an excellent prognosis and surgery is suggested for symptomatic patients with a large cyst (> 4 cm) and when the diagnosis is indefinite.^{90,91,93}

Solid Pseudopapillary Neoplasms

SPN consists of two components: solid (solid pseudopapillary), which is formed by monomorphic epithelial cells, and cystic (hemorrhagic–necrotic pseudocystic). SPNs are large, single, round, and well-demarcated lesions that are often cystic with areas of hemorrhagic degeneration.⁹⁴ These account for about 5% of all PCNs. SPNs are most commonly found in women at their 20s or 30s. Abdominal pain, discomfort, vomiting, and weight loss associated with mass effect may be observed. SPNs are considered as low-grade malignant neoplasms.⁹⁵

CT demonstrates a mass consisting of varying areas of nonseptated soft tissue and necrotic foci, surrounded by a thick, well-circumscribed capsule. Similarly, SPNs are well-demarcated lesions

on MRI.⁹⁶ EUS shows a well-defined hypoechoic mass with cystic and solid parts inside. The cyst fluid is highly cellular and the CEA level is low.⁹⁷

Surgery is curative and the rate of recurrence after surgery is very low.³

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45 Subepithelial Tumors of the Gastrointestinal Tract

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45.1 Introduction

Subepithelial tumors (SETs) of the gastrointestinal (GI) tract are frequently encountered lesions and a common cause of referral for endoscopic ultrasound. While the overall prevalence is unknown, these lesions are often discovered during routine endoscopy or cross-sectional imaging performed for other reasons. On endoscopy, these are most frequently encountered in the stomach. These are often incorrectly referred to as “submucosal” tumors. The term “subepithelial” is more accurate as these tumors can be located in and/or arise from any of the layers deep to the epithelial layer of the mucosa (including the muscularis mucosae, submucosa, and muscularis propria).

SETs typically appear as a bulge within the GI lumen with normal overlying mucosa. Most of the tumors cause no symptoms, but can cause bleeding, obstruction, dysphagia, or, if in close proximity to the ampulla, jaundice, and pancreatitis. These lesions can be benign or malignant, and endoscopic ultrasound (EUS) with fine-needle aspiration (FNA) is an important modality in the diagnostic evaluation of these lesions. EUS is also useful for differentiating between mural tumors and extramural (or extrinsic) lesions. Up to 30% of suspected subepithelial mural tumors identified on routine endoscopy are found to be either extramural lesions or extrinsic compression by adjacent organs or vascular structures when evaluated with EUS.¹

A variety of subepithelial lesions present in the GI tract, including gastrointestinal stromal tumors (GISTs), leiomyomas, carcinoids, lipomas, pancreatic rests (ectopic pancreatic tissue), duplication cysts, schwannomas, or metastatic disease. Abnormal vasculature, such as pseudoaneurysms or varices, may also present as subepithelial lesions.

In this chapter, the types of SETs as well as their endoscopic and endosonographic characteristics are discussed. Histologic and immunohistochemical features are noted, as well as high-risk

features. Methods of tissue acquisition, including EUS with FNA and core biopsy are compared and contrasted. Endoscopic approaches to tumor resection are reviewed, with advantages and disadvantages of each technique.

45.2 Types of SETs

Understanding of the histologic layers of the GI wall is essential in characterizing SETs. The wall is comprised of five layers identified using EUS imaging with frequencies of 5 to 12 MHz. The innermost (first) layer, characterized by a very thin hyperechoic band, represents the superficial mucosa/interface with the lumen. Below this, a thin hypoechoic band represents deep mucosa including the muscularis mucosae (second layer). The submucosa (third layer) appears as a hyperechoic band, and deep to this, the muscularis propria (fourth layer) appears as a thick hypoechoic band. The serosa/adventitia (fifth layer) is thin and hyperechoic, and often unable to be differentiated from surrounding structures.

► Table 45.1 summarizes the most common types of SETs and their corresponding wall layers.

45.2.1 Gastrointestinal Stromal Tumors

GISTs are the most frequently encountered SET of the upper GI tract.² These tumors are believed to arise from the interstitial cells of Cajal, and 10 to 30% are malignant at the time of diagnosis.³ Annually, over 5,000 cases of GISTs are diagnosed.⁴ Small GISTs (< 10 mm) are common in the adult population, with autopsy data from Germany reporting gross detection in 22.5% of adults over the age of 50.⁵ These data suggest that most small GISTs do not progress into large macroscopic tumors despite the presence of the c-kit and *PDGFRA* mutations.⁶

Table 45.1 EUS characteristics of subepithelial tumors of the GI tract					
Lesion	Echogenicity	EUS layers	2nd 3rd 4th		Other features
GIST	Hypoechoic			x	Rarely from 2nd or 3rd, may have internal anechoic echoes
Leiomyoma	Hypoechoic	x	x	x	
Carcinoid	Hypoechoic	x	x		
Duplication cyst	Anechoic	x	x	x	
Lipoma	Hyperechoic		x	Diffusely, strongly hyperechoic	
Lymphoma	Hypoechoic	x	x	x	
Varices	Anechoic	x	x	Flow with Doppler, serpiginous	
Neural tumors	Hypoechoic		x	x	
Pancreatic rest	Hypoechoic	x	x	Heterogeneous	may have anechoic ductal structures
Metastasis	Hypoechoic	x	x	x	
Granular cell tumor	Hypoechoic	x	x		
EUS, endoscopic ultrasound; GIST, gastrointestinal stromal tumor.					
aFirst layer is luminal interface and mucosa, second layer is muscularis mucosa, third layer is submucosa, fourth layer is muscularis propria, fifth layer is serosa or adventitia.					

Endoscopically, the lesions are most commonly encountered in the stomach. These vary in shape and size, and may have an overlying ulcer. On EUS, GISTs appear as hypoechoic masses arising from the muscularis propria (fourth layer) ( Fig. 45.1) or muscularis mucosa (between second and third layer). These are similar in appearance to leiomyomas, and differentiating between the two requires immunohistochemical evaluation of specimens.⁷ GISTs are described as c-kit (CD117)-positive mesenchymal spindle cell or epithelioid lesions. Over 95% are positive for c-kit (CD117).^{8,9} The majority of GISTs are positive for CD34, whereas a minority (20–30%) is positive for smooth muscle actin (SMA), and the expression of the two may be reciprocal. Even fewer express the S100 protein, and fewer than 5% are positive for desmin.^{10,11,12} A newer marker for GISTs, DOG1, has shown high sensitivity and specificity for GISTs, and is particularly useful for diagnosing GISTs that are c-kit negative.^{6,13,14,15,16,17} GISTs typically are found in older individuals, with the stomach being the most common site (60–70%), followed by the small intestine (20–25%), colon and rectum (5%), and esophagus (< 5%).¹²

45.2.2 Leiomyomas

Leiomyomas are benign smooth muscle tumors and appear endoscopically and endosonographically similar to GISTs, but are often

smaller in size (typically < 2 cm). Occasionally, the tumors may become large. These are frequently encountered in the esophagus but can occur throughout the GI tract (► Fig. 45.2). These are characterized by normal overlying mucosa that can easily be tented with biopsy forceps. Similar to GISTs, these may also have a denuded or necrotic central area, particularly with large lesions. On EUS, these appear as a hypoechoic lesion arising from either the second layer (muscularis mucosa) or fourth layer (muscularis propria). Because these are unable to be differentiated from GISTs without immunochemical staining, biopsy is often required to exclude a lesion that may require endoscopic or surgical resection. Unlike GISTs, leiomyomas do not stain positive for c-kit or DOG1.

45.2.3 Carcinoids

Carcinoid tumors (► Fig. 45.3, ► Fig. 45.4) originate from neuroendocrine cells and are most frequently encountered in the small bowel. The ileum is the most common site, followed by the jejunum and duodenum.¹⁸ Carcinoid tumors also occur in the stomach, and account for nearly 10% of all carcinoid tumors. In a retrospective, 50-year analysis of over 500 carcinoids, the male–female ratio has steadily decreased to 0.54.¹⁹ Gastric carcinoids are classified into three types, depending on malignant potential. Type I gastric carcinoids are associated with chronic atrophic gastritis, hypergastrinemia,

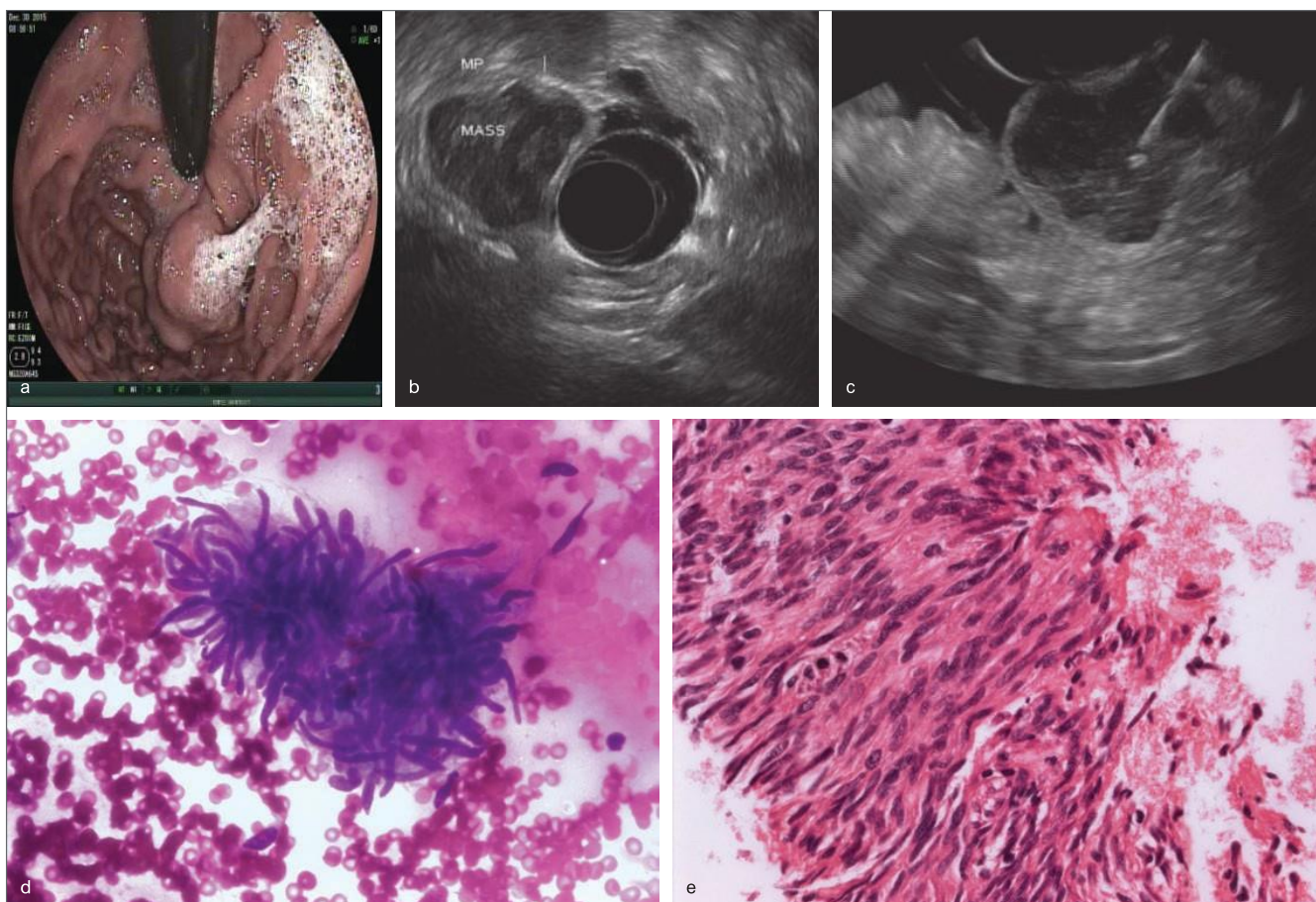


Fig. 45.1 Gastrointestinal stromal tumor (GIST) arising from the fourth wall layer. Immunohistochemistry was positive for CD-117. (a) Endoscopic image showing a medium-sized submucosal nodule in the cardia, best seen on retroflexion. (b) Radial EUS imaging of a 25-mm hypoechoic lesion arising from the muscularis propria. (c) Linear EUS imaging demonstrating a core needle during fine-needle biopsy within the lesion. (d) Diff-Quik staining revealing an abundance of spindle-shaped cells (40× magnification). (e) Hematoxylin and eosin staining show the lesion is composed

of predominantly spindle-shaped cells with oval nuclei and eosinophilic cytoplasm (40× magnification). (Images are provided courtesy of Kaveh Sharzei, MD, Temple University School of Medicine.)

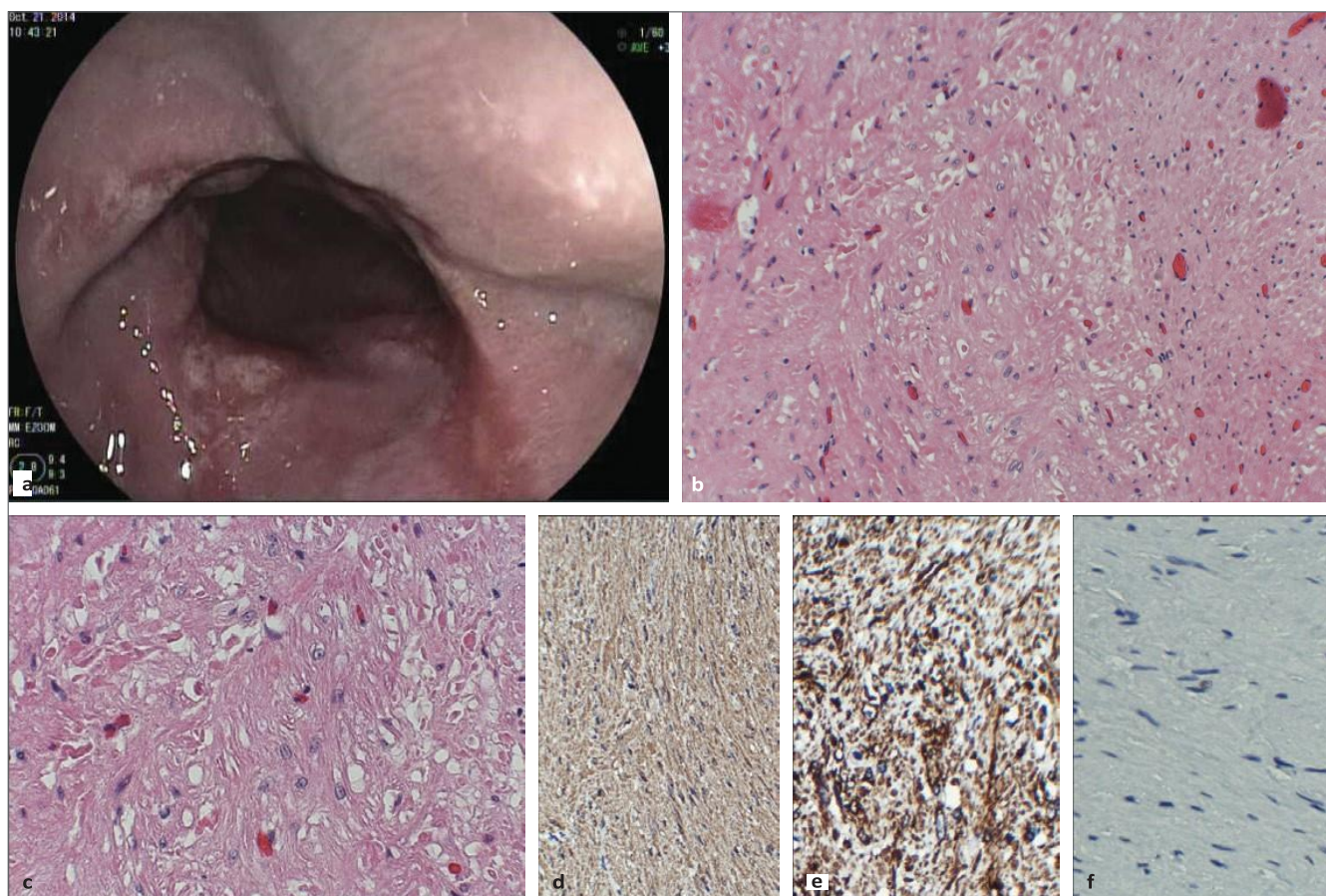


Fig. 45.2 Leiomyoma. (a) Endoscopic image showing a large, submucosal lesion in the distal esophagus. (b) Low-power H&E stain revealing a spindle cell neoplasm. (c) High power H&E stain. (d) Immunohistochemistry stains positive for Smooth Muscle Actin (SMA) and Desmin. (e) confirming a leiomyoma, and negative for C-Kit (CD117). (f) excluding a GIST.

and pernicious anemia (► Fig. 45.3). These occur most commonly in elderly female patients and have very low malignant potential.²⁰ Type II gastric carcinoids are associated with hypergastrinemia due to Zollinger–Ellison syndrome and multiple endocrine neoplasia type 1 (MEN 1). These have intermediate malignant potential. Type III gastric carcinoids are sporadic, not associated with hypergastrinemia, and have the highest risk of malignant transformation.²⁰

Endoscopically, carcinoids appear as sessile or semipedunculated lesions with normal overlying mucosa.²¹ Carcinoid tumors may originate in the mucosal layer and penetrate into the submucosal layer, so they can often be diagnosed by mucosal biopsies.²² On EUS examination, carcinoids appear as oval-shaped or round, hypoechoic, homogeneous tumors, most often arising from the submucosal layer (► Fig. 45.3, ► Fig. 45.4).²³

45.2.4 Other Subepithelial Lesions of the Gastrointestinal Tract

Other subepithelial lesions include lipomas, pancreatic rests, duplication cysts, schwannomas, and aberrant vasculature. Metastatic lesions may also present as subepithelial lesions.

Lipomas are usually asymptomatic and can occur anywhere within the GI tract. Rarely, they can cause bowel obstruction, bleeding, or intussusception.⁸ These have a smooth mucosal surface and often have a yellowish hue to the mucosa. These may

show a “pillow sign” when probed with closed biopsy forceps. On EUS, these appear as well-demarcated, oval, hyperechoic lesions arising from the submucosal layer (▶ Fig. 45.5).

Pancreatic rests, or ectopic pancreatic tissue, are most frequently encountered in the stomach, most notably the antrum, but can occur throughout the GI tract. These do not typically cause symptoms, but can lead to ulceration and hemorrhage, esophageal or intestinal obstruction and intussusception, and biliary obstruction.²⁴ On standard endoscopy, pancreatic rests may have an umbilicated surface, sometimes described as “volcano like.”²⁵ Endoscopic ultrasound images reveal well-circumscribed, mixed echogenicity lesions in the submucosa that can involve the muscularis as well that may contain anechoic, serpiginous ductal structures (▶ Fig. 45.6).

Duplication cysts are uncommon congenital anomalies of the foregut that are often asymptomatic.²⁶ These are typically incidentally found on standard endoscopy or cross-sectional imaging. These appear endoscopically as round bulges that may be compressible with normal or somewhat translucent overlying mucosa. On EUS, these are smooth, spherical or tubular in shape, anechoic, with a well-defined wall, and located in the submucosa, muscularis propria, or serosal layers.²⁷ In the mediastinum, FNA is avoided due to the risk of infection.^{28,29}

Schwannomas are benign nerve sheath tumors that can present with a variety of symptoms, including GI bleeding, abdominal pain, dysphagia, obstruction, and weight loss.⁸ Histologically, they consist of spindle cells and epithelioid cells with peripheral

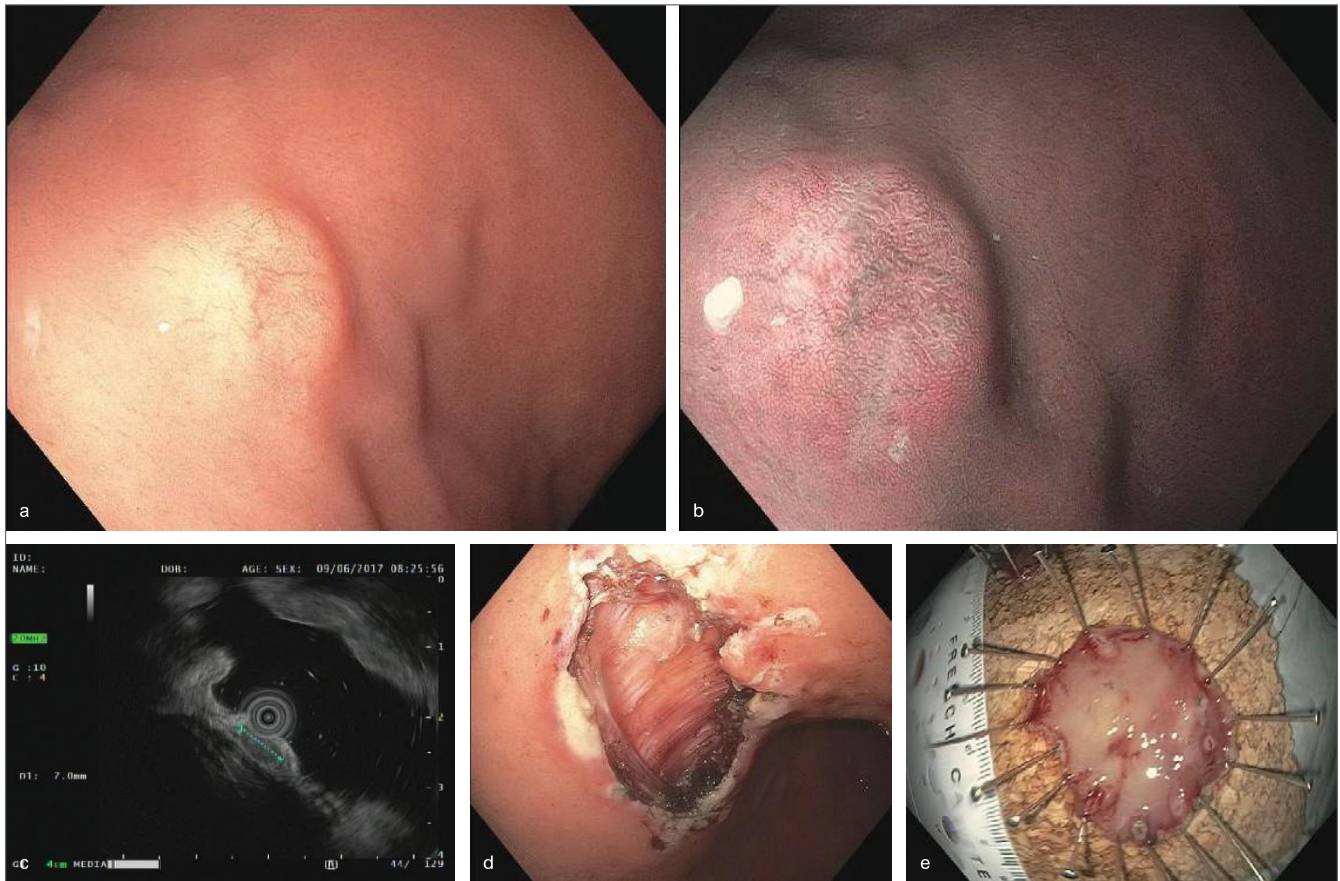


Fig. 45.3 Type I gastric carcinoid. (a) Endoscopic view of a 12 mm gastric carcinoid in the proximal stomach. (b) NBI view better defining the borders of this relatively flat lesion. (c) EUS imaging using a high frequency 20MHz mini-probe demonstrates that the lesion extends deep into the submucosa of the stomach (hyperechoic layer 3) which is usually the case even for small carcinoids. (d) Deep resection crater with exposed muscularis propria after endoscopic submucosal dissection (ESD). Due to the deep submucosal extension of carcinoids, ESD is preferred to snare resection or endoscopic mucosal resection (EMR) which may result in a positive deep resection margin (i.e. incomplete resection). (e) Pinned ESD specimen prior to submission to pathology.

lymphoid cuffing, and stain positive for S100 and vimentin.^{30,31} Endoscopically, schwannomas may have a slightly yellowish hue that can result in misidentification as lipomas. Unlike lipomas, however, endosonographically, these tumors are very low echogenicity lesions arising from the fourth layer (muscularis propria). These typically do not have internal echogenic foci but may have a marginal hypoechoic halo.³²

Granular cell tumors are rare lesions occurring throughout the entire GI tract, with approximately one-third occurring in the esophagus.³³ These generally occur in the fourth, fifth, and sixth decades of life.^{34,35} Granular cell tumors are usually solitary, but may be multifocal. These are usually incidentally found, but may cause symptoms of dysphagia, nausea, and regurgitation with lesions greater than 1 cm.^{33,34} On EUS, lesions are typically less than 2 cm in size, with a homogeneous, hypoechoic lesion arising from the muscularis mucosae or submucosa.³⁶ Most esophageal granular cell tumors have a benign course, but cases of malignancy have been reported. It is generally accepted that tumors causing symptoms and those greater than 1 cm in size should be removed (endoscopically if possible).^{33,37} Vascular abnormalities, such as varices or pseudoaneurysm, may also appear as subepithelial lesions.³⁸ Gastric varices often appear as a submucosal bulge, often in the cardia and fundus, or an enlarged gastric fold. Unlike esophageal varices, gastric varices often do not have a bluish hue because these sit deeper in the gastric wall. Gastric varices should be suspected not only in patients

with portal hypertension due to advanced liver disease, portal vein thrombosis, and Budd–Chiari syndrome, but also in patients with pancreatic disease causing splenic vein thrombosis. On endoscopy, other clues to the presence of portal hypertension may be seen, such as portal hypertensive gastropathy or esophageal varices. On EUS, varices appear as anechoic tubular structures in the submucosa that exhibit flow on Doppler examination.

While metastatic spread to the wall of the GI tract is rare, a variety of malignancies have been shown to spread to the gastric wall. These include melanoma and carcinomas of the lung, breast, ovaries, and kidney.^{2,39,40} These appear as hypoechoic lesions in any of the layers, can have an umbilicated “volcano-like” appearance, and can be diagnosed by EUS-guided FNA (EUS-FNA) or deep biopsies depending on their depth within the wall of the GI tract.

45.3 Risk Stratification of Subepithelial Tumors

While most SETs are benign, several are malignant or have malignant potential, including GISTs, carcinoids, and lymphoma.

While all GISTs are thought to have some degree of malignant potential, GIST lesions within the small bowel are higher risk than those in the stomach or rectum.⁴¹ Several factors, including those

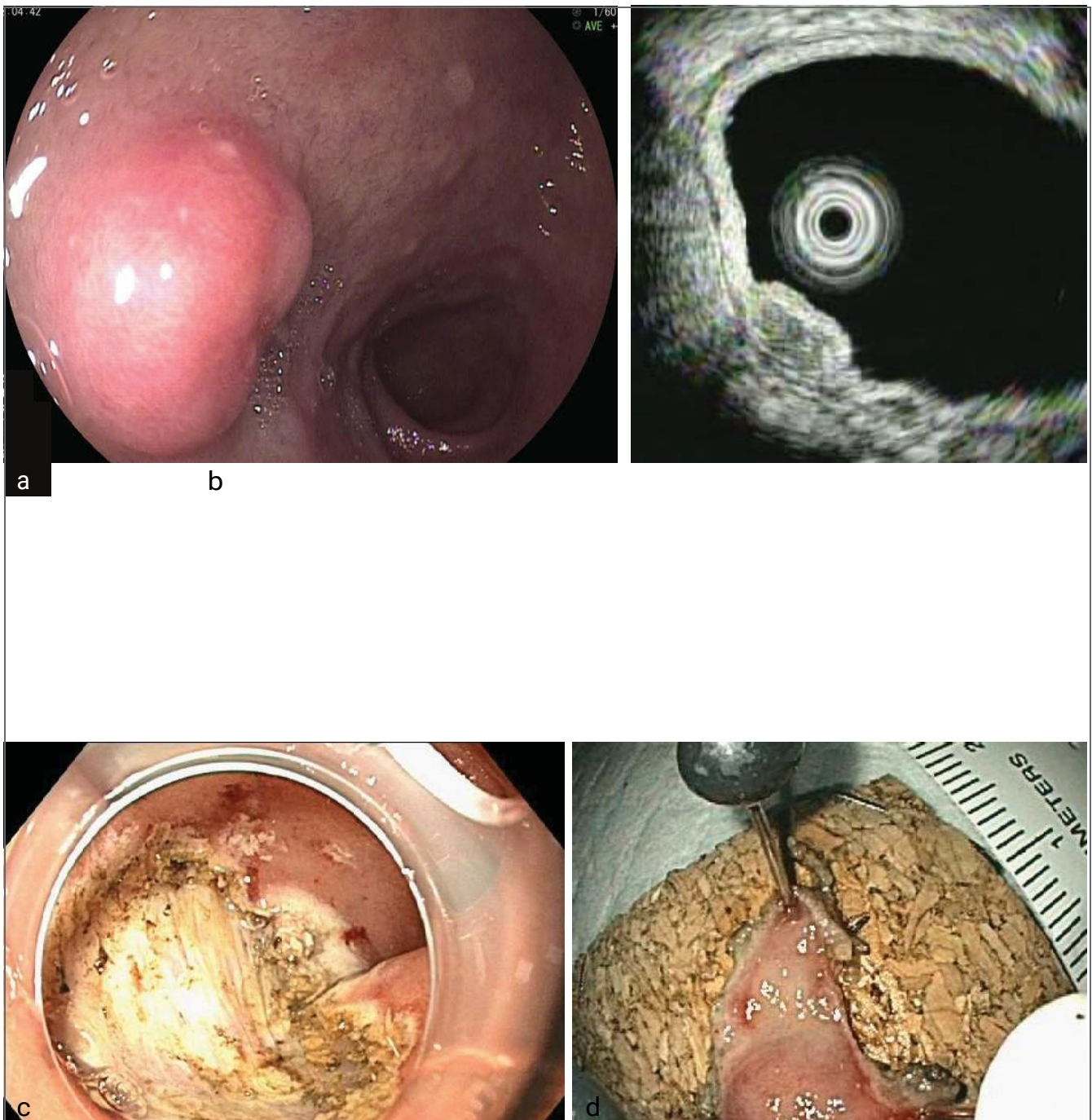


Fig. 45.4 Duodenal carcinoid. (a) Endoscopic view of subepithelial lesion in the proximal duodenal bulb. (b) EUS with miniprobe evaluation demonstrating the lesion in the submucosal layer. (c) Site following endoscopic submucosal dissection. (d) Pinning of the resection specimen onto cork.

based on overall size and mitotic rate, have been used to stratify the risk of malignancy (►Table 45.2).²² Endosonographic features that have been reported to be associated with increased risk of malignancy include lesions with cystic spaces (►Fig. 45.7), an inhomogeneous echotexture, irregular borders, and the presence of enlarged lymph nodes.^{42,43,44,45} Risk stratification is important in formulating an appropriate management strategy for GISTs.⁴⁶

For carcinoids, risk of metastasis appears to be related to the site of the primary lesion. The rate of distant metastasis is higher in patients with small bowel carcinoids than in patients with

neuroendocrine tumors (NETs) in other locations. Jejunoileal lesions are associated with a high rate of transmural invasion and aggressive behavior.⁴⁷ Further, lung and rectal carcinoids tend to remain local.^{48,49}

45.4 Methods for Tissue Acquisition

Pathologic diagnosis of SETs may be helpful in clinical decision making. A variety of techniques have been applied to obtain

adequate tissue for histologic analysis, and include bite-on- bite mucosal biopsies with forceps, biopsy after mucosal incision, endoscopic submucosal resection, EUS-FNA, and EUS-guided core biopsy (EUS-FNB). Several large-bore needles and core biopsy needles are currently in use for tissue acquisition ( Fig. 45.8).

45.4.1 Endoscopic Ultrasound-Guided Fine-Needle Aspiration

EUS-FNA is the most widely used method for tissue sampling, and is safe and effective.^{2,6} Several studies have demonstrated the utility of EUS-FNA for diagnosing subepithelial lesions, and in particular, differentiating GISTs from leiomyomas.^{50,51,52,53,54,}⁵⁵ This is especially true when on-site cytopathologic analysis of sample adequacy is undertaken.⁵⁶ In a retrospective study of 112 patients undergoing EUS-FNA of lesions arising from the fourth endosonographic layer, Hoda and colleagues reported that EUS-FNA was diagnostic in 61.6%, suspicious (spindle cells

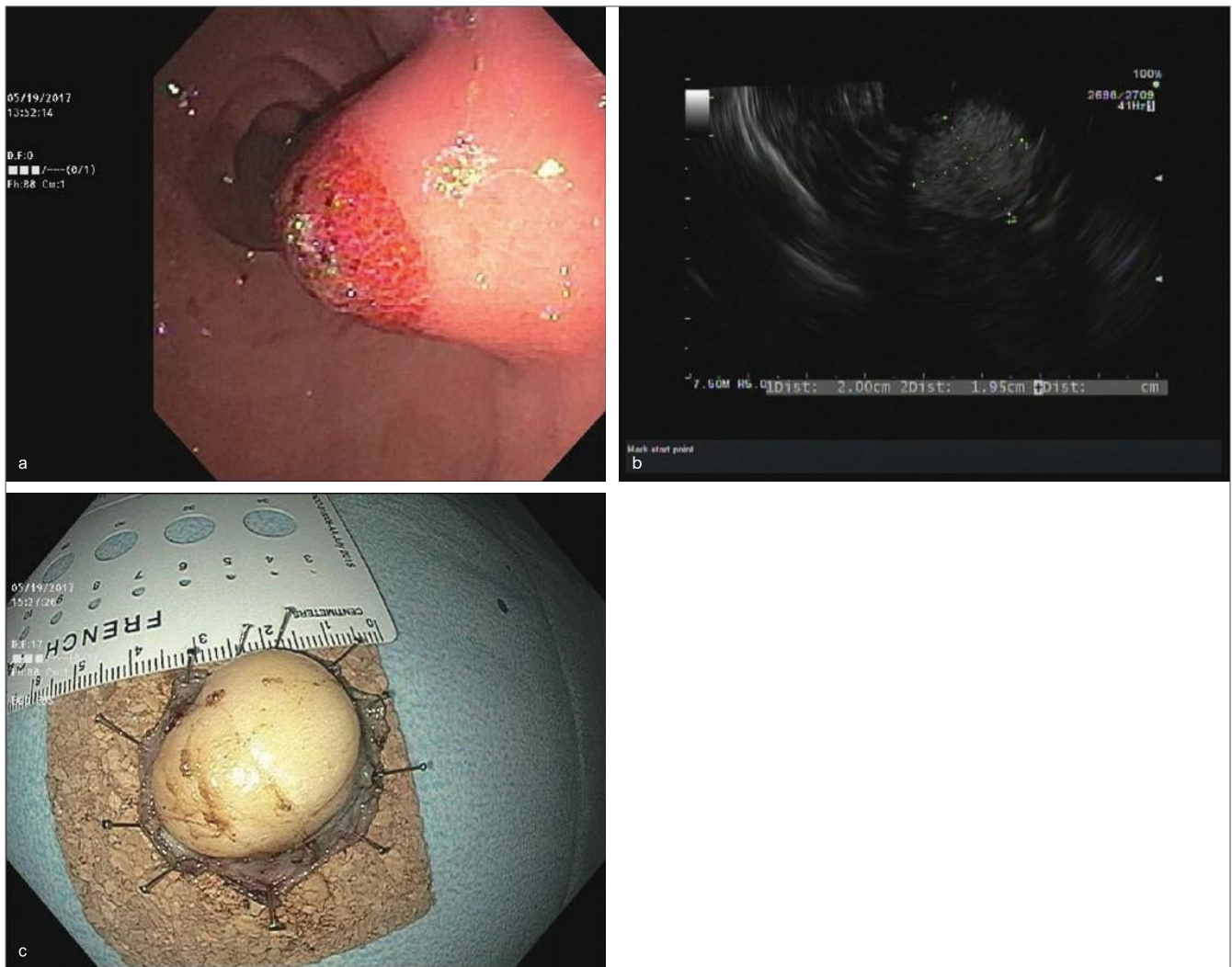


Fig. 45.5 Gastric Lipoma. (a) Endoscopic image showing a 3.5 cm subepithelial lesion with yellowish hue. Erythema of the mucosa overlying the lesion. (b) EUS imaging with a linear echoendoscope at 7.5 MHz demonstrates the typical appearance of a lipoma consisting of an oval, smooth, hyperechoic lesion arising from the submucosa. (c) Due to the relatively large size of the lesion with recurrent ulceration of the surface mucosa that was felt to possibly contribute to the patient's iron deficiency anemia, the lesion was resected via ESD. The image demonstrates complete enucleation of the lesion which was pinned with the mucosa overlying the lesion facing the cork.



Fig. 45.6 Pancreatic rest in the gastric antrum. (a) Classic endoscopic appearance of a pancreatic rest: small submucosal lesion in the gastric antrum with central umbilication. (b) 20 MHz high frequency mini-probe EUS imaging demonstrating pancreatic parenchyma consisting of heterogeneous echotexture (hyperechoic foci in a mildly hypoechoic background) and pancreatic ductal structures consisting of anechoic tubular structures (white arrows). Pancreatic rests often extend into the muscularis propria (MP) causing thickening of the MP (blue arrows).

identified) in 22.3%, and nondiagnostic in 16.1%.⁵⁷ Mekky et al retrospectively analyzed 141 consecutive patients with gastric SETs who underwent EUS-FNA.⁵⁸ Results of the FNA were diagnostic or suggestive in over 82%, with adequate specimens being obtained in 83% of cases. Overall 49% had a definite final diagnosis, of which 60% were GISTs. EUS-FNA results were concordant with the final diagnosis in 66 of 69 lesions (accuracy rate

95.6%). Further, EUS-FNA demonstrated a sensitivity of 92.4% and specificity of 100% in differentiating benign from malignant lesions. Other studies have shown diagnostic yields ranging from 75 to 100% and sensitivities of EUS-FNA of greater than 80%.^{59,60,61,62,63} Ando and colleagues reported on 49 patients with SETs originating from the muscularis propria, and found that for the diagnosis of malignant GIST, the accuracy, sensitivity, and

Table 45.2 Stratification of malignancy risk of GISTs by tumor size, mitotic count, and location

Size	Mitotic count	Risk of progressive disease (%)			
		Gastric	Jejun/Ileal	Duodenal	Rectal
≤ 2 cm ≤ 5 per 50 HPFs	None (0)		None (0)	None (0)	None (0)
> 2 cm, ≤ 5 cm ≤ 5 per 50	HPFs Very low (1.9)	Low (4.3)		Low (8.3)	Low (8.5)
> 5 cm, ≤ 10 cm ≤ 5 per 50	50 HPFs Low (3.6)		Moderate (24)	Insufficient data	Insufficient data
> 10 cm ≤ 5 per 50 HPFs	Moderate (12)	High (52)		High (34)	High (57)
≤ 2 cm ≤ 5 per 50 HPFs	None (0)		High (50)	Insufficient data	High (54)
> 2 cm, ≤ 5 cm ≤ 5 per 50	HPFs Moderate (16)	High (73)		High (50)	High (52)
> 5 cm, ≤ 10 cm ≤ 5 per 50	50 HPFs High (55)		High (85)	Insufficient data	Insufficient data
> 10 cm ≤ 5 per 50 HPFs	High (86)		High (90)	High (86)	High (71)

HPFs, microscopic high-power field in tissue sections.

^aDefined as metastasis or tumor-related deaths.

^bDenotes tumor categories with very few patients.

Source: Data from Miettinen M, Lasota J. Semin Diagn Pathol 2006;23:70–83.

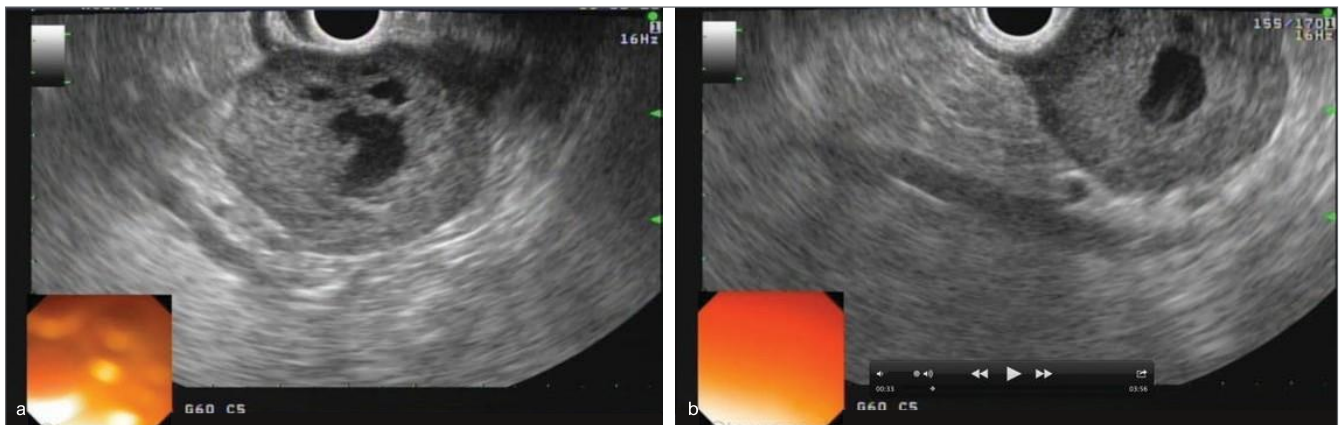


Fig. 45.7 (a, b) Gastric GIST with high-risk endosonographic appearance. This 3 × 4 cm gastric GIST had anechoic cystic spaces on EUS, a high-risk EUS feature. After en bloc endoscopic full-thickness R0 resection of the tumor, histologic analysis revealed a mitotic rate of 8/50 high-power field (HPF), consistent with a higher-risk GIST despite its gastric location and relatively small size.

specificity of EUS-FNA with the addition of immunohistochemical staining was 100%.⁵¹ These data provide support to the use of EUS-FNA with immunohistochemical staining for the diagnosis of GISTs.⁶

Based on the data reviewed, the overall rate of definitive histologic diagnosis with EUS/FNA is relatively modest at 60 to 80%, and the amount of tissue obtained, even if adequate for

definitive histologic diagnosis, may be too limited for histologic risk stratification. One approach to further optimizing tissue acquisition has been to use a larger-bore needle. Disadvantages of this approach are that the 19-gauge needle can be difficult to advance through the scope and into the lesion, resulting in a technical failure, particularly in the setting of an angulated scope. Additionally, more bleeding may occur with a larger needle. Conversely, use of a smaller-gauge (25-gauge) needle has also been explored, with the thought that it is easy to maneuver and may cause less trauma to the sampled area. While the 22-gauge needle is most commonly used, several studies have assessed the use of both 19- or 25-gauge needles.^{64,65,66,67,68,69}

Other sampling techniques have also been studied. EUS-FNA using a forward-viewing echoendoscope is a modification that

has been applied in hopes of increasing the diagnostic yield. Lar- ghi et al reported on the use of a forward-viewing EUS scope in 121 consecutive patients undergoing EUS-FNA of SETs.⁷⁰ Full histologic assessment, including immunohistochemistry, was successful in 93.4%. In terms of neoplastic versus nonneoplastic disease, the sensitivity and specificity were 92.8 and 100%, respectively. Matsuzaki et al conducted a randomized crossover study comparing forward-viewing versus oblique-viewing echo- endoscopes in 41 patients with subepithelial GI lesions.⁷¹ There was no difference in diagnostic yield between the two groups, but the forward-viewing group had shorter procedure times (21 minutes versus 27 minutes, $p = 0.009$), and superior tissue sample areas (2.46 vs. 1 mm², $p = 0.046$). ▶ Table 45.3 summarizes the yield of EUS-guided sampling.

45.4.2 Endoscopic Ultrasound-Guided Fine-Needle Biopsy and Trucut Biopsy

EUS-FNB has been proposed to overcome some of the limitations of EUS-FNA, namely inadequate tissue yield and inability to detect



Fig. 45.8 A sample of currently available core and large-bore needles. (a) Cook ProCore needles. (b) Cook Quick-Core needle. (c) Boston Scientific 19-gauge flex needle. (d) Covidien SharkCore needle schematic. (e) Covidien SharkCore needle. (Cook images used with permission of Cook Medical Incorporated, Bloomington, Indiana; Boston Scientific images used with permission of Boston Scientific Corporation, Natick, Massachusetts; Covidien images used with permission of Covidien Incorporated, Mansfield, Massachusetts.)

malignant potential on cytology specimens⁷ (**Video 45.1**). Levy and colleagues reported on their preliminary experience with the EUS-guided Trucut needle biopsy (EUS-TCB), suggesting adequate safety and a trend toward improved accuracy and fewer passes in 19 patients, when compared to EUS-FNA.⁷² Other studies have shown modest diagnostic rates with EUS-TCB, ranging from 55 to 78%.^{73,74,75,76} Diagnostic rates for EUS-FNB range from 74 to 82%.^{69,77} In a 2015 meta-analysis specifically assessing diagnostic efficacy in sampling of upper GI SETs, Zhang and colleagues reported that neither choice of FNA, TCB, or FNB, nor size of the needle appears to impact overall diagnostic rate.⁷⁸

45.4.3 Other Tissue Acquisition Techniques

A variety of other endoscopic, non-EUS-based techniques have been reported to attempt to increase the amount of tissue obtained from SETs (► Table 45.4). One method involves the use of forceps biopsies to take deep “well biopsies,” also termed “bite-on-bite” technique. In one study of 37 subepithelial lesions found on standard endoscopy, the diagnostic yield of this technique was modest at 38%.⁸⁰ In a larger, multicenter study involving 129 patients with subepithelial lesions, definitive diagnosis with deep forceps biopsies was obtained in 59%.⁸¹ However, 35% experienced significant bleeding following biopsy that required endoscopic hemostasis. Bite-on-bite forceps biopsy may be a reasonable first

approach in areas where EUS-FNA is not readily accessible, but it has modest yield and can be complicated by bleeding.

Another approach is to “unroof” the lesion via snare resection or needle knife incision of the mucosa/submucosa overlying a SET, followed by deep forceps biopsies or partial resection of the lesion (**Video 45.2**).^{82,83,84,85,86,87}

Such techniques may result in severe delayed bleeding and chronic ulceration with bleeding of the residual SET that may convert a small asymptomatic SET into a symptomatic one requiring resection.

45.5 Management of Subepithelial Lesions

Management of SETs depends on the etiology and histology of the tumor. Many lesions, such as lipomas, pancreatic rests, duplication cysts, and varices, require no additional evaluation. Overtly malignant lesions require surgical resection if feasible. GISTs and carcinoid tumors carry significant potential for malignancy, and the management is often controversial.²

Sepe and Brugge proposed an algorithm for managing localized GISTs that has been adopted by the NCCN Task Force Report.^{7,46} For GISTs that are symptomatic, greater than 4 or equal to 2 cm in size, or with suspicious EUS features (irregular borders, cystic spaces, ulceration, echogenic foci, and heterogeneity), resection is recommended. Otherwise, EUS surveillance should be

Table 45.3 Diagnostic yield of various EUS-guided sampling techniques in patients with GI SETs

Author	Year	Sampl ing techni que	Needle size (G)	Number of Patients	Diagnosti c (%)	Adequate for IHC	Non- diagnosti c
Akahoshi	2007	FNA	22	53	79	100	21
Yoshida	2009	FNA	22	49	82	100	18
Hoda	2009	FNA	22	112	62	78	16
Hoda	2009	TCB	19	15	47	87	40
Polkowski	2009	TCB	19	49	63	86	22
Sepe	2009	FNA	19, 22, 25	37	78	35	22
Fernández-Esparrach	2010	FNA	22	40	53	82	30
Fernández-Esparrach	2010	TCB	19	40	55	95	40
Fernández-Esparrach	2010	FNA + TCB	22/19	40	78	n.r.	n.r.
Mekky	2010	FNA	22	141	62	79	17
Philipper	2010	FNA	19, 22	79	34	46	26
Turhan	2010	FNA	19, 22	50	90	100	10
Dewitt	2011	TCB	19	37	79	97	21
Lee	2011	TCB	19	65	57	89	43
Suzuki	2011	FNA	22	47	75	n.r.	25
Watson	2011	FNA	19, 22	65	68	n.r.	32
Eckardt	2012	FNA	19	46	52	91	48
Akahoshi	2014	FNA	22, 25	90	62	n.r.	38
Larghi	2014	FNA	19	121	93	100	7
Matsuzaki	2015	FNA	25, 41	9, 22,	85	n.r.	15

FNA, fine-needle aspiration; G, gauge; IHC, immunohistochemistry staining; TCB, Trucut biopsy; n.r., not reported

Table 45.4 Options for endoscopic resection of SETs

Technique	Indications	Contraindications	Advantages	Disadvantages	Complications
EMR (C, L) SETs	< 1.5 cm SETs limited to submucosa	> 1.5 cm; SETs originating in the MP	Easy, quick technique with high success rate	Can only be applied to small endoluminal, superficial SETs	Minor hemorrhage, which is rare
Endoscopic ligation	SETs up to 2–3 cm arising from the MP with mainly intraluminal growth	SETs with extraluminal component	Easy to perform; short procedure times	Only applied to small, intraluminal SETs; unable to obtain complete pathologic evaluation, leaves tumor residual in muscularis propria	Perforation, major delayed hemorrhage
ESD	SETs limited to the submucosa (e.g., carcinoids)	Tumors with involvement of MP	Allows for en bloc resection, precise histologic evaluation	Requires highly skilled manipulation by specially trained endoscopists; longer procedure times	Perforation, hemorrhage
ESE	SETs in the meeting indications, MP SETs not	SETs with extraluminal component	Not limited by size, shape, or involvement of the MP, en block resection	Similar to ESD (technically difficult, longer procedure time). May leave microscopic tumor residual in MP	Perforation, minor hemorrhage
EFTR	SETs up to 4–5 cm	SETs larger than 4–5 cm that may involve the full-thickness, R0 orifices, high-risk SETs with extraluminal component	Allows for en bloc, not retrievable via luminal manipulation by special- ly trained endoscopists; longer procedure times	Requires highly skilled manipulation by special- ly trained endoscopists; longer procedure times	Perforation, major delayed hemorrhage
STER	SETs up to 4–5 cm	SETs larger than 4–5 cm that may involve the full-thickness, R0 orifices, high-risk SETs with extraluminal component	Allows for en bloc, not retrievable via the tunnel manipulation by special- ly trained endoscopists; longer procedure times	Requires highly skilled manipulation by special- ly trained endoscopists; longer procedure times	Perforation, major delayed hemorrhage

of esophagus, GEJ, and/or luminal orifices, high-risk resection, maintains ly
trained endoscopists; for esophageal STER and cardia, including SETs at high
risk of rupture, SETs GI tract mucosal longer procedure times chest
complications SETs with extralumi- at locations where tunneling is not integrity
facilitating such as
pneumotho-
nal component feasible (e.g., gastric fundus, lesser secure closure rax, infected
pleural curvature etc.)
effusion/emp
yema

EFTR, endoscopic full-thickness resection; EMR (C, L), endoscopic mucosal tumor resection
with a transparent cap (C) or ligation device (L); ESD, endoscopic submucosal dissection;
ESE: endoscopic submucosal enucleation or excavation; GEJ, gastroesophageal junction; GI,
gastrointestinal; MP, muscularis propria; SETs, subepithelial tumors; STER, submucosal
tunneling endoscopic resection.

considered after a discussion with the patient about the risks and benefits. Of note, the NCCN guidelines initially recommended EUS surveillance at 6- to 12-month intervals, but this interval recommendation has been removed from the current version of the NCCN guidelines.^{7,46}

The clinical behavior of carcinoids varies substantially based on type and location. Types I and type II gastric carcinoids tend to have a favorable prognosis.¹⁹ Five-year survival for type I lesions is greater than 95%.⁸³ For types I and II lesions, endoscopic removal of small lesions (< 2 cm) is recommended (if feasible), with subsequent endoscopic surveillance (▶ Fig. 45.3).² Type III (sporadic) carcinoids, however, have a higher malignant potential, and half will become locally invasive or metastatic. As a result, all type III gastric carcinoids, regardless of size, should be resected via partial or total gastrectomy with lymph node resection.^{2,87}

Small duodenal carcinoids (less than 2 cm in size) located in the duodenal bulb can be treated with endoscopic resection (▶ Fig. 45.4). Small bowel carcinoids have the potential to metastasize, regardless of size. As a result, resection of the involved segment and surrounding mesentery is recommended.⁸⁴ As these may be multifocal, evaluation of the rest of the small bowel at the time of resection is indicated.

Rectal carcinoids are often small, confined to the mucosa and submucosa, and localized at the time of diagnosis. As a result, these are frequently amenable to endoscopic resection with standard endoscopic mucosal resection (EMR) or endoscopic submucosal dissection (ESD) techniques. If they are less than 1 cm in size, standard EMR is indicated. For lesions greater than 2 cm in size, or extending into the muscularis propria, radical surgical resection is warranted. For intermediate-size lesions (1–2 cm), a transanal excision or advanced endoscopic excision technique (e.g., endoscopic submucosal dissection) is indicated.^{88,89,}

⁹⁰ Lesions arising from the colon that have not spread should be treated with partial colectomy and lymph node dissection.⁹¹

45.6 Endoscopic Resection of Subepithelial Tumors

Most neoplastic SETs are GISTs, the management of which hinges on risk stratification based on size and mitotic rate. However, as already reviewed, customary endoscopic sampling techniques such as EUS/FNA/FNB fail to achieve definitive histologic diagnosis in up to 30 to 40% of SETs and rarely offer adequate tissue for accurate mitotic rate assessment. Therefore, as reviewed, resection is recommended for all known or suspected GISTs that are symptomatic, have high-risk EUS features, or are ≥ 2 cm in size while lifelong surveillance at 1-year intervals is generally pursued for low-risk GISTs that are smaller than 2 cm.⁴⁶ This algorithm is often also applied to indeterminate lesions or other rare mesenchymal tumors of poorly understood malignant

potential (e.g., schwannomas, glomus tumors, granular cell tumors, etc.) for which little data exist to guide evidence-based management. This approach creates a large burden of surgery and endoscopy for small SETs less than 5 cm the majority of which are low-risk lesions. For most of these, surgery represents overtreatment driven by preoperative uncertainty and anxiety regarding risk. Furthermore, limited surgical “wedge resection” is not always possible particularly in challenging areas such as the gastroesophageal (GE) junction, esophagus, and cardia.

This situation has motivated expert endoscopists to attempt endoscopic resection of SETs smaller than 5 cm. These tumors represent an excellent target for endoscopic rather than surgical resection for the following reasons: (1) Their location in the wall of the GI tract and their frequent intraluminal growth pattern, often make them much easier to locate and remove from within the lumen of the GI tract with no need for resection of any uninvolved healthy tissue. (2) Lymph node resection is not necessary as the tumors do not metastasize via lymphatic pathways. (3) There is no need for a large margin of healthy tissue around the tumor since these tumors do not have the propensity for local recurrence seen with carcinomas; in fact, some studies show similar outcomes after R0 and R1 (macroscopically complete resection with microscopically positive margins) surgical resection of GISTs.^{92,93,94} Initial attempts at endoscopic resection have included collaborative approaches with combined endoscopic and laparoscopic resection. Various techniques have been described ranging from the endoscopist providing minor assistance limited to visualization or mucosal margination of the lesion all the way to the endoscopist performing most of the resection with the surgeon providing assistance in the final stage of the resection and/or closure. Examples of such techniques include laparoscopic endoscopic combined surgery (LECS)⁹⁵ and laparoscopy-assisted endoscopic full-thickness resection (LAEFR).⁹⁵ On a recent review, these techniques were found to have 100% complete resection rates with no severe AEs with mean procedure times of approximately 3 hours and ranging up to 5 hours.⁹⁶ These approaches clearly lack the minimal invasiveness of a purely endoscopic approach since full laparoscopic access is employed. Another more recently reported purely endoscopic resection approach that we can refer to as “device-assisted endoscopic full-thickness resection” involves use of tissue apposition devices (such as devices developed for endoscopic antireflux therapies or over-the-scope clip [OTSC] devices) to achieve seromuscular layer apposition prior to full-thickness endoscopic resection.⁹⁸ Such techniques are limited to small, purely intraluminal SETs that can allow inversion of the GI wall (in the antireflux device technique) or suction of the tumor into a distal cap attachment at the tip of the endoscope (in the OTSC method). Furthermore, these devices are bulky limiting their applicability in difficult locations such as the fundus, esophagus, etc. Of more interest are techniques that have been developed as offshoots of ESD to allow “freehand” endoscopic resection of SETs. These techniques use the same devices as ESD for mucosal neoplasms,

but take the resection to deeper layers including the deep sub- mucosa, muscularis propria, or even the serosa. The first such technique that has been variably termed ESD for enucleation of SETs, endoscopic muscular dissection (EMD) or endoscopic sub- mucosal enucleation or excavation (ESE) was developed in Asia by endoscopists experienced in ESD for mucosal neoplasms. It targets small SETs 2 to 3 cm in size with intraluminal growth and using ESD technique excavates them en bloc from the submucosa and muscularis propria. Tumors arising from the muscularis propria (e.g., GISTs) are removed by maintaining a plane of resection on the surface of the muscularis propria or the inner muscular layer. The intent is to avoid perforation (and thus also full-thickness resection)^{99,100,101,102,103,104,105,106,107,108} (**Video 45.3**). In these ESE series, SETs with mean size 2 to 3 cm, arising from the submucosa or muscularis propria have been targeted with complete resection rates of 65 to 100% (lowest for tumors arising from muscularis propria) and with relatively low perforation rates of 0 to 13% and very low adverse event (AE) rates. With ESE, however, microscopic tumor residua may remain in the muscularis propria and/or serosa since full-thickness resection of the GI wall is not performed. Furthermore, ESE can only target tumors with intraluminal

growth (without any growth directed from the muscularis toward the peritoneal thoracic cavity or mediastinum). Recently, two techniques have been reported that overcome these ESE shortcomings by performing full-thickness resection of SETs. These techniques most commonly referred to as endoscopic full-thickness resection (EFTR) and submucosal tunnel endoscopic resection (STER) represent true natural orifice transluminal endoscopic surgery (NOTES) procedures that aim at en bloc, full-thickness R0 resection of SETs. EFTR was first reported in 2011 by Chinese endoscopists for gastric GISTs.^{109,110} It involves full-thickness direct removal of a SET creating an intentional perforation, usually 1 to 3 cm in size which is then closed endoscopically with endoclip and endoloop techniques.¹¹¹ Our center is pioneering full-thickness resection in the United States (▶Fig. 45.9),¹¹² where, unlike Asia, availability of an endoscopic suturing device (Overstitch, Apollo Endosurgery, Austin, Texas, United States) allows easier and more secure closure of full-thickness defects¹¹³ (Video 45.4). STER was first reported in 2012^{114,115,116} not surprisingly by Asian POEM pioneers as this technique represents a direct offshoot of POEM in as much as it is mainly used for full-thickness resection of esophageal and GE junction SETs and uses a submucosal tunnel to access

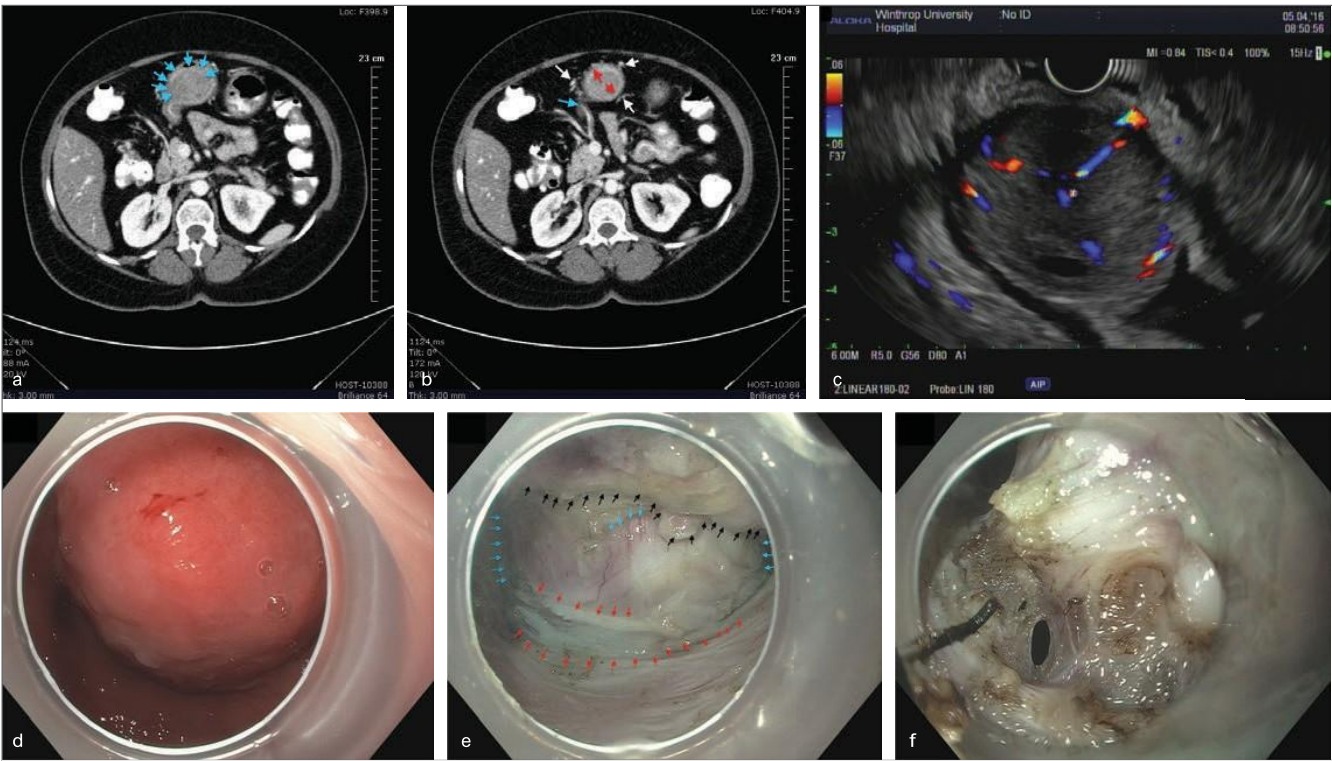


Fig. 45.9 (a) CT image intraluminal portion of GIST. (b) CT image of extraluminal portion of GIST. (c) GIST EUS with Doppler. (d) Endoscopic

(continued)

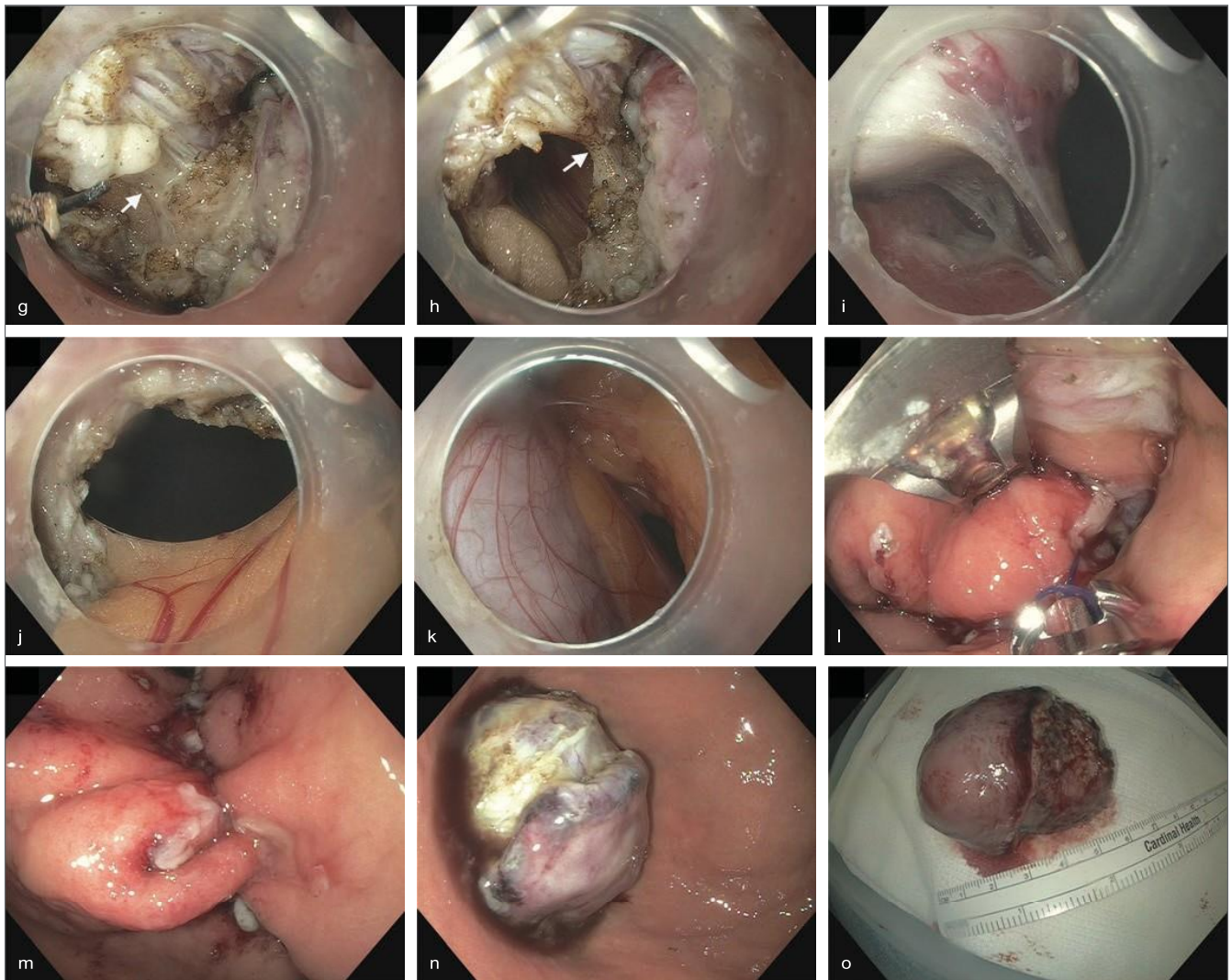


Fig. 45.9 (continued) (g) Progression of EFTR with incision of the mp initiated. (h) full thickness resection incision of muscularis propria circumferentially around the tumor. (i) Dissection of the serosal attachments to the capsule of the extraluminal portion of the GIST. (j) EFTR completed with fat protruding through the defect. (k) Peritoneoscopy through the defect. (l) Defect closure with Overstitch. (m) Completed sutured closure of the defect. (n) Resected GIST within the gastric lumen. (o) Extracted GIST 5 x 6 cm.

the tumor and remove it along with the full-thickness of the GI wall from which it arises taking advantage of the tunnel concept to achieve secure closure of the perforation by simply closing the small tunnel orifice with clips (or suturing) very similarly to POEM (►Fig. 45.10). We summarize the Asian series (Chinese in their majority) reporting on EFTR and STER in ►Table 45.5 and

►Table 45.6, respectively. Our center has reported similar results in the only Western series to date, currently at 48 EFTRs and 14 STERs completed between 4/2012 and 11/2015.¹¹⁷ (**Video 45.4** for EFTR and **Video 45.5** for STER). In the hands of expert operators, EFTR and STER provide high complete resection rates for SETs in

the 2- to 4-cm range with procedure times and adverse event rates that are similar or superior to those of surgery and with the additional advantage of minimally invasive organ-sparing resection, particularly for tumors difficult to target surgically (e.g., difficult locations and intraluminal growth pattern). EFTR and STER permit removal of lesions that have either intraluminal or extra-luminal growth, but there is a size limitation of approximately 3 to 4 cm for the tumor's smallest diameter (since a larger diameter would hinder removal of the intact tumor from the tunnel and/or the mouth).

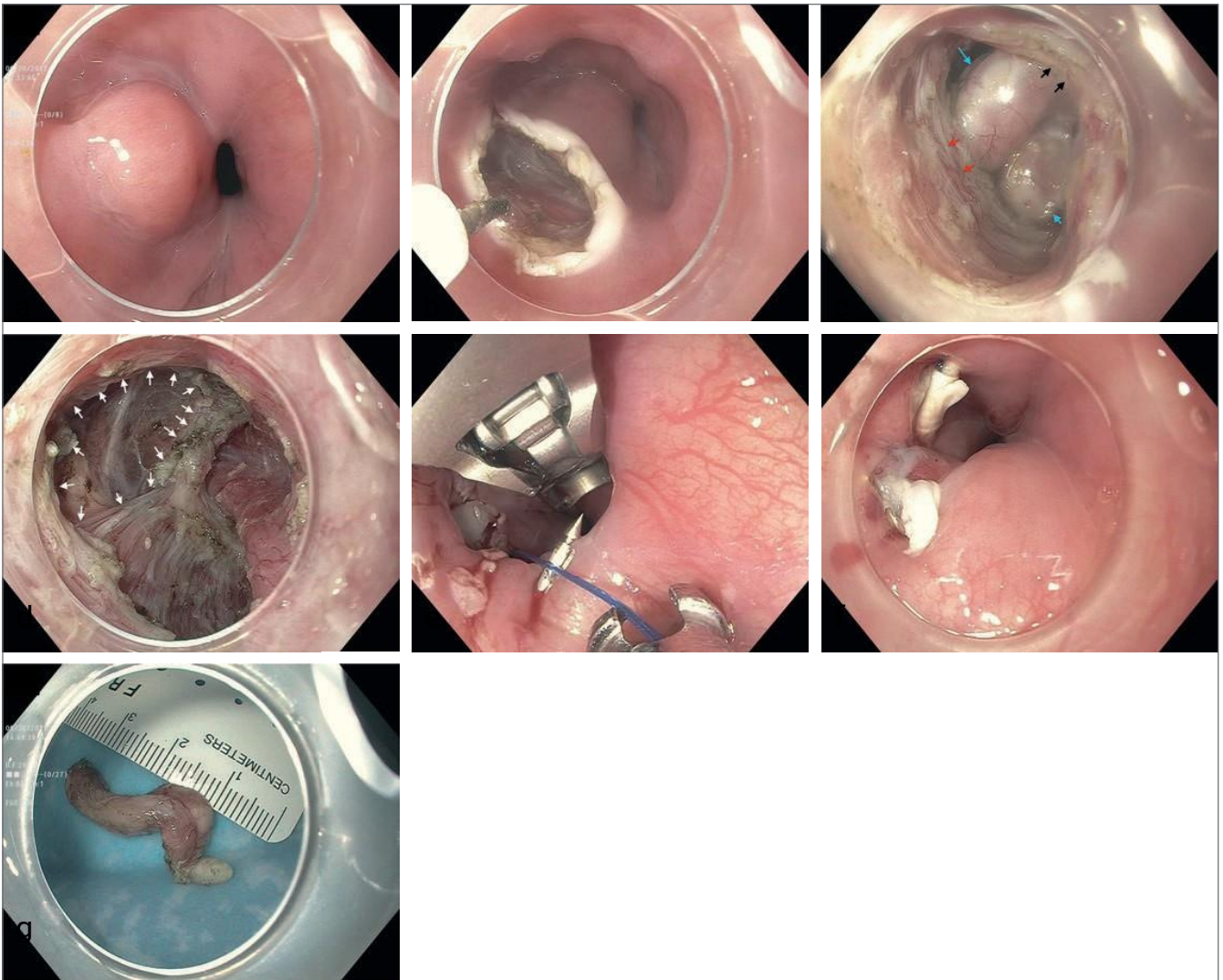


Fig. 45.10 Submucosal Tunneling Endoscopic Resection (STER). (a) Esophageal tumor at the EGJ of a 17 year old girl diagnosed as leiomyoma on prior EUS FNA. Due to the patient's young age the patient and her parents opted for resection rather than surveillance. (b) Initiation of the STER tunnel. Injection of saline in the submucosa approximately 3 cm proximal to the tumor followed by a 10-15 mm mucosal incision that will form the tunnel entry orifice. (c) Dissection of the tunnel and the mucosa surrounding the tumor achieves exposure of the irregularly shaped tumor (blue arrows). The tunnel can be clearly seen with the mucosa forming the ceiling of the tunnel (black arrows) and the muscularis propria with its circular muscle fibers forming the floor of the tunnel (white arrows). (d) Completion of the resection. A full thickness defect is seen (white arrows). The muscularis propria has been removed to achieve complete margin negative resection of the tumor exposing the mediastinal pleura, which appears as a thin transparent membrane at the bottom of the defect. (e) Closure of the tunnel entry using endoscopic suturing. (f) Completed closure of the tunnel entry sealing the tunnel and the full thickness defect under the overlying mucosa. (g) Ex vivo picture of the resected tumor with its intact capsule (white capsule with small vessels). The tumor has an irregular serpiginous tubular shape with dimensions of 1 x 3 cm.

Table 45.5 Selected series of endoscopic full-thickness resection (EFTR) (UGI tract except for one series by Xu et al that involved colonic SETs)

Study	Year	N	Size (mm)	Complete resection (%)	Time (min)	LOS (days)	Significant adverse events
Zhou, Surg Endosc	2011	26	28 (12–45)	100	105 (60–145)	5.5 (3–8)	None
Wang, Surg Endosc	2011	31/66 FTR	15 (8–17)	97	54	8	14% drains for peritonitis
Feng, J LEAST	2014	48	16 (5–48)	100	60 (30–270)	4–7	None
Ye, Surg Endosc	2014	51	24 (12–35)	98 1 conversion	52 (30–125)	5.9 (3–9)	None
Huang, WJG	2014	35	28 (20–45)	100	90 (60–155)	6 (4–10)	None
Guo, Surg Endosc	2015	312	(6–20)	100	40 (16–104)	3 (2–5)	2 peritonitis, conserve tx
Yang, Surg Endosc	2015	41	16	100	79	-None	
Xu, Endoscopy 201	3 9	1 Colon series	18 (12–30)	84; 2 lap assist clo-sure, 1 conversion	67 (45–130)	-	2 localized peritonitis, 1 bleeding

Table 45.6 Selected series of STER studies

Study	Year	N	Size (mm)	Complete resection (%)	Time (min)	LOS (days)	Significant adverse events
Esophageal STER series							
Inoue, <i>Endoscopy</i> 2012		11	12–30	82 (aborted 2, large [> 5 cm])	84–365	4–16	None
Gong, <i>Endoscopy</i> 2012		12	19 (10–40)	83% en bloc	48	-2 pneumotho	rax (PTX)
Xu, <i>GIE</i> 2012		15 (8 FTR)	19 (12–30)	100	79 (25–130)	3.8 (3–5)	1 PTX (drain)
Lee, <i>Surg Endosc</i> 2013		5	21 (16–24)	100	35	2.8	None
Liu, <i>Surg Endosc</i> 2013		12 (7 FTR)	18 (10–30)	100	78 (130–	-	4 PTX/1 drain, 2 pleural

					150)		effusion
Wang, <i>Surg Endosc</i> 2013	1833	-			67	2.3	3 bleeding, 1 PTX/drain
Ye, <i>Surg Endosc</i> 2014	85	(10 FTR)	19 (10–30)	100	57 (30–115)	5.9	6 PTX
Lu, <i>Surg Endosc</i> 2014	45		12	98	84	-None	
Zhou, <i>WJG</i> 2015		21 (9 FTR)	23 (10–40)	86% en bloc 100% complete	63 (45–90)	4.3 (3–7)	1 pleural effusion/drain
Nonesophageal STER series							
Study	Year	N	Size (mm)Com	plete resection (%)	Time (min)	LOS (days)Sign	ificant adverse events
Wang, <i>Surg Endosc</i> 2014	57 (1	7 FTR) GE junction lesions	21.5 (6–35)	100	47 (15–120)	-	2 effusions/drained; 5 PTX/2 drained
Li, <i>Surg Endosc</i> 201532		Gastric lesions	23 (10–50)	100	52 (25–125)	3.9 (2–9)	1 500-cc bleed, 3 PTX/1 drain, 4 eff/1 drain, 1 abscess/drain
Lu, <i>PLOS one</i> 2015	45	Gastric lesions	19 (12–30)	93 (2 conversions)	79 (45–150)	-	7 pain, fever, no drainage
Hu, <i>Cancer Res Ther</i> 2014	12	Rectal lesions	14 (10–30)	100	49 (40–70)	3.1 (2–8)	5 fever, 1 leg swelling, emphysema

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Part 2 Literature Review

ENDOSCOPIC ROBOTIC ESOPHAGECTOMY

Historical Background

"The history of esophageal surgery is a tale of men repeatedly losing to a stronger adversary yet persisting in this unequal struggle until the nature of the problems became apparent and the war was won."

A discussion on robotic esophagectomy is appropriately prefaced by this quote by Emslie, which provides the most accurate perspective for the struggle of surgeons with this elusive organ (1).

The anatomic remoteness of the esophagus, along with the many challenges of intraoperative management, have dictated the approach to esophagectomy through the ages. Galen described the patient with esophageal cancer in the second century AD. In the tenth century, Avicenna described esophageal tumors as the most common cause of dysphagia (2). Although surgery of the esophagus was first recorded by the Egyptians in 2500 BC with "repair of the gullet," the first successful resection of cervical esophageal cancer was performed by Czerny in 1877 (3). This work was predicated on Billroth's work in 1871 who demonstrated the feasibility of resection and re-anastomosis of the cervical esophagus in an animal model (4). However, it was six decades later that a successful esophageal resection with intrathoracic anastomosis was performed (5).

In 1913, Torek performed the resection of a squamous cell carcinoma (SCCA) of the thoracic esophagus through the left chest (6). Esophageal gastric continuity was established using a rubber tube that connected the cervical esophagus to the stomach. The patient survived 13 years. For the first decades of the twentieth century, many techniques for the establishment of continuity of the alimentary tract were investigated. In 1911, Kelling described the use of colon for esophageal replacement (7). The use of stomach, based on the right gastroepiploic artery and the right gastric artery, was first demonstrated in the laboratory by Kirschner in 1920 (8). In 1933, Ohsava of Japan performed the first successful esophagectomy with an intrathoracic esophagogastric anastomosis through the left chest (9). This pioneering work was followed by similar reports from Marshall, Adams, Phemister, Churchill, and Sweet in the United States who advocated a left transthoracic approach (10–12). In 1946, Ivor Lewis reported esophageal resection through separate laparotomy and right chest incisions with an intrathoracic anastomosis at the apex of the right chest (5). In order to avoid the consequences associated with an intrathoracic anastomotic leak in 1972, McKeown advocated the placement of the esophagogastric anastomosis in the neck through a separate cervical incision after the Ivor Lewis procedure (13). It is of interest that presently the issue of intrathoracic anastomotic leaks continues to dictate the approach to esophageal resections. Furthermore, it should be noted that the present controversy between the advantages of transthoracic esophagectomy (TTE) versus transhiatal esophagectomy (THE) is not new. Indeed, this controversy has its roots in two different approaches that were advocated throughout the twentieth century.

The transhiatal approach (THA) began in 1913 when Denk demonstrated in cadavers the feasibility of blunt dissection of the esophagus by working from the neck down and

up through the esophageal hiatus (14). This approach was performed by a lapa- rotomy and a cervical incision and obviated the need for a thoracotomy. In 1933, Turner reported the first “blunt” esophagectomy followed by an antethoracic skin tube reconstitution of the esophagogastric continuity (15). Ong and Lee in 1916 and LeQuesne and Ranger in 1966 reported a small series of patients with “blunt” esophagectomy with transhiatal gas- tric pull up and a cervical esophagogastrostomy (16,17). In 1978, Oringer resected the technique of transhiatal transcervical esophagectomy without a thoracotomy (18).

Epidemiology

Cancer of the esophagus is one of the most common malignancies worldwide. Approximately 13,000 new cases of esophageal cancer were diagnosed in the United States in 1998. Almost 12,000 patients died within the first year (19). Presently the rate of esophageal cancers has increased dramatically. Esophageal cancer is unusual compared to other solid tumors due to the geographic variations in incidence and the cell type. Although SCCA is the most common histologic subtype of esophageal cancer globally, the primary esophageal adenocarcinoma (ACA) is the predominant histologic subtype in North America (20).

In 1991, Blot and colleagues examined more than 9,000 esophageal cases registered in nine National Cancer Institute surveillance, epidemiology, and end results program areas (21). They found that:

1. Adenocarcinoma of the lower esophagus accounted for 17 percent of primary esophageal cancers overall.
2. From 1976 to 1987, the average rate of increase for primary esophageal adenocarcinoma exceeded that of any other cancer.
3. During the last 3 years of this study, 1984–1987, adenocarcinoma accounted for 34 percent of all esophageal tumors in white males.

By 1993, adenocarcinoma accounted for 48.1 percent of all cancers of the lower esophagus in the United States (22). In the 1998 update of the original study by Blot, Devasa et al. reported a 350 percent increase in the rate of adenocarcinoma of the esophagus in white North American males from 1976 to 1994 (23).

With the observation that many adenocarcinomas of the esophagus occur in association with Barrett’s epithelium, the metaplasia–dysplasia– carcinoma sequence has been clearly demonstrated (24). Prospective studies estimate that patients with Barrett’s epithelium have at least a 30- to 40-fold higher risk for development of invasive adenocarcinoma (25). Presently Barrett’s epithelium, which exhibits mutation of the P53 tumor suppressor gene, is considered premalignant (26). This marked change in the biology and epidemiology of esophageal cancer has impacted the therapeutic strategy for this disease significantly. As noted, there has been a shift from predominance of SCCA associated with tobacco and alcohol exposure to adenocarcinoma arising in a Barrett’s esophagus as a consequence of reflux disease. In contrast to SCCA, the clearly delineated metaplasia–dysplasia–carcinoma sequence with adenocarcinoma provides an opportunity for early detection and better outcomes after resection.

Historically, the role of surgery in SCCA of the esophagus has been one of palliation. The

risk of surgical procedures associated with the locally advanced nature of SCCA of the mid-esophagus has prevented oncologically efficacious procedures. The shift from SCCA of the mid-esophagus to adenocarcinoma of distal esophagus and gastroesophageal junction makes these tumors more amenable to complete resection. Furthermore, recent refinements in operative technique and perioperative management have enabled greater safety in accomplishing the more efficacious en bloc tumor resection and nodal exoneration. Not only has there been a shift in the cell type and location of esophageal carcinoma, there has also been a shift in the surgical approach from palliation to one with curative intent.

Therapeutic Strategies

Although surgery has been the mainstay of treatment of esophageal carcinoma, the high morbidity and mortality rates associated with surgery have necessitated more palliative procedures as well as the search for nonsurgical therapies. Results of surgical resection have improved. In the 1960s and 1970s, the operability rate of esophageal carcinoma was 58 percent, resectability rate was 39 percent, mortality associated with resection was 29 percent, with an overall 5-year survival of 4 percent (27). In the 1980s, the resectability rate was 56 percent, mortality rate with resection was 13 percent, and 5-year survival was 10 percent (28). Presently in specialized centers that perform greater than 50 procedures per year, the mortality rate is reported at 4.5 percent with a 5-year survival of 50.4 percent overall (29). Clearly, this dramatic change in the overall survival and operative risk is due to the earlier diagnosis of esophageal carcinoma, refinement of surgical technique and perioperative care, and greater use of multimodality therapy.

Preoperative Neoadjuvant Chemotherapy Alone

The use of preoperative chemotherapy in locally advanced esophageal carcinoma has been the subject of numerous trials. Most trials have evaluated preoperative chemotherapy, given for one to six cycles followed by a definitive surgical procedure (30–33). Later trials have given chemotherapy both preoperatively and postoperatively. Overall preoperative chemotherapy with cisplatin-based combination therapy has achieved a major response in 17–66 percent of patients with pathologically confirmed complete response of 3–10 percent. Operability has ranged from 50 to 100 percent with resectability of tumors ranging from 40 to 90 percent. Operative mortality after preoperative chemotherapy has been comparable to surgery alone. However, the overall survival of patients treated with preoperative chemotherapy has been disappointing. The median 5-year survival has ranged from 10 to 26 percent. In support of smaller studies, the landmark American Intergroup Trial reported by Kelsen and colleagues showed no benefit for neoadjuvant chemotherapy over surgery alone (34).

Preoperative Neoadjuvant Radiotherapy Alone

Trials of neoadjuvant radiotherapy have failed to show increased resection rate or improved survival compared to surgery alone (35).

Preoperative Neoadjuvant Combined Chemoradiation Therapy

The Radiation Therapy Oncology Group (RTOG 85-

01) randomized trial showed superiority of neoadjuvant chemoradiation therapy over radiation alone (36,37). The combination of chemoradiation with surgery has resulted in significant disease downstaging and has increased the proportion of R0 resections. However, a consistent survival advantage for neoadjuvant chemoradiation followed by surgery has not been demonstrated. All these studies have been hampered by the inclusion of both SCCA and adenocarcinoma and inconsistent surgical procedures. A survival advantage with neoadjuvant chemoradiation followed by surgery over surgery alone was shown in two trials of patients with adenocarcinoma. Three-year survival rates were 32 percent for combined modality therapy versus 6 percent for surgery alone. From the limited data available, it seems that chemoradiation may help local disease control, when combined with surgical resection (38). No randomized trials have directly compared chemoradiation with surgery when the surgical procedure has been performed with curative intent rather than palliation. Urschell et al. performed a meta-analysis of randomized trials comparing neoadjuvant chemoradiation and surgery versus surgery alone. There were nine studies with 1,116 patients. Combined modality therapy was superior to surgery alone with respect to (1) 3-year survival, (2) complete resection, (3) locoregional tumor recurrence, and (4) distant recurrence. Twenty-one percent of patients obtained complete pathologic response. Results were best when chemo and radiation therapy were given concurrently. Operative mortality was higher after multimodality therapy.

Furthermore, although it has been suggested that chemoradiation alone can be adequate without surgical resection, a number of considerations argue against the omission of surgery:

1. False complete response rates based on imaging modalities are commonly seen, and true complete response can only be determined after resection.
2. With chemoradiation alone, persistent local or locally recurrent disease is seen in approximately 50 percent of patients. The addition of surgery reduces local disease recurrence (39). Furthermore, even with sterilization of the primary tumor, persistent nodal disease is observed. Surgery cleans any persistent nodal disease and provides posttherapy pathologic staging of the disease.
3. Surgical treatment following chemoradiation provides far more superior relief of dysphagia and resumption of oral intake compared to chemoradiation alone. In one report, solid food intake was 100 percent with surgery as compared to 45 percent without surgery (40).

In a perspective study, O'Rourke et al. reported incidence of stricture as 16 percent with surgery and 50 percent after chemoradiation alone (41). Furthermore, postoperative anastomotic strictures respond to dilation very easily as compared to postchemoradiation malignant strictures, which do not respond to dilation and require stenting or other endoscopic procedures.

Even though further clinical studies are needed to identify the best multimodality regimens, their dose levels, and methods and schedules of administration, an increasing number of patients are receiving neoadjuvant therapy. As shown by Rice et al., patients with advanced disease (T₃N₁) who respond to neoadjuvant therapy have better outcomes

than with surgery alone (42). These authors have shown that neoadjuvant therapy has not been beneficial in patients with clinical early-stage disease. Consequently, at the present time, surgery remains the standard treatment for resectable early-stage cancer of the esophagus. Patients with advanced local regional disease should be offered preoperative chemoradiation therapy prior to surgery in order to achieve cytoreduction and improved resectability. As a majority of patients with carcinoma of the esophagus are diagnosed at a late stage, the majority of patients are candidates for preoperative

neoadjuvant chemoradiation therapy followed by surgery.

Surgical Therapy

Currently, most esophagectomies are carried out either through the transhiatal approach (THE) or through the Ivor Lewis transthoracic approach (TTE). Other procedures such as left thoracoabdominal approach (43), left thoracoabdominal cervical approach (44), left transthoracic approach (45), synchronous combined abdominothoracic cervical approach (46), and transabdominal approach (47) are either of historic interest or reserved for unusual circumstances.

Transhiatal Esophagectomy

Transhiatal esophagectomy without a thoracotomy was resurrected and popularized by Orringer in 1978. This procedure, which uses a laparotomy and cervical incision, removes the esophagus "bluntly" and, after passing the stomach tube through the hiatus and the bed of the esophagus, a cervical esophagogastrotomy is accomplished. The advantage of THE is that it avoids the morbidity associated with a thoracotomy. Furthermore, the proponents of THE note that cervical anastomotic leaks are not associated with the mediastinitis and high mortality associated with leaks of the intrathoracic anastomosis.

Although a number of small series has been reported, the largest reported series by Orringer and colleagues presents data on 1,085 patients with THE (48). In this series, THE was possible in 98.6 percent of patients and a stomach was used in 96 percent of patients. A total of nine patients (0.8 percent) had excessive intraoperative hemorrhage with three intraoperative deaths. Other complications included entry into the pleural spaces (77 percent), splenectomy (3 percent), recurrent laryngeal nerve injury (7 percent), chylothorax (<1 percent), pneumonia (2 percent), wound dehiscence (3 percent), anastomotic leaks (13 percent), and hospital mortality (4 percent).

Even though mortality from an anastomotic leak is very low, it is important to note that the leak rate after THE is quite high. In fact, a leak rate has been reported to be as high as 25 percent in less experienced centers (49). The cervical esophagogastrotomy is positioned on the highest point in the stomach, which has worse perfusion and relies on blood flow through transmural vessels connecting with the gastroepiploic artery. A cervical anastomotic leak usually results from using the portion of stomach conduit with porous blood flow. Furthermore, although mortality is low with a cervical anastomotic leak, the morbidity of a draining esophagogastric fistula in the neck and future stricture formation is quite daunting.

An additional shortcoming of THE is the high rate of phrenic nerve injury with its associated sequela. Aside from the technical concerns relating to cervical esophagogastrostomy, the critics of THE have asserted that it gained popularity in an era when esophageal surgery was associated with high mortality and morbidity. A significant part of morbidity and mortality of esophagectomy was associated with a thoracotomy, which is obviated by THE technique. Furthermore, the critics have noted that THE violates the basic surgical principles of adequate hemostasis and exposure and falls short as a "cancer operation" by avoiding an en bloc dissection of mediastinal lymph nodes. These authors have observed that recent studies showing better survival with en bloc resection and mediastinal nodal exoneration as well as advances in surgical and anesthetic techniques relegate THE to the era of palliation versus era of surgery with curative intent. These observations suggest that with better staging, earlier diagnosis, and combined modality therapy, the traditional focus of surgery, which has been palliation for dysphagia typically in patients with end-stage esophageal cancers, should be abandoned. In contrast, many investigators have asserted that surgical treatment of esophageal adenocarcinoma should have cure as the driving force.

Ivor-Lewis Procedure, Right Thoracic Abdominal Approach

If the primary goal of treatment of esophageal cancers is cure of the neoplasm, with the relief of dysphagia as an important secondary concern, surgical resection should encompass the entire tumor, draining lymph nodes, and adequate proximal and distal margin. The combined laparotomy and right thoracotomy approach with an intrathoracic esophagogastrostomy, which was originally described by Ivor Lewis in two stages, has evolved into a single-stage procedure (50). The potential advantage of this procedure is a complete resection of the tumor with surrounding nodes under direct vision.

The greatest concerns with the Ivor-Lewis procedures are the requirement for thoracotomy and morbidity and mortality associated with intrathoracic anastomosis. Matheson and other proponents of the Ivor-Lewis approach have emphasized that the leak rate can be very low in the chest and have stressed the importance of how anastomosis is performed rather than where it is performed (51). In centers with high volumes of esophagectomy, leak rates of intrathoracic anastomoses have ranged from 0 to 2 percent (52). In a study from the Lahey Clinic comparing THE and TTE with the same surgeons performing the procedures, respiratory insufficiency and atelectasis occurred more commonly after TTE versus THE (27 ± 19 versus 13 ± 8) (53). With TTE recurrent nerve palsy, chylothorax and posterior tracheal tears were very uncommon. Historically, despite the theoretical advantages of en bloc dissection and full lymphadenectomy, studies comparing TTE and THE have shown no difference in overall survival.

In a single-institution nonrandomized study, Matheson has shown improved survival with TTE (51). In a recent study of 263 patients with resectable esophageal adenocarcinoma from the single institution, Portale et al. showed better survival after TTE versus THE (70 percent versus 35 percent in all stages). Furthermore, the survival trends persisted for each stage of the disease. In a European study of 425 patients undergoing TTE versus THE, Gockel et al. showed a survival advantage with TTE as compared to THE (54). Based on this data, these authors have advocated complete en bloc resection. Altorki and Skinner have reported a 40

percent 5-year survival after en bloc resection of tumors of the lower esophagus (55). Sihvo and colleagues showed the 5-year survival of 50 percent after esophagectomy with extensive lymphadenectomy compared to 23.2 percent with less extensive procedures (56).

In a randomized trial, Hulscher and co-workers showed a trend toward better survival after TTE versus THE (57). The survival benefit of TTE is not limited only to patients with early-stage disease. Collard et al. and Swanson et al. showed that TTE esophagectomy for adenocarcinoma is superior to THE in patients with transmural esophageal adenocarcinoma with as many as eight involved lymph nodes (58,59). In these studies, there was a virtual absence of local recurrence within the operative field, an observation which may explain the superior results with TTE. In addition, this observation would make TTE more appropriate when resection is performed as a “clean-up” and staging maneuver following neoadjuvant chemoradiation therapy.

The McKeown variation on the Ivor–Lewis procedure is carried out in three stages.

1. Right thoracotomy
2. Abdominal exploration
3. Cervical incision.

In this procedure, esophagogastrostomy is placed in the neck. Therefore, the McKeown procedure suffers from problems associated with cervical esophagogastrostomy as were outlined for THE. In our view, the McKeown procedure is hampered by the shortcomings of both TTE and THE approaches and is best suited for tumors, usually SCCAs in the upper esophagus where an adequate proximal resection may not be possible through the chest.

Video-Assisted Minimally Invasive Techniques for Esophagectomy

With the advent of video-assisted techniques and their application to procedures in the abdomen and chest, there has been an attempt to apply these techniques to resection of the esophagus. The investigators have reasoned that minimally invasive techniques can decrease morbidity associated with an esophagectomy.

Thoracoscopic esophageal mobilization combined with conventional THE: The first attempt was to use video-assisted thoracoscopy to mobilize the esophagus followed by a laparotomy and a cervical esophagogastrostomy (60). Akaishi et al. showed less postoperative pain and more complete recovery of vital capacity as compared to a conventional esophagectomy (61). Other authors, however, were not able to demonstrate a clear advantage for thoracoscopic esophageal mobilization (62).

Total laparoscopic THE: DePaula et al. reported a laparoscopic THE with a cervical esophagogastrostomy (63). Others have reported a similar approach.

Although operative mortality has been very low, this procedure has been hampered by a number of problems: (1) unsatisfactory completion of intrathoracic esophageal mobilization, (2) unsatisfactory lymph node dissection, and (3) complications associated with conventional THE.

Combined laparoscopic and thoracoscopic THE with cervical esophagogastrostomy: This procedure was championed by Luketich et al. (63). The esophagus is mobilized by thoracoscopy followed by laparoscopic mobilization of the stomach and a cervical esophagogastrostomy. The early results of this technique for minimally invasive esophagectomy were reviewed by Luketich (64). Twenty-five of 77 patients (32 percent) were operated on for Barrett's esophagus with high-grade dysplasia. Ninety percent of patients had adenocarcinoma. The majority of patients underwent combined thoracoscopic and laparoscopic THE. Twelve of 77 patients (16 percent) required conversion to a laparotomy or thoracotomy. The mean operative time was 7.5 hours, mean ICU stay of 1 day, and mean hospital stay of 7 days. Thirty-day operative mortality was 0.27 percent for patients who suffered from major complications. There were seven (10 percent) anastomotic leaks. Mean lymph node yield was 16, with 60 percent of the nodes removed from the abdomen. At 20 months, overall survival was 81 percent. However, with the same 20-month follow-up, 18 of 77 patients (23 percent) had cancer recurrence (10 percent distant recurrence and 13 percent local recurrence).

Our experience with combined laparoscopic and thoracoscopic esophagectomy has been similar. Based on this experience, a number of conclusions can be made:

1. A laparoscopic approach to gastric mobilization and intraabdominal lymphadenectomy is not comparable to the degree of gastric mobilization and nodal dissection that is obtained by a laparotomy. Although the laparoscopic approach may be ideal for patients with Barrett's esophagus with high-grade dysplasia, in patients with more advanced locoregional disease, the present laparoscopic techniques do not enable en bloc lymphadenectomy and violate the principals of oncologic efficacy. In practice, firing a stapling device across the left gastric axis leaves a significant amount of tissue behind. This tissue would be easily dissected with an open procedure.
2. The combined laparoscopic and thoracoscopic approach suffers from the shortcomings of THE, which were outlined earlier. Consequently, in its present form, this approach may represent a return to the palliative error of esophageal surgery at a time when curative intent should be emphasized.
3. Although thoracoscopic mobilization of the esophagus is feasible, complete mediastinal exenteration with the removal of paraesophageal tissue requires deeper dissection into the mediastinum. In our experience, by virtue of the shortcomings of thoracoscopic instrumentation, a degree of dissection is not comparable by thoracoscopy to that which can be obtained by a thoracotomy during conventional Ivor-Lewis esophagogastrostomy. These concerns are highlighted by the very high rate of local recurrence, which is seen shortly after conventional minimally invasive procedures. Based on this experience, we have concluded that a more sophisticated

minimally invasive approach to en bloc esophageal resection and nodal exoneration with an intrathoracic esophagogastrostomy is required.

Robotic Esophagectomy

Over the past decade, our program for esophageal carcinoma has followed the concept of en bloc resection of the tumor with extensive periesophageal lymphadenectomy. The en bloc resection of esophageal cancer has been accomplished using the Ivor-Lewis approach. In 2011, based on the Society of Thoracic Surgeons database, for patients undergoing esophageal resection using this technique at our institution, the mortality rate was 2 percent, pneumonia was seen in 11 percent of patients, and there were no anastomotic leaks.

This experience has formed the basis for robotic esophagectomy program at our institution. At the outset of the robotic esophagectomy program, a number of parameters were identified:

1. Our experience with VATS and laparoscopy had clearly demonstrated the feasibility of esophagectomy using minimally invasive techniques. However, in our experience the thoracoscopic approach impaired the ability to perform mediastinal nodal exoneration, which has been a requirement of our conventional approach. The thoracoscopic approach was more akin to the lymphadenectomy that was achieved by THE.
2. Posterior gastric dissection and celiac as well as mediastinal nodal exoneration were far less satisfactory with laparoscopy.
3. The significant morbidity of conventional esophagectomy is due to cervical esophagogastrostomy during THE and morbidity associated with a thoracotomy during TTE. In order for the robotic program to obviate these difficulties, the thoracic portion of the procedure would need to be performed by minimally invasive techniques and the esophagogastric anastomosis needed to be positioned in the chest.
4. The ideal robotic procedure would be one where a combined robotic video-assisted thoracoscopic and laparoscopic procedure would be accomplished with the placement of an esophagogastrostomy in the chest.

With the advent of the da Vinci robot, robotic surgical techniques have been applied to laparoscopic mobilization of the stomach, transhiatal resection of the esophagus, and open cervical esophagogastrostomy and robotic transthoracic mobilization of the esophagus combined with THE and a cervical esophagogastrostomy. To the best of our knowledge, our center has been one of the few centers that have emphasized video-assisted approach to esophagogastrostomy in the chest. It has been our contention that the addition of new robotic technology to the technique of THE suffers from the shortcomings of conventional THE.

Based on our experience with conventional esophagectomy, we determined that a robotic esophagectomy program should be designed based on the following parameters: (1) Oncologic efficacy of conventional procedures should be retained. (2) The complications associated with thoracotomy should be obviated. (3) An intrathoracic esophagogastrostomy should be performed.

At the present time, the patients undergoing robotic esophagectomy at our institution

undergo a transabdominal robotic laparoscopic mobilization of the stomach followed by a transthoracic robotic thoracoscopic esophagectomy and an intrathoracic video-assisted esophagogastrostomy.

Part I: Laparoscopic gastric dissection: The patient is placed in a supine position. Five abdominal ports are placed on the anterior abdominal wall, an approach similar to laparoscopic antireflux procedures. We prefer a 10–12 VersaPort (Auto Suture; US Surgical Inc.) for each of the trocar sites and Visiport instrument (Auto Suture) for entry into the peritoneum. The peritoneum is entered below the umbilicus using the Visiport instrument. The abdomen is inflated and ports #2 and #3 are placed at the level of the umbilicus at the right and left mammary lines. A Diamond-Flex (Snowden Penser, Tucker, GA) liver retractor is introduced through port #2 and placed under the left lateral segment of the liver. The retractor is fixed by a self-retaining system (Mediflex; Velmed, Waxford, PA) to the operating table. This maneuver exposes the esophageal hiatus. An endoscopic Babcock is introduced through port #3 and used to retract the stomach inferiorly. Ports #4 and #5 are placed in the subcostal region and are positioned to “line up” with the left and right sides of the esophageal hiatus. The phrenoesophageal ligament is opened using Endoshears and the esophagogastric junction is exposed. The Harmonic Scalpel (Ethicon Endo-Surgery) is used to divide the gastrocolic omentum and the short gastric vessels. The gastroepiploic artery is preserved. The endoscopic Babcock is removed and fan retractor (Auto Suture) is positioned through incision #3 and the stomach is retracted superiorly. The left gastric pedicle is divided using an endoscopic reticulating 45-mm vascular stapler (Ethicon Endo-Surgery). We generally do not perform a pyloromyotomy or pyloroplasty during the laparoscopic procedure. The occasional postoperative pyloric obstruction has been shown to be easily amenable to balloon dilatation. The gastric tube is constructed by dividing the stomach using an EZ 45 stapler (Ethicon Endo-Surgery) starting just proximal to the right gastric artery on the lesser curve of the stomach and proceeding to the apex of the greater curve. Due to the greater ease of suturing in the chest, the gastric suture line is oversewn using 000 Polypropylene suture during the robotic video-assisted portion of the procedure. The esophagus is divided using the EZ-45 stapler at just above the gastroesophageal junction. Using an endostitch with 0 Ethibond suture, the proximal gastric tube is attached to the transected distal esophagus. The jejunostomy is fashioned by suturing a loop of proximal jejunum onto the anterior abdominal wall with an endostitch instrument and 00 Ethibond suture. A needle catheter jejunostomy kit (Compact Biosystems, Minneapolis, MN) is used to percutaneously place a jejunostomy catheter into the jejunum. The jejunal entry site is further fixed to the anterior abdominal wall in order to prevent spillage and torsion. At the conclusion of the procedure, the right and left side of the right crural arch is sutured using an endostitch instrument with 0 Ethibond suture. This maneuver facilitates suture ligation of the phrenic vein, which overlies the crural arch. The crural arch is opened with Endoshears and the distal esophagus is further mobilized. This maneuver invariably results in a loss of pneumoperitoneum and should be reserved for the conclusion of the procedure. The trocar sites are closed using an EXIT instrument and 0 Vicryl (Ethicon Endo-Surgery). Subcutaneous tissues are closed with 00 Vicryl and the skin is closed with staples. In these patients, esophagectomy and intrathoracic esophagogastrostomy is accomplished using robotic right video-assisted thoracic surgical techniques.

Part II: Robotic right video-assisted thoracic surgical esophagectomy with an intrathoracic esophago- gastrostomy: This portion of the procedure is similar for groups 1 and 2. The room setup on preparation of the robot is covered in a separate chapter in this book.

Anesthesia

Patients undergoing robotic esophagectomy require single-lung ventilation. We prefer a left-sided double-lumen endotracheal tube to a bronchial block. With a double-lumen tube, lung collapse is superior and hilar manipulation does not result in movement of the blocker and compromise in patient ventilation and surgical visualization. It is imperative for the lungs to remain deflated during the robotic procedure. Longer tubing is required as the anesthesiologist occupies a more remote position during the robotic procedure than in the usual video-assisted thoracic surgical procedures.

Patient Positioning

The patient is placed in a full lateral decubitus position. The table is flexed to open the intercostal spaces. The position of the double-lumen tube is reconfirmed after final patient positioning. The patient is then prepared and draped in a routine manner as with all video-assisted thoracic surgical procedures. The superior portion of the drape is allowed to cover the patient's head. The robot is brought in perpendicular to the patient's back. Final fine docking maneuvers are performed by unlocking the table and positioning the patient into the robotic arms.

Stage 1: Routine VATS for Division of the Azygous Vein

The procedure begins with using standard video-assisted thoracic surgical instrumentation and incisions. The surgeons stand facing the patient's back. A 2-cm incision is made in the sixth intercostal space in the mid-axillary line (incision #1). A 10-mm metal trocar is introduced, and a zero-degree Olympus EndoEYE video endoscope is used for this portion of the procedure. Three other 2-cm incisions are made. Incision #2 is made in the third intercostal space in the anterior axillary line. Incision #3 is made in the fifth intercostal space in the posterior axillary line. Incision #4 is made in the eighth intercostal space in the anterior axillary line. Incisions #1, #2, and #3 are used during the VATS portion of the procedure. Incisions #1, #2, and #4 are used during the robotic portion of the procedure. An atraumatic paddle retractor (Auto Suture) is introduced through a 10-mm port in the seventh intercostal space in the anterior axillary line. At the end of the procedure, a 28-Fr straight chest tube is introduced through this port and positioned in the posterior aspect of the pleural space. The paddle retractor is used to sweep the lung medially and enhances exposure of the posterior mediastinum. Once the optimal position of the retractor is attained, it is held in place by a mechanical holder (Mediflex; Velmed, Wexford, PA) and fixed to the operating room table. At this point, a 30-degree Olympus EndoEYE video endoscope is introduced through incision #1. Incisions #2 and #3 are used to dissect the azygous vein. An endoscopic reticulating 45-mm vascular stapler (Ethicon Endo-Surgery) is used to divide the azygous vein.

Stage 2: Robotic Esophagectomy

Following the division of the azygous vein, esophagectomy is accomplished using the robot. A paddle retractor is introduced through incision #4 and the lung is retracted medially. The robot is brought over the head of the patient. The camera port is positioned in incision #1. The right robotic arm with the hook cautery is positioned through incision #2. The left robotic arm with a robotic DeBakey forceps is positioned through incision #3. A metal suction is introduced by the first assistant under the robotic arms in incisions #2 and #3 and used to evacuate smoke, provide retraction, and remove blood from

the field. Dissection is started just posterior to the right mainstem bronchus and the subcarinal nodes are dissected away from the carina and toward the esophagus. Next dissection is continued in a caudad direction just posterior to the lung down to the level of the esophageal hiatus. Tissue is removed from back of the pericardium and the inferior pulmonary vein and all tissues are swept toward the esophagus. Next a posterior dissection is begun in a line parallel to the anterior border of the azygous vein. All periesophageal tissue is dissected from the esophageal hiatus to above the azygous vein. At the conclusion of the dissection, the left pleura should be seen at the depth of field of dissection. Furthermore, the posterior pericardium should be seen anteriorly, the aorta should be seen posteriorly, and the left mainstem bronchus and distal trachea should be clearly visible superiorly. Following an en bloc dissection of the esophagus, the right robotic arm is used to place Hemoclips on the thoracic duct, which is invariably damaged as a result of extensive mediastinal exenteration. The nasogastric tube is withdrawn and the esophagus is transected above the azygous vein.

Stage 3: Intrathoracic Stapled Esophagogastrostomy or Robotic-Hand-Sewn Esophagogastrostomy

We have used two anastomotic techniques. Both techniques will be presented. Presently, our preference is a robotic-hand-sewn end-to-side esophagogastrostomy.

After an extensive esophageal dissection, which is enabled by the robot, conventional video-assisted thoracic surgical techniques are used for the creation of esophagogastric anastomosis. A 30-degree Olympus EndoEYE video endoscope is placed in incision #4 and provides a panoramic view of the pleural space. The esophagus specimen is placed in an Endopouch and withdrawn through incision #2. The pathologist is instructed to examine the proximal and distal resection margins. Using atraumatic pediatric lung clamps, the stomach tube is delivered into the right chest. Great care is exercised to avoid excessive tension on the gastric wall in order to avoid disruption of the intraluminal vessels. Furthermore, just enough stomach is pulled to the level of thoracic inlet in order to prevent kinking at the level of the hiatus. Finally, the greater curve is positioned in the mediastinum and care is taken not to twist the stomach tube. For the creation of an intrathoracic esophagogastric

anastomosis, we prefer a circular 25-mm End-to-End Anastomosis Stapler (Ethicon Inc). In order to ensure incorporation of the esophageal mucosa into this staple line, the esophageal mucosa and muscle are sutured together at 3, 6, 9, and 12 o'clock positions. Long 000 silk sutures are used and two dots are placed using extracorporeal knot-tying techniques and a knot pusher. A purse string suture of 000 polypropylene is placed on the esophagus using "Lewis" thoracoscopic needle drivers (Thoramet, New Jersey, USA) introduced through incisions #2 and #3 and used to drive and retrieve the needle. The

anvil of the stapling device is introduced into the esophagus and the purse string suture is tightened using a knot pusher. At this point the anvil is held in place using a kidney pedicle clamp, which is introduced through incision #2. The placement of the clamp on the distal aspect of the anvil prevents migration into the proximal esophagus. The anterior wall of the stomach tube is opened using electrocautery and two full-thickness sutures of 00 polypropylene are placed at 3 and 9 o'clock positions and brought out through incision #1. These sutures will provide appropriate traction on the stomach wall during stapling maneuvers. A disposal suction is used to clear the stomach tube of all contents. This allows manipulation of the stomach without spillage into the pleural space. The shaft of the EEA instrument is introduced through incision #1 into the pleural space. The EEA is then passed through the gastrostomy toward the apex of the stomach tube. After exiting through the apex of the stomach, the EEA instrument is used to engage the anvil and closed, thus creating an esophagogastrostomy. Following the creation of the anastomosis, the instrument is withdrawn from the gastrostomy and placed in an Endopouch and withdrawn out of the pleural space. The doughnuts of tissue are examined to determine the need for further reinforcement of a specific location on the circular anastomosis. The internal aspects of the anastomosis is further inspected by visualization through the gastrostomy. We routinely place 000 silk horizontal mattress seromuscular sutures at the anastomosis. These sutures are tied using extracorporeal knot tying techniques and a knot pusher. The gastrostomy is closed using a roticulating 45-mm endoscopic stapler (Ethicon Inc.) with a thick tissue insert. The staple line is further reinforced with a running 000 polypropylene suture. The nasogastric tube is passed by the anesthesiologist through the esophagogastric anastomosis and positioned at the distal portion of the stomach tube. All suture lines are covered with "crossseal" (Ethicon Inc.) fibrin sealant. The gastric tube is tacked to the posterior pleural using 000 silk sutures. A small flat Jackson-Pratt drain is introduced through incision #4 and positioned in the mediastinum adjacent to the esophagogastric anastomosis. As stated earlier, the retractor is removed and replaced with a 28-Fr straight chest tube, which is positioned in the posterior aspect of the pleural space. The lung is reinflated. The four incisions are closed with en bloc musculo-subcutaneous sutures of 0 PDS (Ethicon, Inc). Skin is closed with interrupted mattress sutures of 00 polypropylene.

In order to accomplish robotic hand-sewn anastomosis, the robot is positioned with camera through incision #1, right and left robotic arms each carrying a needle driver through incisions #2 and 3. A two-layer running anastomosis is fashioned. The esophagus is placed onto the superior aspect of the stomach tube. A running barbed nonabsorbable suture (V-Lock PBT; Covidian, USA) is used to approximate the posterior layer of the esophagus to the serosa of the stomach. This suture is left in the chest and used to complete the anterior nonabsorbable layer. The stomach is opened and using a running barbed absorbable suture (V-Lock 180; Covidian) the inner posterior and anterior layer of the anastomosis is completed. Following the inner layer the nonabsorbable suture is picked up and used to complete the anterior second layer of the anastomosis.

Patients routinely undergo bronchoscopy with removal of secretions and tracheobronchial toilet prior to extubation. An upper gastrointestinal study with water-soluble contrast is

obtained on postoperative day 7.

Results

During a 24-month period, 46 patients underwent robotic Ivor–Lewis esophagogastrostomy with intra-thoracic esophagogastrostomy at our institution. There were 31 men, 15 women, with a mean age of 72 ± 5 years. All patients had preoperative neoadjuvant therapy. Mean operative time was 8.6 hours with a range of 8–17 hours. Esophagogastrostomy was performed above the azygous vein in all patients. During the early part of our robotic experience, 13 intrathoracic esophagogastronomies were performed using the EEA technique. In the latter portion of our experience, 33 of 46 patients underwent a robotic-hand-sewn esophagogastrostomy. There were two nonemergent conversions to a thoracotomy due to difficulty with the anastomosis. These were both in patients who underwent the EEA technique. All tumors were in the distal esophagus. The average number of nodes was 16 ± 3 . The median intensive care unit stay was 3 days with a range of 1–7 days. The median hospitalization was 9 days with a range of 8–12 days. There was one anastomotic leak with the EEA technique. The major complications were pneumonia in 3 percent and atrial fibrillation in 16 percent of patients. There were no in-hospital deaths.

ROBOTIC TRANSTHORACIC HELLER MYOTOMY

The emergence of video endoscopic techniques changed the approach to the surgical therapy of achalasia. Laparoscopic techniques allowed for better transabdominal visualization and manipulation of the gastroesophageal junction. Until the advent of laparoscopy, visualization of the gastroesophageal junction by virtue of its location deep under the costal arch required extensive retraction. Even with the use of self-retaining retractors, visualization of the gastroesophageal junction remained suboptimal. As a direct result of the inability to see, open transabdominal myotomy was associated with poor results. The extensive use of laparoscopy for fundoplication in patients with gastroesophageal reflux disease provided greater facility and familiarization with the anatomy of the gastroesophageal junction. It was not difficult to extrapolate the techniques used for fundoplasty to the procedure of esophageal myotomy, which, if performed transabdominally, required an antireflux procedure at any rate. Unlike conventional surgery, video endoscopic techniques were associated with lower morbidity and pain, as well as shorter hospital stays. Therefore, these minimally invasive techniques with the promise of better long-term results were more favorable to nonsurgical approaches and found acceptance among patients and medical practitioners.

In 1991, Shimi et al. reported the first laparoscopic experience for Heller myotomy, and Pellegrini et al. reported a series of patients who had undergone esophageal myotomy using the thoracoscopic approach (65,66).

Laparoscopic Approach

The object of laparoscopic esophageal myotomy and anterior fundoplication is to perform myotomy of the lower 6 cm of the esophagus and the proximal 2 cm of the stomach. In

order to access the intra- thoracic esophagus, this procedure requires full dis- section of the right crus of the diaphragm and the entire esophageal hiatus. Consequently, following myotomy, a partial anterior gastric fundoplication is performed as an antireflux procedure. Invariably, all series reporting the laparoscopic approach to Heller myotomy have shown excellent relief of dysphagia (67). In one series of 133 patients who had undergone laparoscopic myotomy with a partial fundoplication, Patti et al. reported 11 percent persistent dysphagia, 17 percent new gastroesophageal reflux, and 5 per- cent mucosal perforations, which were amenable to laparoscopic closure (68). The majority of difficulties with the laparoscopic approach were related to reflux and the technical aspects of fundoplication. In a series of 69 patients undergoing laparoscopic myotomy and fundoplication for achalasia, Finley et al. reported a median operative time of 1.9 hours, one mucosal per- foration that was amenable to laparoscopic repair, 96 percent patient satisfaction for relief of dyspha- gia, and a 9 percent rate of new postoperative gastro- esophageal reflux (69).

Thoracoscopic Approach

During the thoracoscopic approach, the esophagus is approached through the left chest. The myotomy is carried down to the gastroesophageal junction. During this approach, either the gastroesophageal junction is left intact or the left rim of the right crus is opened and subsequently reapproximated following the myotomy. With the thoracoscopic approach, an antireflux procedure has not been necessary. Whereas the complications of the laparoscopic approach have been related to reflux and antireflux procedures, the thoracoscopic approach has suffered from the dif- ficulty of residual achalasia and the steep learning curve associated with obtaining a complete myot- omy. The most important complication following the thoracoscopic approach has been incomplete myot- omy and persistent dysphagia. Pellegrini et al. have reported that after thoracoscopic myotomy, dyspha- gia was relieved in 70 percent of patients, 12 percent of patients had residual achalasia, and mild reflux was seen in 20 percent of patients. Stewart et al. reported esophageal perforation in 12 percent of patients undergoing thoracoscopic esophageal myotomy and conversion to thoracotomy in 21 percent of patients. The mean hospitalization for this group of patients was 6 days. In the same group at 42 months, 31 percent of patients had relief of dysphagia and 23 percent of patients had new gastroesophageal reflux. Patti et al. reported a 6 percent conversion to a thoracotomy, a 73 percent rate of relief of dysphagia, and a 25 per- cent rate of incomplete myotomy. The data shows the laparoscopic procedure to have a lower conversion rate to an open procedure and to be associated with lower morbidity and shorter hospitalization. Most importantly, the laparoscopic Heller myotomy with an anterior fundoplasty has shown excellent relief of dysphagia at the expense of a higher rate of new gastroesophageal reflux. Due to these results at the present time, the laparoscopic approach has become the initial approach of choice for patients undergoing surgical palliation for achalasia.

Thoracoscopic Heller Myotomy Program at Our Institution

Our experience with both laparoscopic and thoraco- scopic approaches to esophageal myotomy has led to the following conclusions:

1. Although easier, the laparoscopic approach necessitates the disruption of the esophageal hiatus and extensive mobilization of the esophagus. Due to this fact,

the antireflux procedure is added to the myotomy. The clinical results reveal an excellent relief of dysphagia.

However, the complications associated with this technique relate to the high rate of gastroesophageal reflux disease even with an antireflux procedure and the problems

associated with the added antireflux procedure itself.

2. When performing a thoracoscopic Heller myotomy without disrupting the esophageal hiatus, the thoracoscopic approach is associated with a much lower rate of new postoperative gastroesophageal reflux disease. However, this procedure is hampered by the technical difficulties of performing a complete myotomy. Consequently, this technique has suffered from lower rates of dysphagia relief. We have reasoned that adapting the procedure performed through a left thoracotomy and described by Ellis et al,

where a through transthoracic approach a Heller myotomy was performed without the need for an

antireflux procedure, to video endoscopic techniques, there would be excellent relief of dysphagia with low

incidence of new gastroesophageal reflux disease. Indeed, this

has been the goal of our thoracoscopic Heller myotomy program.

Our experience with the thoracoscopic approach to esophageal myotomy has been in two phases.

Phase I: VATS with Intraoperative Manometry

The first thoracoscopic Heller myotomy by the senior author was performed in 1992. As a result of the initial thoracoscopic experience, it was obvious that with a loss of tactile input during VATS, assessment of the completeness of esophageal myotomy was very difficult. This problem was resolved by the use of intraoperative esophageal manometry.

Online direct intraoperative monitoring of pressure at the distal esophagus by manometry was invaluable in confirming the completeness of myotomy. As the last circular esophageal muscle fibers responsible for high distal esophageal pressure were divided, the online esophageal monitoring would record a decrease in pressure to the normal range. We reasoned that normal pressure reading (8–15 mmHg) at the esophagogastric junction reflected completeness of myotomy and the intact nature of the anti-reflux barrier. Using this technique, the results were gratifying.

In an 8-year period, 32 patients underwent VATS esophageal myotomy with intraoperative manometry. There were five intraoperative mucosal injuries, which were repaired primarily. Postmyotomy, the mean esophagogastric junction pressure decreased from 26 ± 3.3 to 9.1 ± 0.9 mmHg. The median hospitalization for patients with and without a mucosal injury was 7 and 4 days, respectively. Mean follow-up was 38 months. All patients experienced postoperative improvement in dysphagia. Fifty-six percent had no dysphagia, and 44 percent had mild to moderate dysphagia. The patients with postoperative dysphagia had a dilated esophagus on preoperative esophagography. Of these patients, 9 out of 14 (64 percent) showed improvement of dysphagia at the time of follow-up. During follow-up, 84 percent of patients had

good to excellent relief of dysphagia, and 28 percent of patients had mild reflux, which responded to ant-acid therapy.

Although the results with VATS Heller myotomy were gratifying, this approach represented a technically challenging procedure that required significant experience with video-assisted thoracic surgery. It was obvious that in order for this approach to gain widespread acceptance, the procedure needed to be refined and become more "surgeon-friendly." A number of obstacles remained.

1. During video-assisted thoracic surgery, thoracoscopic instruments are introduced through a small hole in the chest wall. The instruments pivot at the entry point, which makes fine control of the instrument tip, usually located at a remote location, difficult and cumbersome. The "chopstick" nature of the movements of VATS instruments stems from the fact that the rigid shaft axis of the instruments is fixed at entry site on the chest wall. Consequently, the VATS instruments are limited to maneuvering in four directions (up, down, left side, and right side). Obviously, this technical feature of VATS presents the greatest limitation for complex dissection, especially in a remote confined space. During pivoting at the chest wall, as the tip of the VATS instrument is moved further from the entry site, mobility of the instrument and its maneuverability in relation to the remotely positioned tissue decreases. Indeed, it is as though the surgeon is operating at the apex of a pyramid with instruments that are pivoted at the base of that structure.

2. Another shortcoming of the VATS technique is the lack of three-dimensional visualization. Although a surgeon with facility and experience with VATS uses the two-dimensional information from the video monitor and combines the visual input with tactile input to form a three-dimensional mental image, the fragile nature of the tissues, the confined space, and the paucity of tactile information when performing an esophageal myotomy result in a very poor mental three-dimensional image. Binocular three-dimensional vision with adequate depth perception is crucial to the task of separating the esophageal mucosa from the muscle and dividing the esophageal muscle fibers.

By addressing these shortcomings, the da Vinci robot represents an ideal tool for the accomplishment of video endoscopic transthoracic Heller myotomy. The beneficial features of the da Vinci platform are:

The EndoWrist

The EndoWrist is a cable-driven wrist at the end of the robotic arm. The placement of the robotic arm through the VATS hole is comparable to the chopstick maneuvers of conventional VATS instruments. The EndoWrist at the distal end of the robotic arm is then positioned in the confined space and brings four more degrees of freedom and six more directions of movement to the maneuverability already possible by the movement of the robotic arm pivoting at the entry site. The movement of EndoWrist allows for movement of distal instruments much like the movements of the surgeon's wrist during conventional surgery.

Downscaling

The da Vinci robotic system is designed to provide downscaling from the motion of the surgeon's hands to that of the robotic arm. This is invaluable in dissecting the fine and fragile

tissues of distal esophagus. Furthermore, a fixed Hz motion filter is used to filter out the tremor in the surgeon's hand and enhance the accuracy of surgical dissection.

Binocular Vision

The binocular robotic camera provides superb three-dimensional visualization and, by nature of being mounted on the central robotic arm, it is manipulated by the surgeon. The result of this is an immobile field of vision with high resolution and magnification and total control of movements by the surgeon. The ability to manipulate the camera and the robotic arms recreates the surgeon's own natural head, eye, and wrist motions as used during open procedures and enhances hand-eye coordination.

Operative Technique

Anesthesia

Patients undergoing video-assisted thoracic surgical Heller myotomy require single-lung ventilation. We prefer a left-sided double-lumen endotracheal tube over a bronchial blocker. With a double-lumen tube, lung collapse is superior and hilar manipulation does not result in movement of the blocker and inadvertent expansion of the lung. As is addressed in a separate chapter in this book, the facility of the anesthesiologist with robotic techniques is crucial to the conduct of the surgery. Following the induction of anesthesia, with the patient in the supine position, upper GI endoscopy is performed. The gastroesophageal junction is identified and a nasogastric tube is positioned under direct vision into the stomach. Decompression of the stomach facilitates retraction of the diaphragm and enhances visualization of the gastroesophageal junction. While the patient is in the supine position, the gastroscope is pulled back to the distal esophagus and secured for patient positioning. As described by Pellegrini et al., the gastroscope plays a significant role during the myotomy procedure. First, it allows for identification of the left lateral wall of the esophagus without the need for extensive mobilization of a circumferential dissection of the esophagus. Second, it transilluminates the esophageal mucosa and helps in identification of the area of incomplete myotomy. Third, by application of intraluminal suction to the mucosa during the myotomy procedure, the mucosa is pulled toward the lumen of the esophagus, thereby exposing the anterior plane between the esophageal mucosa and the muscle of esophagus.

Patient Positioning

The patient is placed in an extended right lateral decubitus position. The table is fully flexed to enlarge the space between the ribs. The surgeon stands behind the patient. A monitor is positioned at the patient's feet and a second monitor is positioned in front of the patient facing the surgeon. The robot is positioned in front of the patient. During the robotic portion of the procedure, the robot is brought into the operative field from an anterior to posterior direction facing cephalad at 30 degrees to the axis of the patient.

Myotomy

After the patient is prepped and draped, a 2-cm incision (#1) is made in the seventh intercostal space in the mid-axillary line. This incision will serve as a camera port during the VATS and robotic portions of the operation. A second 2-cm incision (#2) is made in the

sixth intercostal space anteriorly at the anterior axillary line. A third 2-cm incision (#3) is made in the sixth intercostal space posteriorly at the mid-scapular line. A fourth 1-cm incision is made one interspace below the anterior incision and as far inferiorly as possible. This incision will be used for the placement of diaphragmatic retractor, and at the conclusion of the procedure, it will be used for the placement of drainage chest tubes. It is paramount that this incision be positioned as far anteriorly from incision #2 in order to decrease interference with the robotic arm. As has been described in Chapter 19 in this book, we prefer the Olympus EndoEYE video endoscopic system. A 10-mm 0-degree end-viewing scope is positioned initially viewing cephalad over the diaphragm. The inferior pulmonary ligament is divided and the lung is retracted superiorly. The table is positioned in Trendelenburg to allow the lung to fall into the apex of the chest. The camera is then rotated 180 degrees to view the distal esophagus at the diaphragm. The surgeon and the surgical team then rotate their field of vision and use the video monitor at the patient's feet for the next phase of the procedure. In order to retain intuitive spatial relationships, it is imperative that the surgical team view the surgical site in the same direction and axis as the video endoscope. The gastroscope is rotated to the patient's left and its tip is flexed, thus allowing the surgeon to visualize the distal esophagus without the need for further dissection. Using conventional Endosheers (Ethicon Endosurgery, Cincinnati, OH) with cautery attachment, the pleura overlying the esophagus is divided. An Endostitch instrument (Auto Suture, US Surgical, Norwalk, CT) with a 2-0 Ethibond suture is used to place retraction sutures on the two edges of the pleura. The sutures are then brought out through the anterior and posterior incisions (incisions #2 and #4) and fixed to the drapes. This maneuver creates a pleural sling and elevates the esophagus from its normal mediastinal location into the left pleural space. A fan retractor (Ethicon Endosurgery, Cincinnati, OH) is introduced through the anterior (#4) incision and positioned on the posteromedial aspect of the diaphragm and used to retract the diaphragm inferiorly. This retractor is fixed to the table by the use of a mechanical holder (Mediflex; Velmed, Inc., Wexford, PA). The esophageal hiatus is identified and the left lateral limb of the right crus of the diaphragm is divided using the Endosheers with cautery. The dissection is discontinued with the visualization of the phrenoesophageal ligament on the underside of the diaphragm. Using the Endostitch instrument with a 0 Ethibond suture, full-thickness retraction sutures are placed on the cut edges of the diaphragm and brought out through the anterior and posterior incisions, respectively (#2 and #4). The sutures are fixed to the drapes. This maneuver allows for a full visualization of the esophagogastric junction. At the end of the procedure, the cut edges of the right limb (RL) of the right crus of the diaphragm are reapproximated using an Endostitch instrument with 0 Ethibond suture. Usually, three such sutures are necessary. By avoiding disruption of the anterior crural arch and by restoring the integrity of the RL of the right crus of the diaphragm, the crural sling is preserved and the antireflux barrier remains intact. At this point, the VATS camera is removed and the robot is positioned. The robot is brought in from the anterior aspect of the patient. It is positioned caudad to cephalad with 30-degree rotation in the cephalad direction on the patient's axis. The camera port is positioned in the camera incision (#1) and a 30-degree down-viewing scope is positioned viewing caudally onto the distal esophagus. The

right robotic arm with a hook end-effector instrument connected to a cautery is placed through the anterior incision (#2) and its EndoWrist is positioned directly over the distal esophagus. A left robotic arm with a DeBakey forceps as its distal end-effector instrument is positioned through the posterior incision (#3) and its EndoWrist is positioned directly over the distal esophagus. A metal suction with a blunt tip is positioned through the anterior incision below the entry point of the right robotic arm. The suction is used by the assistant to evacuate cautery smoke, control bleeding, and provide downward force on the esophageal mucosa during the myotomy, should this become necessary. With binocular view and depth perception and the facility of EndoWrist movements, the performance of esophageal myotomy is quite accurate and uncomplicated. The muscular wall of the esophagus is exposed and the muscle is divided with a hook cautery at the midpoint of exposed esophagus. The anatomic plane between the mucosa and the muscle is identified. The blunt metal suction is positioned on the mucosa, endoluminal suction is also applied using the video gastroscope. The robotic forceps are used to elevate the muscle layers. The culmination of these maneuvers allows for the hook cautery (blended coagulation current set at 30

W) to be used to divide the muscle of the esophagus. As the distal aspect of the esophagus and the intussuscepted portion of the esophagus into the proximal stomach is approached, the robotic forceps are used to reduce the intussusception by pulling the esophagus in a cephalad direction. The hook cautery then completes the myotomy approximately 1 cm onto the cardia of the stomach. Myotomy is discontinued when the submucosal vascular plexus of the stomach wall is visualized. At this point, the gastroscope is advanced past the gastroesophageal junction into the stomach. The ease of movement of the gastroscope into the stomach and the lack of resistance confirms a complete division of the esophageal muscles at the gastroesophageal junction. Furthermore, the gastroscope is retroflexed to view the gastroesophageal junction from a caudad to cephalad direction. The observation of the transilluminated mucosa of the proximal portion of stomach cardia from the light of the robotic camera serves as the final confirmation for a completion of esophageal myotomy. Following the completion of myotomy, the chest is filled with saline and the gastroscope is used to insufflate air into the stomach and esophagus to rule out any mucosal perforation. Any mucosal perforations are easily repaired by the endoscopic techniques and use of 4-0 Prolene sutures. The robotic arms are retracted and the robot is moved away from the table. At this juncture, the conventional VATS EndoEYE camera is inserted through the camera port, and the left limb (LL) of the right crus of the diaphragm is reapproximated as described earlier. At this point, a 2-cm square piece of Vicryl mesh (Ethicon, Inc., Somerville, NJ) is positioned at the distal aspect of the mediastinum. This absorbable mesh is attached to the edges of the mediastinal pleura using the Endostitch with 2-0 Ethibond sutures. We have found that the Vicryl mesh, which is absorbed and replaced by scar tissue approximately 8 weeks following implantation, reestablished the integrity of the pleura on the left lateral aspect of the esophagus and repositions the distal esophagus into the mediastinum. Furthermore, this maneuver with the resultant scarring of the pleura prevents the formation of a mucosal diverticulum at the distal portion of the esophagus. It has been

hypothesized that the mucosal diverticulum may be one of the causes of chronic dysphagia even with an adequate myotomy when a fundoplasty is not performed. In fact, some authors have proposed that one of the benefits of fundoplasty is the prevention of a mucosal diverticulum by placing external pressure on the mucosa. Prior to the employment of this technique, we had observed mucosal out-pouching at the distal esophagus and the level of gastroesophageal junction in a number of patients. This technique seems to have addressed that issue without any negative sequelae. Following pleural closure, the diaphragmatic retractor is removed. The lung is reinflated under direct vision. A 28-Fr straight chest tube is inserted through incision #4 and positioned posteriorly in the pleural space. ON-Q Pain Buster catheters are positioned in a subpleural tunnel extending from the second to the eighth intercostal spaces and the incisions are closed as described in Chapter 19 for video-assisted surgery. The gastroscope is used to confirm the appropriate position of the nasogastric tube. The patient is extubated in the operating room. Postoperatively, we routinely obtain an upper GI contrast study with water-soluble contrast to rule out mucosal perforation and to confirm completeness of distal esophageal myotomy. With a satisfactory study, a soft diet is started, the chest tube is removed, and most patients are discharged on the second postoperative day.

ROBOTIC LAPAROSCOPIC BELSEY MARK IV FUNDOPLASTY

Gastroesophageal reflux disease is the most common disease of human, affecting approximately 20 percent of Americans (70). Normal individuals experience some GERD on a regular basis (71,72). Pathologic reflux results in injury to the esophagus and the upper aerodigestive tract. GERD has been shown to be a strong risk factor for esophageal carcinoma (73). Curiously, esophageal adenocarcinoma has nearly quadrupled in frequency in the United States since the 1980s, when oral and acid medications have had their greatest use (74,75). GERD classically presents as heartburn and regurgitation. In addition to the classic presentation, GERD can present with a number of atypical symptoms that stem from exposure of the upper aerodigestive tract to gastric contents (76).

This procedure combines the excellent visualization and maneuverability of the da Vinci robot for the dissection and identification of hiatal structures, with the speed and ease of laparoscopic suturing techniques.

The procedure has two parts: (1) robotic dissection and exposure, (2) conventional laparoscopic crural closure and fundoplasty.

Robotic Dissection and Exposure

The patient is placed in the lithotomy position. The surgeon stands between the legs. Two laparoscopic insufflators are used. We prefer to use the Visiport instrument (US Surgical Corp.) for initial port entry into the peritoneum. Port #1 (camera port) is placed inferior to the umbilicus. A small curvilinear incision is made under the umbilicus. A Kocker clamp is used to grasp the frenulum of the umbilicus and to elevate the anterior abdominal wall. Upward traction

on the clamp provides a countertraction, which is necessary for safe peritoneal entry under video endoscopic guidance using the Visiport instrument. Pneumoperitoneum is created using CO₂ gas to a maximum pressure of 15 mmHg. The table is placed in a steep reverse Trendelenburg position. Under direct video endoscopic guidance, four other ports are placed. We prefer to use the 10–12 Visiport trocar (US Surgical Corp.) for all ports. These ports do not require reducer caps. The capless design of these ports enables rapid instrument change without loss of pneumoperitoneum. A 0-degree Olympus EndoEYE video endoscope is introduced through port #1. Port #2 is placed in the right paraumbilical region at the right mammary line. Port #3 is placed in the left paraumbilical region in the left mammary line. An endoscopic paddle retractor is introduced through port #2 and used to place downward traction on the gastroesophageal junction and to expose the phrenoesophageal ligament. Using the video endoscope, the left and right limbs of the right crus are identified. Port #4 is placed in the subcostal region halfway between the umbilicus and the xiphoid just to the left of the midline. This port is aligned with the RL of the right crus of the diaphragm. Port #5 is placed in the subcostal region two finger breaths to the left and caudad to port #4. Port #5 is aligned with the LL of the right crus of the diaphragm. A Diamond-Flex retractor (Snowden Pencer, Tucker, GA) is placed through port #5 and fixed to the table using a self-retaining system (Mediflex). The laparoscopic insufflator is disconnected from port #1 and attached to port #4. A second insufflator is attached to port #5. The use of two high-flow insufflators facilitates rapid extracorporeal knot placement while preserving pneumoperitoneum and exposure of the esophageal hiatus.

At this point the da Vinci robot is brought in over the patient's head. The head of the table is rotated 30 degrees away from the anesthesia machine on its longitudinal axis to facilitate docking of the robot. A 30-degree down-viewing robotic binocular camera is introduced through port #1. The right robotic arm with a hook cautery instrument is introduced through incision #5. The left robotic arm with a DeBakey grasper instrument is introduced through port #3. The entire dissection uses electrocautery and meticulous hemostasis. Port #5 is used to vent smoke out of the peritoneal cavity. Blood and fluid accumulate in the hiatus, are difficult to evacuate, and tend to discolor the structures. We avoid using a suction irrigator system. The right crural arch is identified. The phrenoesophageal ligament is divided. The hepatogastric omentum is divided and the caudate lobe of the liver is identified. This maneuver necessitates division of the hepatic branch of the anterior vagal nerve and a small arterial branch of the left gastric artery. This vessel is to be distinguished from a large aberrant left hepatic artery, which arises from the left gastric artery in 25 percent of patients. In these patients the hepatic artery should be avoided and dissection should be confined to the superior aspect of the artery. At this point the RL of the right crus is visualized. The lateral and medial borders of the RL are identified. This maneuver facilitates the identification of the esophagus. Lateral traction is placed on the esophagus. The fatty tissue overlying the RL is excised and the RL is followed inferiorly to its junction with the LL of the right crus. Next the dissection of the RL is carried superiorly onto the crural arch and around to the LL of the right crus. The LL is dissected inferiorly by taking down the angle of His and gastric fundal attachments. Medial traction moves the esophagus medially and facilitates the exposure of the entire crural sling. *Importantly, encirclement of the esophagus or division of the short gastric vessels is not required.*

After complete dissection of the esophageal hiatus, the robot is undocked. The remainder of the procedure is accomplished by conventional laparoscopy.

Conventional Laparoscopic Crural Closure and Fundoplasty

Posterior Crural Closure

A 30-degree Olympus EndoEYE video endoscope is introduced through port #1. Posterior crural closure is accomplished by reapproximating the RL and LL with three sutures. We prefer the Endostitch instrument (Auto Suture) with 0 Ethibond suture. The Endostitch instrument is an ideal suturing device for laparoscopy as it facilitates one-handed suturing thereby allowing the surgeon's left hand to provide appropriate exposure. Furthermore, when approximating the RL and LL of the right crus posterior, the straight needle of the Endostitch instrument passes in a tangential plain to the anterior aspect of the aorta and carries a lower risk of inadvertent aortic injury, which results from deep suture placement. Conversely, the curved needle used with a laparoscopic needle driver can pass deeper than intended and can engage the anterior wall of the aorta.

The grasper in the surgeon's left hand is placed on the medial aspect of the esophagus and used to retract the esophagus lateral and to the left. The maneuver exposes the "V"-shaped posterior junction of the RL and LL of the right crus. A 1 cm² absorbable pledget cut from Vicryl mesh (Ethicon, Inc.) is passed through port #4. The end stitch with 0 Ethibond is passed through port #5. Intracorporeally the pledget is loaded onto the needle. The needle is passed through LL and RL. Next intracorporeally the needle is passed through a second Vicryl pledget, which is introduced with the grasper in the surgeon's left hand. The Endostitch carrying the suture is withdrawn out of the entry port #5 and extracorporeal knots are placed using a knot pusher. The suture is cut above the knot. This technique is repeated for all the posterior crural sutures.

Anterior Crural Closure

In a similar manner to the posterior crural closure, 0 Ethibond sutures on the Endostitch instrument with intracorporeally loaded pledgets of Vicryl mesh are used to reapproximate the anterior portion of the crural arch. This step represents a modification of the original Belsey Mark IV technique. However, in our experience, the anterior crural closure allows for the formation of an acute angle at the gastroesophageal junction and recreates one of the important features of the normal antireflux barrier. The sutures are passed through port #5, a Vicryl pledget is loaded on the suture intracorporeally, and the suture is passed through the RL and LL of the crural arch. A second Vicryl pledget is loaded intracorporeally onto the suture and the suture is tied using extracorporeal technique as outlined previously. Usually two or three anteriorly placed sutures are required. The crural closure is sized properly based on the passage of a 60-Fr bougie. After an extensive number of cases, we have determined that the ability to pass a grasper freely between the esophagus and the anterior crural closure reapproximates the sizing of the crural closure, which is achieved with the bougie. Presently we prefer this technique

for crural sizing. Following crural closure, the Belsey fundoplasty is performed.

Belsey Fundoplasty

The anterior intussusception of the esophagus into the stomach is accomplished for the anterior 270 degrees (from RL to LL of the right crus) of the 360-degree circumference of the esophagogastric junction. The esophagogastric fat pad is removed. The esophagus is marked 2 cm above the esophagogastric junction at the medial border of the left vagus nerve (E1), the lateral border of the right vagus nerve (E3), and half way in-between (E2). The stomach is marked 2 cm below the gastroesophageal junction at the greater curvature (G1), the lesser curvature (G3), and at a point half way between G1 and G3 (G2). The Endostitch instrument with 00 Ethibond is introduced through port #5. The first Belsey suture (E1-G1, greater curve) passes in mattress fashion from G1 to E1 back to G1. A Vicryl pledget is introduced with a grasper through port #4. The pledget is loaded onto the Endostitch intracorporeally before and after it is passed through E1. Placement of absorbable pledget on the two sides of the esophageal "bite" decreases the risk of tears of the esophageal muscle. Consequently the order of suture placement is (G1-pledget-E1-pledget-G1). The suture is withdrawn through port #5. Metal clips are placed on the free ends of the suture to facilitate identification and recovery of the suture at a later point. The untied suture is reintroduced through port #5 and deposited in the left upper quadrant away from the gastroesophageal junction. This suture is tied a later time. Placing a tie on the "G1-E1" suture at this time will obscure the precise placement of "E2-G2" and "E3-G3" sutures. A second Belsey suture ("E3-G3," lesser curve) is passed in a similar manner from G3 to E3 back to G3, withdrawn through port #5, tagged with metal clips, and deposited in the right upper quadrant away from the gastroesophageal junction. This suture will be tied a later time. The third Belsey suture ("E2-G2," midpoint) is introduced in the same manner from G2 to E2 back to G2. This suture is withdrawn from port #5 and tied using a knot-pusher and extracorporeal knots. Next the "E1-G1" suture is withdrawn out of port #5 and tied. Finally the "E3-G3" suture is withdrawn out of port #5 and tied.

Placement of the first row of mattress Belsey sutures results in the intussusception of the esophagus into the stomach by 2 cm for 270 degrees.

Next three mattress sutures of 00 Ethibond are placed from the stomach at G1, G2, and G3 onto the anterior crural closure at LL, midpoint of the crural arch, and RL of the right crus, respectively. This second row of sutures places the entire fundoplast under the diaphragm. An Endostitch instrument with 00 Ethibond is introduced through port #5. The suture is passed into the stomach just below G1 and through the RL of the right crus. The suture is withdrawn from port #5 and tied by extracorporeal technique. A second 00 Ethibond suture is placed on the stomach just below G2, passed through the midpoint of the anterior crural closure and tied. A third 00 Ethibond suture is passed just below G3, passed through the LL of the right crus of the diaphragm and tied. The trocar sites are closed using an EXIT instrument and 0 Vicryl (Ethicon Endo-Surgery). Subcutaneous tissues are closed with 00 Vicryl and the skin is closed with staples.

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Part 3 Research Overview

Overview of Robot-Assisted Surgery

Roya Saffary, Alex Macario, and Bassam Kadry

Development of Robots

In 1921, the Czech playwright Karel Capek introduced the term “robot” in his play *R.U.R.*, and while he has been credited for coining the term (1), he later acknowledged his brother, Josef Capek, as the real inventor (2). Originating from the Czech word *robota*, meaning “forced labor,” this term referred to the type of labor that peasants had to perform in a feudalistic society. For his play, Capek used the term to describe

manufactured humans or clones. In contrast, the current definition of the word describes “a machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer” (3).

The word “robot” evokes different images for different people. Science fiction, both in print and in movies, has played a major role in shaping our understanding and familiarity with the idea of robots, which has ranged from helpful assistance completing small tasks to fully functioning, human-like machines. As their mechanical complexity and precision has improved, they have been deployed in a growing number of industries, with their usage likely to increase further. This chapter is intended to provide an overview of robotic development over time. In addition to providing a timeline (Box 1.1), this chapter also offers details about the specific models with a summary of the unique innovations in Table 1.1.

Since the dawn of the field, robotic design has progressed from simple, repetitive functions to multistep complex tasks. One of the first roboticists, William Grey Walter, built two three-wheeled robots, Elmer and Elsie, which were capable of phototaxis (4). These machines, which consisted of a smooth shell and a sensor stalk, were equipped to mimic two senses, touch and sight. In the dark, Elmer and Elsie scanned their surroundings for light sources and slowly crawled forward with help from a battery-powered motor. Once they identified a light source, they were able to steer toward it. Similarly, when encountering

Box 1.1 Timeline

1921 Karel Capek introduces the term "robot"

1947 W. Grey Walter publishes his work on robots capable of phototaxis

1969 Victor Scheinman develops the "Stanford Arm" 1977 The Stanford Arm is sold to Unimate, leading to the development of the Programmable Universal Machine for Assembly (PUMA) system

1985 Kwoh et al. use the PUMA 200 to perform the first robot-assisted stereotactic brain biopsy; the subsequent model, PUMA 560, is used for prostate surgeries

1988 PROBOT is invented and used in prostate surgeries

1992 ROBODOC is invented and used for hip surgeries in Europe

1994 AESOP is invented and cleared by the Food and Drug Administration (FDA) for minimally invasive surgeries

1995 Zeus Robotic Surgical System (ZRSS) is developed and subsequently tested on animals

1998 Tubal reanastomosis and CABG are performed using the ZRSS system

2000 da Vinci model is approved by the FDA

2001 ZRSS is approved by the FDA

2001 Transcontinental robot-assisted cholecystectomy is performed

2008 ROBODOC receives FDA

clearance

2014 Fourth-generation da Vinci system, the Xi model, receives FDA approval

a physical barrier, they were able to alter their trajectory to maneuver around it. Walter used these simple machines to illustrate how fairly complex behavior can be observed with such a simple system consisting of only two senses and two different motor activities.

While Walter tried to imitate life and characteristics such as spontaneity and purposefulness, George Devol focused on a specific task at hand and

10:31:14, subject to the Cambridge Core terms of use

Table 1.1 Timeline of new innovations in robotic systems

Year	Name	Use
1947	Elmer and Elsie	Capable of two senses, its goal was to emulate characteristics such as spontaneity, free will, purposefulness
1969	Stanford Arm	Use in assembly line and welding
1977	PUMA	Stanford Arm sold to Unimate and development of PUMA

		systems began
1985		PUMA 200 is used to perform brain biopsies
		PUMA 560 is used for prostatectomy
1988	PROBOT	Volume of resection preprogrammed by surgeon; no further input required from surgical team
1992	ROBODOC	Developed to improve precision of hip arthroplasty; robot capable of milling femur with superior precision
1994	AESOP	Allowed surgeon to operate camera with a hand or foot switch
1995	ZRSS	First master–slave system with surgical console and cart
2000	da Vinci	Most advanced master–slave system, with endowrist instruments

believed that the automated transfer of items would be useful in factories. In 1954, he invented Unimate, which became the first industrial robot when General Motors bought it in 1962 and installed it shortly thereafter to lift hot pieces of metal (5). This new development heralded a trend toward using robots to assist in industrial assembly lines.

The automobile industry was one of the first sectors to appreciate the vast opportunity that automation presented and began to rely on robotic arms to perform tasks that would be difficult and potentially dangerous for human workers. Over time, more industries discovered the utility of robots and have increasingly welcomed the integration of various types of robots. Here, we focus on the history of robots used in medicine.

First Robots Used in Medicine

The first laparoscopic cholecystectomy was performed in 1985 (6). This new technology provided a minimally invasive approach to surgery and resulted in shorter hospital stays and decreased postoperative pain due to smaller incisions and limited tissue dissection. With these obvious benefits, the list of surgeries performed laparoscopically quickly expanded and currently includes a variety of surgical specialties. However, despite its advantages, this surgical approach does carry limitations. During the surgery, the operator is confined to an uncomfortable posture and is required to view the surgical field on a screen, therefore making hand-eye coordination challenging. In addition, the images projected are two-dimensional, and the instrumentation does not allow for the same degree of tactile feedback as is possible with conventional surgeries. Perhaps most importantly, the range of motion of laparoscopic instruments is significantly limited when compared to that of the human hand, thereby restricting the surgical access and dexterity of the operator.

Some of these limitations have been addressed over time with the introduction of robots. Increasingly, more complex robotic systems have been introduced into the medical field and are able to perform more sophisticated surgical procedures. One interesting difference between robots used in medicine as compared to those used in other industries is the fact that robotic systems in the medical field continue to require human intervention. They are generally not expected to perform preprogrammed tasks independently. Instead, they are manipulated by the human operator either physically or through voice

recognition and can be considered an extension of the operator's hand rather than as an autonomous actor in the classical sense.

The first medical robot was the PUMA 200. Initially developed in 1969 by Victor Scheinman, a mechanical engineering student at Stanford University, the robot was designed to assist with assembly and arc welding. In 1977, Scheinman sold his invention, known as the Stanford Arm, to Devol's company Unimation, which then used it to develop a series of PUMA robots. Although the 200 series was a desktop version, it was similar to the other versions as it consisted of a mechanical arm and a control system. In 1985, Kwoh et al. used the PUMA 200 to perform stereotactic

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Credentialing for Robotic Surgery

Daniel M. Herron

Introduction: Why Is Robotic Privileging So Highly Charged?

The emergence of robotic surgery has perhaps had a more polarizing effect on surgeons and patients than any other new surgical technology in recent memory.¹ While some surgeons feel that robotic surgery is the new frontier of minimally invasive surgery, others feel its value is more as a marketing tool, with little or no concrete data to support its use. Proponents of robotic surgery claim that it is an enabling technology that improves surgical precision, speed, and outcomes while providing a more ergonomic operating environment for the surgeon. Critics emphasize the great financial cost associated with the use of robot and the dearth of controlled studies demonstrating any superiority of the technique over standard laparoscopic or thoracoscopic surgery.

This controversy is enhanced by the fact that, as of 2016, there is only one brand of surgical robot approved for clinical use, the Intuitive daVinci system. The lack of technological alternatives gives Intuitive a monopoly on surgical robotics, allowing the company to unilaterally set prices for the

robot, its associated disposables, service contracts, and mandatory training programs. Intuitive has taken a very aggressive approach to marketing their devices, implying that hospitals and surgeons who do not adopt the robotic technology will become surgical dinosaurs, tantamount to the general surgeons of the 1990s who failed to adopt new laparoscopic procedures into their practice.

Many surgeons have used robotic surgery as a means of differentiating themselves from their competition, suggesting rightly or wrongly to patients that their practice is superior to others that do not offer robotic procedures. Vast amounts of such marketing materials become immediately evident upon performing an Internet search using the terms “robotic surgery” and the specialty or procedure of interest.

This perceived value of robotic surgery as a marketing force, coupled with most surgeons’ natural interest in trying out new technology, has the potential to encourage surgeons to initiate a robotic practice for reasons other than documented clinical benefit.

This eagerness for robotic surgery is often met with pushback from hospitals that may wish to limit the number of robotic procedures in order to limit costs. Additionally, there may be resistance to new robotic surgeons from existing robotic practices that have invested heavily in training and marketing to differentiate themselves. Finally, there may be concerns from all parties that surgeons are overly eager to start robotic surgery, eagerly seeking privileges to perform such surgery without first obtaining adequate training or supervised experience.

For these reasons, it is critical for hospitals to have appropriate and carefully vetted credentialing and privileging protocols in place to ensure that surgeons who will perform robotic procedures are appropriately trained

Background: Definition of Credentialing and Privileging

The terms “credentialing” and “privileging” are often used interchangeably by surgeons and are frequently confused. It is important to understand the differences between these terms. “Credentials” refers to the collection of documents and evidence that supports a surgeon’s education, residency training, fellowship training, licensure, clinical experience, or other qualification that would impact his or her ability

to perform a given procedure.²⁻⁴ Credentialing is thus the process whereby a hospital, surgical center, or other health center confirms the veracity of a surgeon's training and experience.

"Privileges" is the term referring to the permission granted by a hospital to a surgeon to perform a particular group of services or procedures at a particular

location or locations.⁵ Thus, while it is common to hear a surgeon state "I am credentialed to perform this procedure," it would be more appropriate for the surgeon to state "the hospital completed my credentialing process by verifying my education, training and clinical experience, then granted me privileges to perform this procedure."

Why Are Attitudes about Robotic Privileging So Variable?

The process for credentialing and privileging is very dependent upon the scope of the privileges requested. Some categories of privileges are extremely broad, encompassing an entire medical or surgical specialty. As an example of a broadly specified category, my hospital grants "core general surgery privileges" to qualified general surgeons who have completed a general surgery residency program, are board-eligible or board-certified, and who meet the department's requisite criteria. Core general surgery privileges allow the surgeon to perform a broad range of abdominal and other procedures – as diverse as appendectomy, thyroidectomy, and esophagectomy – that would be considered to fall under the rubric of standard general surgery. This group of privileges gives the surgeon permission to perform a set of procedures appropriate to his or her specialty, but does not specify or limit how the procedures should be performed or what tools should be used to perform them. We can describe this broad-based category of privileges as a "specialty-based" one.

At the other end of the spectrum, the same hospital offers other categories of privileges that are extremely narrow in scope, focused more on a particular instrument than a medical specialty. One example is the use of various medical lasers. Surgeons or specialists in other departments may request privileges for one or more different types of laser, e.g., holmium laser, KTP laser, YAG laser. The applicant must demonstrate adequate training in the use of the specific laser and must confirm competence to a departmental preceptor at the hospital. The laser privilege confers permission to use a specific type of device but does not restrict the type of procedures for

which the device is used. Thus, this category of privilege is device-limited, not specialty-limited. We can describe this type of privilege as a “tool-based” or “device-based” one.

These two different types of privileges – specialty-based vs. device-based – become critical to appreciate when we try to tackle the issue of robotic privileges. Asked plainly, is the robot a new tool or is it a new type of surgery? Are we considering “robotic surgery” to be its own subspecialty with a unique set of robotic operations? Or is it a new tool, albeit a complex and highly technology-intensive one, which, once mastered, can be used to perform any of the other procedures for which the surgeon is already privileged. Unfortunately, the only legitimate answer to this question is unsatisfyingly indeterminate: it depends!

More specifically, the answer depends upon what specialty we are addressing, as well as the background of the surgeons in question. Consider, for example, the typical young minimally invasive general surgeon at my hospital. Such a surgeon will have completed a residency in general surgery as well as a fellowship in minimally invasive or laparoscopic surgery. The surgeon will typically have privileges to perform both basic and advanced general surgical procedures via laparoscopic approach, i.e., using narrow instruments that are placed through a trocar into the peritoneal cavity. The surgeon will already be familiar with complex dissection techniques as well as with suturing, energy devices, and staplers that are deployed through a laparoscopic approach.

For this type of surgeon, the robot is not a new specialty but rather an advanced new tool. It brings incremental changes – some positive, some negative – to the procedures that the surgeon is already performing. The beneficial changes are debatable, but include features such as an improved hand-to-instrument interface and the ability to articulate at the wrist. However, the robot also eliminates certain advantages of traditional laparoscopy, such as the presence of haptic feedback, the ability to rapidly visualize and address all four quadrants of the abdomen, and the utility of changing the angle of view of the angled laparoscope. Nonetheless, it is a relatively straightforward process for the fellowship-trained laparoscopic surgeon to apply the robot – a novel tool – to the body of existing operations that he or she already performs. Once the details of the robotic tool are mastered, the tool can be applied to any appropriate procedure for which the

laparoscopic surgeon is currently privileged.

In contrast, let us consider an older urologist who was trained in the era of open surgery and does not yet perform advanced laparoscopic procedures. This surgeon may have minimal or basic laparoscopic skills and be unfamiliar with complex laparoscopic dissection and suturing. If this surgeon adds robotic prostatectomy to his or her skill set, this represents an entirely new paradigm of operation – we are not introducing a new tool but rather an entirely new type of procedure. This surgeon is learning how to view tissues on a video monitor, operate through trocars, and utilize a completely new interface. In this situation, the surgeon is truly learning a new procedure, almost a new subspecialty. Clearly the privileging guidelines would need to reflect this difference.

Interestingly, the question of whether it matters if a surgeon has been trained in laparoscopic procedures before starting a robotic practice has been investigated. A 2013 study looked at the proficiency of laparoscopic-trained vs. robotic-trained surgeons who performed radical prostatectomy.⁶ Interestingly, only minor differences in patient outcomes were seen between the two groups.

Guidelines from Specialty Organizations

A number of specialty organizations from diverse specialties – including general surgery, urology, and gynecology – have published guidelines intended to lay a framework for hospitals initiating a new robotic credentialing and privileging program.

The Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) organized a consensus conference on robotic surgery in conjunction with the Minimally Invasive Robotic Association in 2006. One of the primary purposes of the meeting was to address the issues of training and credentialing/privileging in robotic surgery. A consensus document, including guidelines for surgeon training and credentialing, was included in the resultant publication.⁷ One of the primary purposes of the document was to promote uniformity of standards. As stated in the consensus document:

Uniform standards should be developed which apply to all medical staff requesting privileges to perform procedures utilizing these technologies. Criteria must be established which are medically sound, but not unreasonably stringent, and which are universally applicable to all those wishing to obtain privileges. The goal must be the delivery of high quality patient

care. Surgical proficiency should be assessed for every surgeon, and privileges should not be granted or denied solely based on the number of procedures performed. Ongoing review of results and comparison to published data and/or recognized benchmarks is encouraged.⁷ The consensus document included an appendix entitled “Guidelines for Institutions Granting Privileges in Therapeutic Robotic Procedures,” which was meant to serve as a basis for institutions seeking guidance in the development of their privileging processes. While the guideline requires that all applicants for robotic privileges must have completed an accredited surgical residency in the appropriate specialty, it accepts that adequate robotic training may be acquired during residency, fellowship, or by practical experience. The document also suggests that maintenance of privileges should require monitoring of performance and appropriate continuing medical education. Of note, there is no requirement that surgeons perform a specified minimum number of cases to maintain their privileges.

Similar guidelines have been put forth by other specialty organizations, including the American Urological Association (AUA), the Society of Urologic Robotic Surgeons, the American College of Obstetricians and Gynecologists (ACOG), and the American Association of Gynecologic Laparoscopists (AAGL).^{2,8–11} While there are necessarily some minor differences among the different guidelines, the documents share many similarities. Each organization agrees that the privileging process remains the responsibility of the individual hospital, with the immediate oversight of the process being controlled by the chief of the appropriate service. Similarly, all agree that board certification or eligibility in the appropriate specialty, plus formal training in robotic procedures, whether through residency, fellowship, or practice experience, is mandatory.¹²

However, each organization’s documents extend beyond these generally shared precepts. The AUA provides a very formalized protocol for currently practicing urologists who have had no formal training in robotic surgery, describing specific AUA curricula and intuitive surgical training modules that should be completed by the urologist applying for privileges.¹¹ The AAGL document describes separate privileging protocols for “basic” and “advanced” procedures and provides

very specific recommendations for maintenance of robotic privileges, such as performance of at least “20 procedures each calendar year.”¹³

A “Fundamentals of Robotic Surgery” course has been designed with the hope of standardizing the curriculum used in the training of robotic surgeons.¹⁴ Similar in concept to the “Fundamentals of Laparoscopic Surgery” or FLS course initiated by SAGES and now required as part of certification by the American Board of Surgery, the program could potentially provide a standardized, if basic, level of training.^{15,16} Many other institutions have developed proprietary training programs to address robotic skill acquisition.^{17–19}

A Typical Robotic Privileges Document

To better understand the details of the robotic privileging protocol, it may be helpful to review the process of robotic privileging as practiced in this particular author’s hospital. While every hospital will have a slightly different process in place, in general there are more similarities than differences from one institution to another.²⁰

Our institution has created a “Surgical Executive Committee” that manages all applications for robotic privileges. General surgeons applying for robotic privileges will apply for one of three privilege levels:

1. ***Provisional Privileges*** give the surgeon permission to perform cases under the direct supervision of a proctor.
2. ***Full Privileges*** are given to a surgeon who has performed three or more proctored cases without incident and obtained approval from the department chair or designated subordinate.
3. ***Proctor Privileges*** are given to a surgeon who holds full robotic privileges and has completed a minimum of fifteen robot-assisted privileges. The applicant must apply for the proctoring designation to the Surgical Executive Committee, which will consider the request.

All applicants must hold an MD or DO degree and be board-certified or board-eligible within their specialty. They must hold privileges to perform, using open or laparoscopic techniques, the same procedures for which they are requesting robotic privileges and must document that they have performed an adequate number of these open or laparoscopic procedures with

acceptable outcomes.

All applicants must initially apply for provisional privileges. They must confirm that they have either successfully completed an ACGME/AOA-approved residency or fellowship with a structured experience in robotic surgery, or that they have undergone experiential, nonresidency-based training, including both formal didactic and practical lab experience.¹⁴ Simulator experience is not required by the institution, but is part of the training protocol provided by Intuitive, and has been shown to have some predictive validity for skills.²¹

Once approved for provisional privileges, the applicant must perform a minimum of three proctored procedures, being supervised by a preceptor who holds proctor privileges and is privileged to perform the procedure being observed. The proctor then completes a proctor report form, which is submitted to the department chair for review. If approved by the chair, the file is forwarded to the Credentials Committee of the Medical Board.

At each reappointment cycle, the surgeon must document both volume and clinical outcomes for the robotic procedures. The decision to renew robotic privileges is then made in accordance with standard privileging processes as outlined in the medical staff bylaws. In order to facilitate the availability of proctors for future applicants for privileges, all surgeons who meet the numerical case requirements for preceptor privileges must agree to participate as proctors for future applicants.

Medicolegal Issues

Just as robotic surgery has attracted the attention of both surgeons and patients, it has also presented new opportunities to medical malpractice attorneys. A recent article in a journal for plaintiffs' attorneys noted that injuries from robotic surgery had more than doubled in the first eight months of 2013 compared to the same time period in 2012.²² Potential targets include not only the robotic surgeons but the company manufacturing the robot and even proctoring surgeons.^{23–25}

How Will Robotic Surgery Evolve? How Will This Affect Privileging?

At present, there is only a single surgical robotic system in clinical

use, namely the Intuitive daVinci. Thus, our current conception of privileging guidelines must necessarily accommodate the existing technical paradigm that this single platform creates. This is to say that current privileging guidelines are set up to address a two-part surgical robot with a large, immersive console, in close proximity and connected by cables to a moveable, dockable, bedside console with independently actuated arms.²⁶

It is highly likely that future robotic systems will be created using significantly different configurations. Some approaches that seem likely would include, operating table rail-mounted arms, consoles that put the surgeon in closer proximity to the operative field, freestanding mechanical or electromechanical instruments with articulating wrists that are used in place of a standard laparoscopic instrument, etc. Just as was impossible to imagine thirty years ago that commonplace appliances like a washing machine or refrigerator would be equipped with high-powered microprocessors, one could easily imagine that the programmable microprocessors and high-powered electromechanical actuators that are now commonplace in cellphones, drones, and even electronic toys will make their way to the surgical instruments of the near future.

As these new tools evolve, it may become difficult to know exactly where the dividing line lies between robotic and traditional surgery. A standard surgical stapler is a highly complex mechanical device, yet is clearly considered to be a traditional surgical instrument. When this evolves into a powered device with a self-contained electrical supply, an internal microprocessor and electromechanical actuators that allow it to articulate, deploy its staples, and assess the adequacy of the firing, it is not so clear whether this is now a different type of surgical robot, albeit one with a highly focused purpose.²⁷ Does this advanced surgical stapler require a brief in-service with an explanation by the equipment representative? Or does it require additional formal training, with didactic and hands-on training components? Is it just a more advanced version of an existing surgical stapler, or does it require its own set of privileging guidelines? This is just one example of what will undoubtedly be many surgical tools that blur the boundaries between surgical instruments and robots.

The Future of Robotic Surgery and Mandates for Future Privileging

In the relatively near future, we will likely find ourselves in a surgical environment populated by many surgical “robots.” These will likely not represent true robots that perform surgical tasks independently but rather advanced surgical tools that make use of advanced electronic and electromechanical components to improve or automate various surgical tasks such as tissue manipulation, dissection, suturing, and anastomosis. It will be necessary to make sure that privileging guidelines exist to promote the safe use of such instruments without creating an undue burden to hospitals and surgeons. Ultimately, the goal must be to use available surgical technology to optimize patient care in an appropriately monitored and controlled environment. Hospitals will need to stay abreast of updates in technology and guidelines from professional organizations so that privileging practices will evolve in a corresponding manner.

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brain biopsies (7). Using CT guidance, this system was able to determine its own depth through a negative feedback input. The same system and a

more advanced model, the PUMA 560, were subsequently used for transurethral prostate resections by Davies et al. (8). However, both models still required guidance from the surgeon, and although they closely resembled the human arm, the greater flexibility came at a price of lower precision. These characteristics made the PUMA more suitable for assembly lines and welding where lack of precision cannot have detrimental effects as compared to patient care.

In 1988, researchers at the Imperial College London developed the PROBOT based on the PUMA system. The goal was to build a robot that would have a small enough working environment to allow safe operations within the human body (9). In contrast to previous robotic systems, this robot utilized a fixed path system that was programmed based on preoperative imaging. The robot was capable of moving in three different axes and contained a resectoscope that could move in a fourth axis. Prior to surgery, the length of the prostate was determined from the bladder neck to an anatomical landmark, the verumontanum. Surgery was limited to this area to prevent damage to the sphincter muscles. The robot was then positioned at the bladder neck and an ultrasound probe passed through the resectoscope acquired three-dimensional (3D) images in 5 mm intervals. Based on this 3D image, the surgeon then determined the exact region to be removed. Once programmed, the robot was then able to resect the predetermined tissue without any additional input from the surgeon, using small rough rotational movements. These movements resulted in resection of small, cone-shaped pieces of prostate tissue starting at the center and sequentially moving to the periphery by increasing the size of the cones. This process was repeated until the preprogrammed limits had been reached.

In the late 1980s, Howard A. Paul and William L. Barger collaborated to develop a robot that would increase the precision of hip arthroplasty. The resulting product consisted of a preoperative planning workstation (ORTHODOC) and a surgical assistant (ROBODOC) (10). Prior to surgery, a CT was obtained with fiducial markers. The images were then used to create 3D reconstructions of the bone that the surgeon could use to plan the operation. The initial exposure of the bone was similar to standard hip arthroplasty. However, once the bone had been exposed, the

surgeon guided the surgical arm of ROBODOC toward the bone and the robot began milling the cavity for subsequent stem placement. Throughout the surgery, the surgeon had control over the robot and could both halt and redirect the surgical arm. Based on studies funded by the manufacturer, the precision of the cavity was significantly increased when compared to manual preparation (11). In 1992, the first total hip arthroplasty was performed in Europe; however, this system did not become commercially available in the United States until 2008 when it was finally approved by the FDA (11).

The next wave of new robots started with a growing interest in telesurgery. Researchers from NASA and the Stanford Research Institute collaborated to enable surgeries to be performed without the surgeon being physically present at the operating table (1). The goal was to enable remote access, without losing the physician–patient relationship. Once developed, the idea was to deploy this technology during wars and allow surgeons to remotely perform surgeries on wounded soldiers. This collaboration eventually led to the development of the automated endoscopic system for optimal positioning (AESOP). The device, which was cleared by the FDA in 1994, allowed the surgeon to operate the camera using a hand or foot switch instead of relying on an assistant, with later models being controlled by voice. A similar robot, the EndoAssist, was developed a few years later. The robot was able to adjust the camera based on the head movements of the surgeon, who wore an infrared headpiece. Compared to the AESOP, which was mounted on the operating room table and therefore moved with the table, the EndoAssist was free-standing and had to be adjusted when changes were made to the operating table (12). In both systems, the robot was limited to driving the camera, and the surgical instruments continued to be of laparoscopic type.

Advanced Robotic Systems

In 1995, the first master–slave robotic system was developed by Computer Motion. This robotic system consists of an input console (master) and a robotic surgical system (slave). The ZRSS consisted of three separate arms. The first arm was a voice-activated AESOP and provided the surgeon with a view of the surgical site. The other two arms were able to hold a variety of instruments and mimic the surgeon's hand movements. It was initially tested on animals, but by 1998, the first

tubal reanastomosis and CABG had been performed using this system (13). In 2001, the ZRSS was cleared by the FDA, and at that time, the two robotic arms were able to hold twenty-eight different instruments. In 2003, a merger between Computer Motion and Intuitive Surgical, a rival company, led to the ZRSS being phased out with the aim to focus on the more advanced da Vinci Surgical System.

The first da Vinci model had been approved by the FDA and was introduced by Intuitive Surgical in 2000. Similar to the ZRSS, this system also consisted of a multi-arm patient-side cart and a surgeon console. As of 2015, the newest da Vinci system, the da Vinci Xi, has four arms that can hold the camera as well as a wide array of instruments. The surgical cart could be placed at any position around the patient; it comes with a laser targeting system that, when pointed at an area of interest, will optimally position the boom part of the system. The available endowrist instruments all have seven degrees of freedom (up/down, forward/back, right/left, wrist yaw, wrist pitch, wrist roll, grasp) and therefore provide the surgeon with significant surgical dexterity paralleling that of a human wrist. The surgeon is able to view 3D images of the surgical field within the surgeon console. Hand motions are scaled into micromovements to account for tremor and translated into movements of the surgical instruments. Although the system is referred to as a robot, it does not fulfill the abovementioned definition. Rather than performing a preprogrammed task, the da Vinci system is an example of a master–slave system and depends on the direct input from the operator without the ability to function independently.

Since its introduction, the da Vinci system has been used in an increasing number of procedures across multiple surgical specialties. In addition to urological and gynecological surgeries, more and more general surgical procedures, such as cholecystectomies and hernias, are being performed using the robotic system. In their 2014 annual report, the company noted that the yearly number of procedures had been steadily rising since 2009, and that the procedure growth for 2014 was 9 percent, with a 33 percent increase in general surgical procedures (14). These numbers indicate that robotic surgery not only has been widely accepted by the medical community but also is gaining popularity and is being used in an increasing number of surgical procedures. Figure 1.1 shows the steady increase in the number of surgeries performed using robotic systems over the last three years and, in particular, illustrates

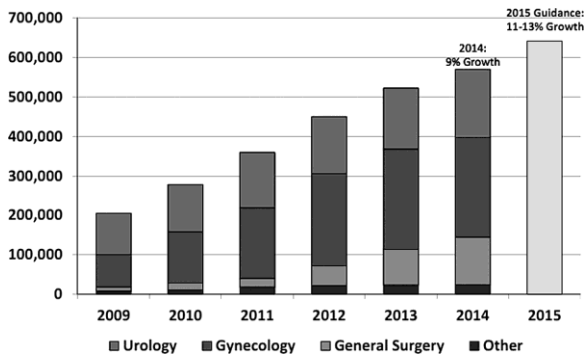


Figure 1.1 Annual utilization of robotic systems in different surgical departments (© 2017 Intuitive Surgical, Inc.; used with permission).

the increase in the number of departments that have started using the robotic system.

It is undeniable that robotic systems are no longer just used in the automotive industry and laboratories but are increasingly being used for a wide variety of medical procedures. Despite some technical limitations such as lack of tactile feedback posing a challenge (15), as advances are made in the technology and as our experience grows, gradually more complex cases will be performed using robotics. In 2001, a transcontinental robotic cholecystectomy was performed on a patient in Strasbourg (16). It is, therefore, not unreasonable to expect that, as the field of telesurgery improves, particularly with improved time lags for transmission, more complicated and uncommon surgeries might be performed in areas of the world where the surgical expertise is not accessible. In the most extreme case, technology might advance far enough that robots will be capable of performing surgeries autonomously.

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Part 4 Method (A Practical Approach to Medical Image Processing)

Image Processing

1.1 Introduction

In this introductory chapter the basic terminology of image processing is presented. The ImageJ program is introduced using practical exercises, so that the reader is able to perform image processing tasks. Fundamental imaging processing principles, covering both the grayscale and spatial properties of an image, are described. The chapter closes with an overview of the content of the book, which is based around the five classes of image processing: image enhancement, image restoration, image analysis, image compression and image synthesis.

1.1.1 Learning Objectives

When you have completed this chapter, you should be able to

- Define the important basic terms used in image processing
- Understand methods of image enhancement that use the histogram
- List several different measurements, both spatial and grayscale, which can be made from images
- Discuss the five classes of image processing
- Use ImageJ to load and save an image, and perform simple tasks

1.1.2 Example of an Image Used in This Chapter

The first self-assessment question in each chapter is based on

one of the images that appears later in the chapter. The question usually requires some background knowledge of medical imaging technology and is intended to help those who have previously studied medical imaging to start to integrate medical image processing with their existing knowledge. Those who lack this background knowledge should not be concerned if they cannot answer the first question in each chapter, and note that no prior knowledge is assumed in the other questions in each chapter.

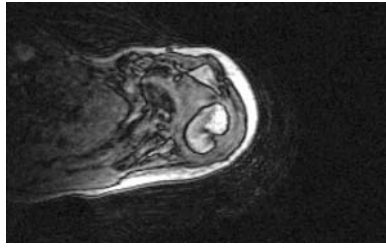


Figure 1.1

Image of a shoulder for self-assessment question 1.01.

Self-assessment question 1.01

Figure 1.1 is an example of an image used in this chapter. It shows the shoulder joint. The original image was 256×160 pixels in size and each pixel represented a 0.8 mm cube of tissue. Which imaging modality has been used to acquire the image shown? Note the loss of image information towards the left of the image. What does this suggest about the particular equipment that was used to acquire the image?

1.2 Definition of Image Processing

Image processing refers to the manipulation and analysis of pictorial information, for example by improving, correcting, changing or analyzing the image. The simplest example is the action of prescription spectacle lenses, which are designed to counteract distortion caused by defects in the owner's eye. The action of the lens is called an *optical process* because the lens is acting on an optical image. Optical images can be converted to analog images. An analog image is a two-dimensional representation of a scene; the image contains continuously varying tone (e.g., in a monochrome or black and white photograph) or continuously varying color.

1.2.1 The Digital Image

An analog image can be sampled to give an array of discrete points, each of which has an associated brightness value. This is a *digital image*, which is simply an array of numbers, one for each sample point (Figure 1.2). Each sample point is known as a picture element, or *pixel*. An image is generally sampled using a rectangular array of pixels. The process of sampling and assigning the numerical value is called *digitization*. Thus a digital image is an array of pixels, each of which has a value. When these data are displayed in the correct arrangement, with each pixel value used to give the brightness or color at that point, we see the image. The image *size*, or *matrix*, is expressed

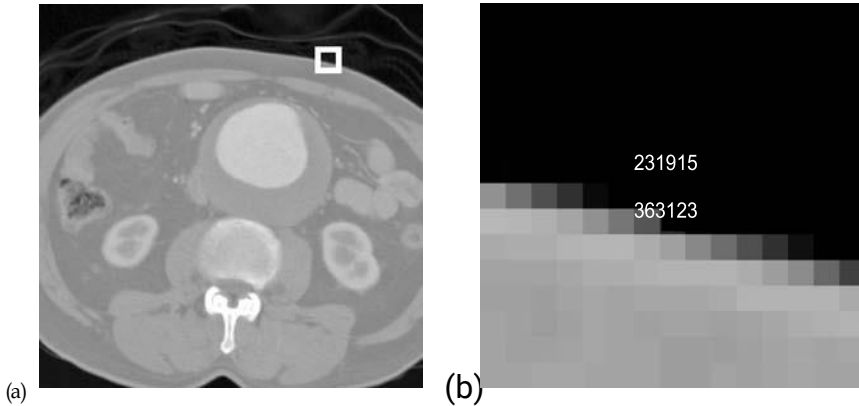


Figure 1.2

A digital image is an array of pixels, each of which has a value. (a) A digital image showing the location of a small square region of 15×15 pixels. (b) An enlargement of the 15×15 region of the image. The numerical values associated with the central pixels are shown overlaid.

in terms of the number of pixels in the rectangular array, for example 256×256 pixels. When image processing is performed on such an image, it is more fully described as digital image processing. In medicine, some digital images are acquired in digital form from the outset (e.g., computed tomography), while others are acquired as analog images (e.g., a chest x-ray on film) that may later be digitized. Three-dimensional data sets consist of a series of images each representing a slice through the object. In this case pixels are known as voxels.

1.2.2 Image resolution

The *resolution* of an image is a measure of the fidelity (faithfulness) of the representation of the original scene. Resolution is related firstly to the characteristics of the imaging system and secondly to the number of pixels and to the range of brightness values that are used for digitization. In the discussion in this chapter, it will be assumed that the digitization

process is performed on a perfect representation of a scene, so the properties of the imaging system may be ignored. The effects of the imaging system are considered in Chapter 7.

The question addressed when considering image resolution is “Does the digital image resolve elements of the original scene?” There are two components of resolution: grayscale resolution and spatial resolution. The question therefore has two parts: Can objects that are similar in tone or color be distinguished? Can small objects be seen?

1.2.2.1 *Grayscale Resolution*

The digitization process assigns a number to each pixel to represent the brightness at that location in the original image. The grayscale, or brightness,

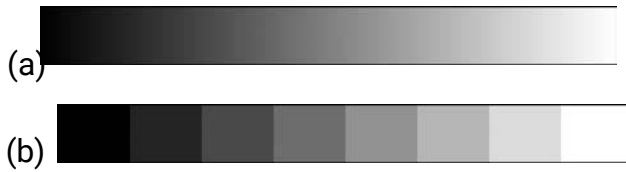
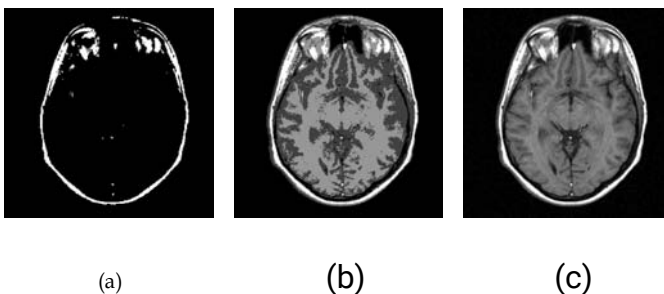


FigUrE 1.3

Grayscales associated with images of two different bit depths. (a) An 8-bit grayscale (256 shades of gray). (b) A 3-bit grayscale (8 shades of gray).

resolution is affected by how many brightness values are allowed. It is very common to assign the pixel value to one of 256 discrete values (from 0 to 255). Each value is displayed as a separate shade of gray, and these shades run smoothly from dark (0) to light (255). An image with 256 discrete values is known as an 8-bit image, because $2^8 = 256$. An 8-bit grayscale is shown in Figure 1.3a.

It is quite possible to digitize to gray scales using a different number of shades of gray. For example, 128 shades of gray are associated with a 7-bit image (as 2^7 is 128), and 8 shades of gray (Figure 1.3b) gives a 3-bit image, since 2^3 is 8. In Figure 1.4a through g, one image is shown displayed with several different grayscale resolutions. Notice that with decreasing grayscale resolution (i.e., fewer gray values) the images appear progressively coarser. *Contouring* occurs when too few gray levels have been used; gradual changes in image brightness are rendered as discrete bands.



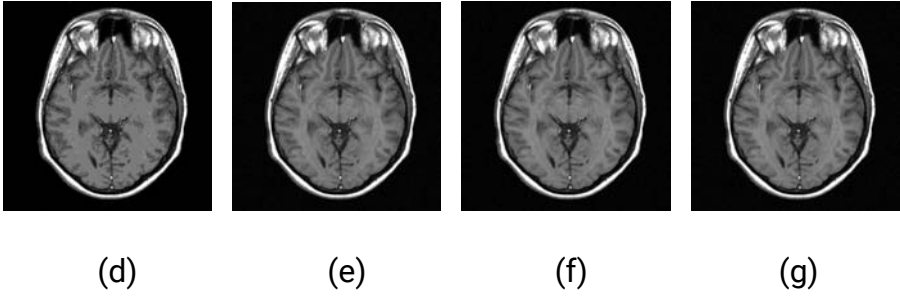


FigUrE 1.4

An image displayed using a range of grayscale resolutions. (a) 2 gray levels (1-bit), (b) 4 gray levels (2-bit), (c) 8 gray levels (3-bit), (d) 16 gray levels (4-bit), (e) 64 gray levels (6-bit), (f) 128 gray levels (7-bit), (g) 256 gray levels (8-bit).

The *dynamic range* of a gray scale is the range of pixel values used, for example, from 0 to 255 for the full 8-bit scale.

Self-assessment question 1.02

How many shades of gray would there be in a 5-bit image scale?

Self-assessment question 1.03

What is the derivation of the word “pixel”?

1.2.2.2 Spatial Resolution

The digitization process assigns a number to each pixel to represent the brightness at that location in the original image. The spatial resolution is affected by how close together the samples are taken.

The concept of *spatial frequency* is useful when considering spatial resolution. Details in images are made up of changes from dark to light to dark. The rate of this change is called the spatial frequency. In Figure 1.5 the image has just one spatial frequency. In a real image, however, a range of spatial frequencies is present. The higher spatial frequencies correspond with fine detail, and low spatial frequencies with larger objects that have little change of gray level within. Sampling theory requires that the image must be sampled so that at least two samples are acquired within the smallest detail that is to be represented. Thus, the highest spatial frequencies that can be resolved in a digital image must have a frequency half that of the sampling rate. If sampling is done at a low rate, high spatial frequency details will not be seen in the digital image. This effect is demonstrated in Figure 1.6. The sampling rate gets progressively lower from Figure 1.6a to e, leading to low spatial resolution, and a consequent lack of detail. The effect where the pixels are very apparent is called *pixelation*.

Spatial aliasing occurs when an image has been undersampled (Figure 1.7).

The term aliasing is derived from the word “alias.” High spatial frequencies are misrepresented as lower ones, and so could be considered to have

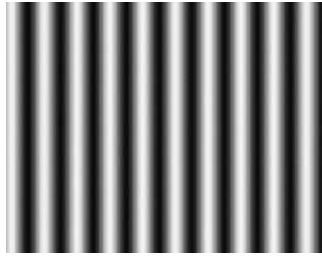


FigUrE 1.5

An image with a single spatial frequency associated with the frequency of the sinusoidal variation in image intensity. Typical medical images include a range of spatial frequencies ensuring that features of different scales are represented.

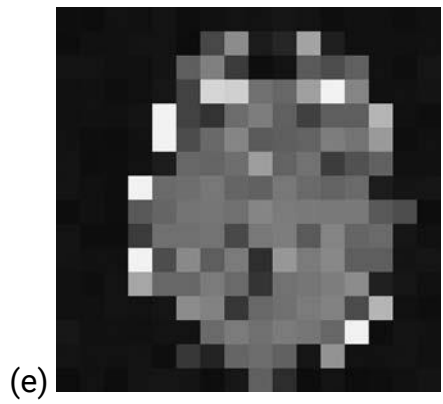
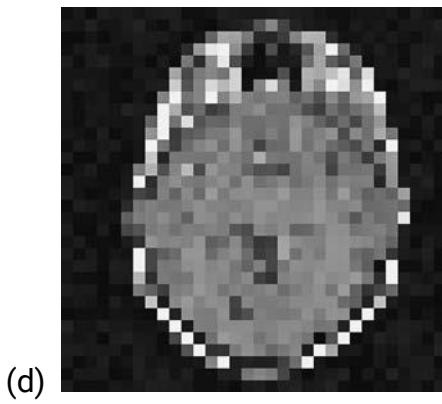
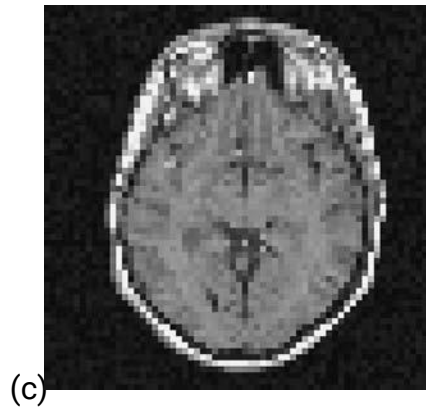
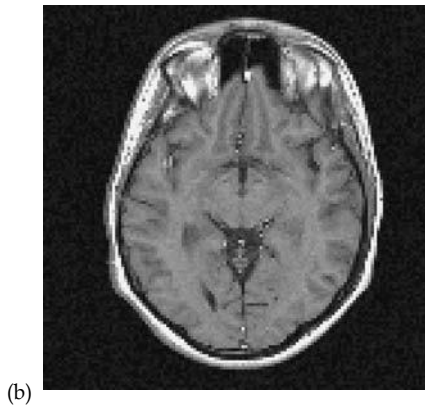
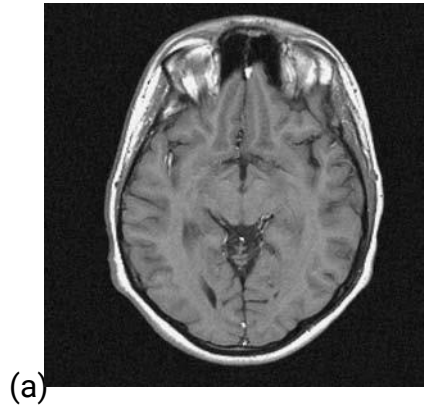


FigUrE 1.6

The effect of sampling rate on image resolution. (a) Original, (b)–(e) the effect of repeatedly halving the sampling rate.

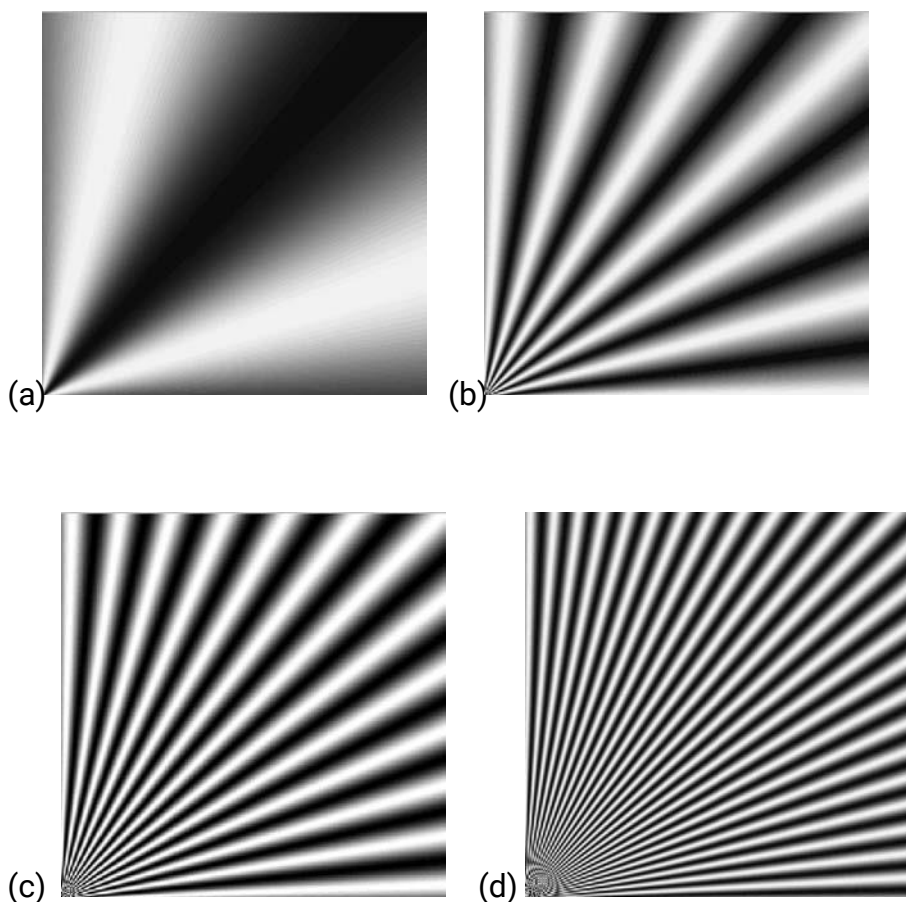


FigUrE 1.7

Sampling rate and aliasing. In each image, spatial frequency increases towards the bottom left hand corner. The spatial frequencies present in each image increase from (a)–(d). All the images have been sampled at the same rate. There is no aliasing in (a), which contains low frequencies. In (b)–(d), Moiré patterns appear when the spatial frequency is over half the sampling rate, leading to the occurrence of apparent low-frequency features that are not in fact present in the original. Aliasing requires repetitive high-frequency details, so is not often seen in clinical images, but may be seen in images of test objects.

assumed an alias. In practice, aliasing is not often seen, unless an image has repetitive high-frequency details.

Spatial resolution can be expressed numerically in several different ways. One of the most common is to determine the maximum number of black and white stripes in 1 mm that can be resolved by the eye, and do not blur into gray. This is quoted as a number of line pairs per millimeter, or lpmm^{-1} . To determine spatial resolution from an image, it is obviously necessary to know the pixel size in millimeters. This can be achieved by calibration, which is described in Chapter 5.

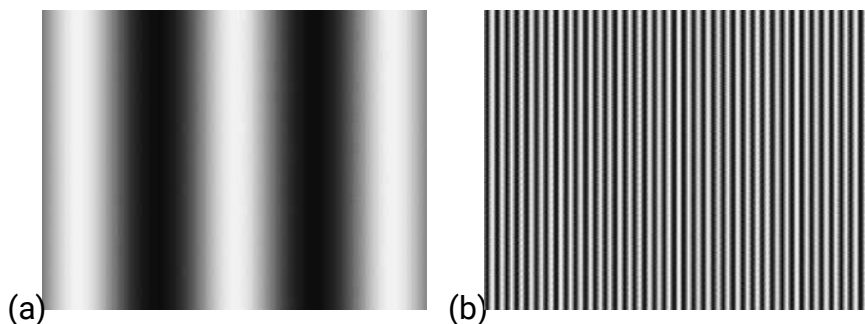


Figure 1.8

(a)–(b) Images for self-assessment question 1.04.

Self-assessment question 1.04

Which of the patterns in Figure 1.8 has the higher spatial frequency?

1.2.3 Image Data Types

Computer operations are based on binary arithmetic, where there are just two possible options, 0 or 1. In imaging, an image with only two possible gray values is termed a binary image. Such an image can be displayed using a 1-bit scale because there are two possible options requiring 2^1 bits. Binary images, however, for reasons of compatibility, are often stored using a data type that would allow many more gray values.

Integer numbers are most easily stored in a computer in either 1-byte (8 bits) or 2-byte (16 bits) format, so it is most common for images to be 8-bit or 16-bit images. A 16-bit image corresponds with a gray scale having 2^{16} gray levels running from 0 to 65535. It is rare for medical images to have such a wide dynamic range. For example, in MRI a maximum value of 4095 is very common, corresponding with a 4096 gray level scale, which corresponds with 12 bits. However, because of the ease of storage in 2 bytes, the 16-bit format will often be used even if the actual image gray values only occupy the lower end of the scale.

The image data types discussed so far are unsigned types, allowing storage of values of 0 and above. Signed data types can represent the same number of gray values as their unsigned counterpart, but the range of values will differ. For example, 256 values can be stored using an 8-bit data type. The range of values stored in an unsigned 8-bit image is from 0 to 255; in a signed 8-bit image it will be -128 to 127.

Self-assessment question 1.05

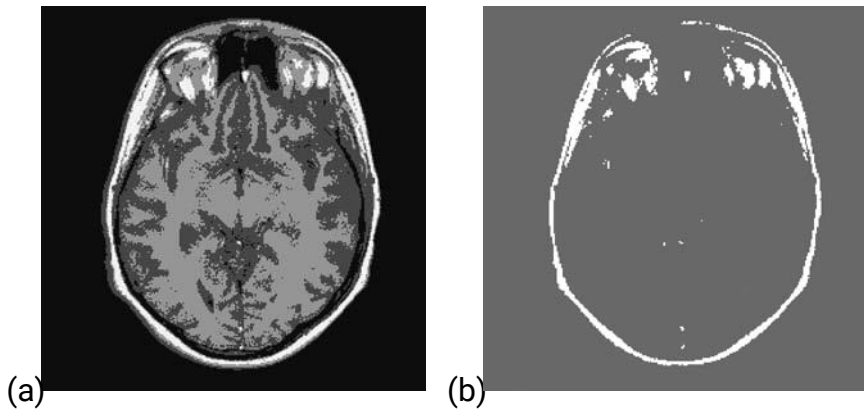
This is a list of some of the image data types recognized by various image processing and analysis programs (for example, ImageJ): binary, 8-bit unsigned, 8-bit signed, 16-bit unsigned, 24-bit color and floating point.

- How many gray values are expected for the binary data type?
- Do the signed and unsigned 8-bit data types both support the same maximum value?
- Why are 16 bits often stored even when only 12 bits are used?

It is worth commenting on the 24-bit color data type. This is an interesting representation, where each pixel has three different 8-bit scales associated with it, one each for red, green and blue. It is sometimes known as an RGB scale. Each of the three scales runs from 0 to 255, and the color in which the pixel is displayed depends on the value in all three. For example, if all three are 255 then the pixel is white, but if, for example, the value was 0 for the green channel, and 255 for the red and the blue, the result would be magenta.

Self-assessment question 1.06

Select the binary image from the four images in Figure 1.9.



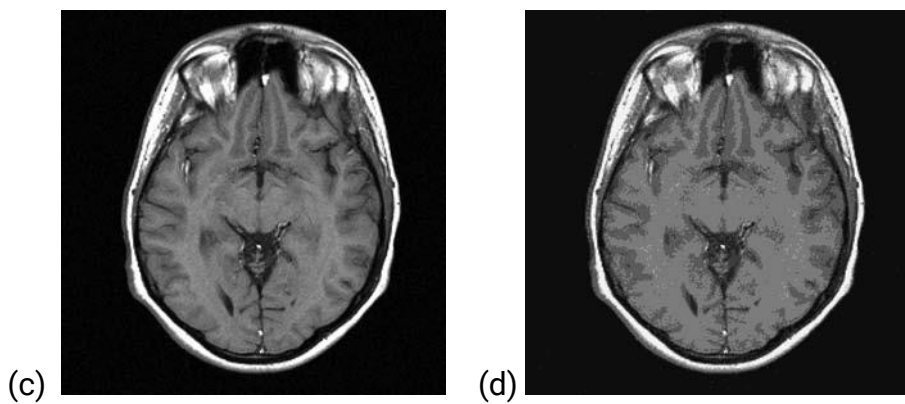


FigUrE 1.9

(a)–(d) Images for self-assessment question 1.06.

Self-assessment question 1.07

Define what is meant by the dynamic range of a gray scale.

1.3 Introduction to ImageJ

In the rest of the book, the program ImageJ will be used extensively to support material in each chapter. In this section, basic skills are covered, such as loading images, so that in later activities familiarity can be assumed.

Activity: Starting and Closing ImageJ

Start ImageJ. Depending on how your system is set up

1. Use the microscope icon on your desktop, or
2. Start | Programs | ImageJ | ImageJ.

The program will appear on your desktop: the initial display is one window, with a dropdown menu row and a row of buttons. You will still see your wallpaper and desktop icons, as in the example in Figure 1.10. Try dragging the small window around your monitor.

Leave ImageJ running at present, but note that when you have finished using ImageJ, the program may be closed if you select File | Quit. If there are any images open that have not been saved following changes, you will be asked if you wish to save them.

Activity: Loading an Image with ImageJ

Place the CD in the computer's CD drive and select File | Open from the main ImageJ menu (Figure 1.11).

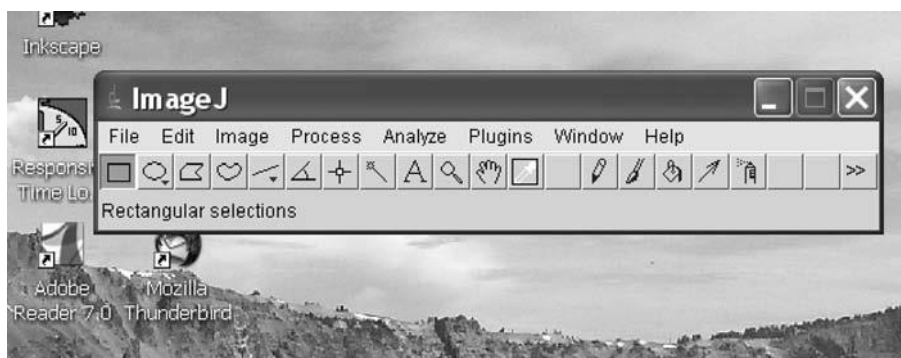


FigUrE 1.10

The ImageJ window on a Windows desktop.

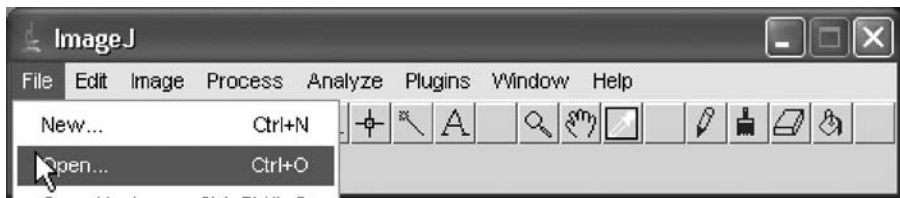


FigUrE 1.11

File | Open on the main ImageJ menu.



FigUrE 1.12

The image hip.bmp when opened using ImageJ. Information about the image data size and type is shown in the panel above the image.

ImageJ displays a standard Windows[®]* “Open File” window. Navigate to the CD drive, select the folder for Chapter01 and then the file hip.bmp. Click on the “Open” button.

The image will be displayed in its own window on your desktop, with information about its size and data type in the white panel

(Figure 1.12).

Run the cursor across the image (without clicking). At the bottom left of the ImageJ menu, the status bar changes to show the x and y coordinates of the cursor, and the gray value of the pixel at that location. Notice that all the pixel values are integers in the range from 0 to 255 as is expected for an 8-bit image.

* Registered trademark of Microsoft Corporation, Redmond, Washington, USA.

Select File | Quit to close ImageJ. You will be asked if you wish to save any open images; answer No.

Activity: 16-Bit and 8-Bit Images

Start ImageJ.

Place the CD in the computer's CD drive and select File | Open from the main ImageJ menu (Figure 1.11).

ImageJ displays a standard Windows "Open File" window. Navigate to the CD drive, select the folder for Chapter01 and then the file chapter01.tif. Click on the "Open" button.

The image is a 256×256 pixel image, in the 16-bit data type, and this information is displayed in the white panel above the image.

Run the cursor across the image (without clicking), and while doing so check the status bar at the bottom left of the ImageJ menu. Note how in this 16-bit image there are pixel values much greater than the maximum of 255 that could be accommodated by the 8-bit data type.

Select Image | Type | 8-bit; this will convert the data type of the image from 16-bit to 8-bit.

Note that the data type indicated in the white panel above the image is now 8-bit. When the cursor is run across the image, the pixel values are now all in the 8-bit range from 0 to 255. The image looks much the same, because the image display uses only values between 0 and 255 for displaying both 16-bit and 8-bit images. However, the dynamic range of the actual gray values in this image has been much reduced by the reduction from 16 to 8 bits.

Click on the cross at the top right of the image window to close the image. Answer No when you are asked if you wish to save the changes to the image.

Self-assessment question 1.08

Variations of the image chapter01.tif are shown in Figure 1.13. By eye, place the images in descending order of spatial resolution.

Activity: Spatial resolution

Start ImageJ if it is not already running.

Place the CD in the computer's CD drive and select File | Open from the main ImageJ menu. Open the file chapter01.tif and then open chapter01_c.tif.

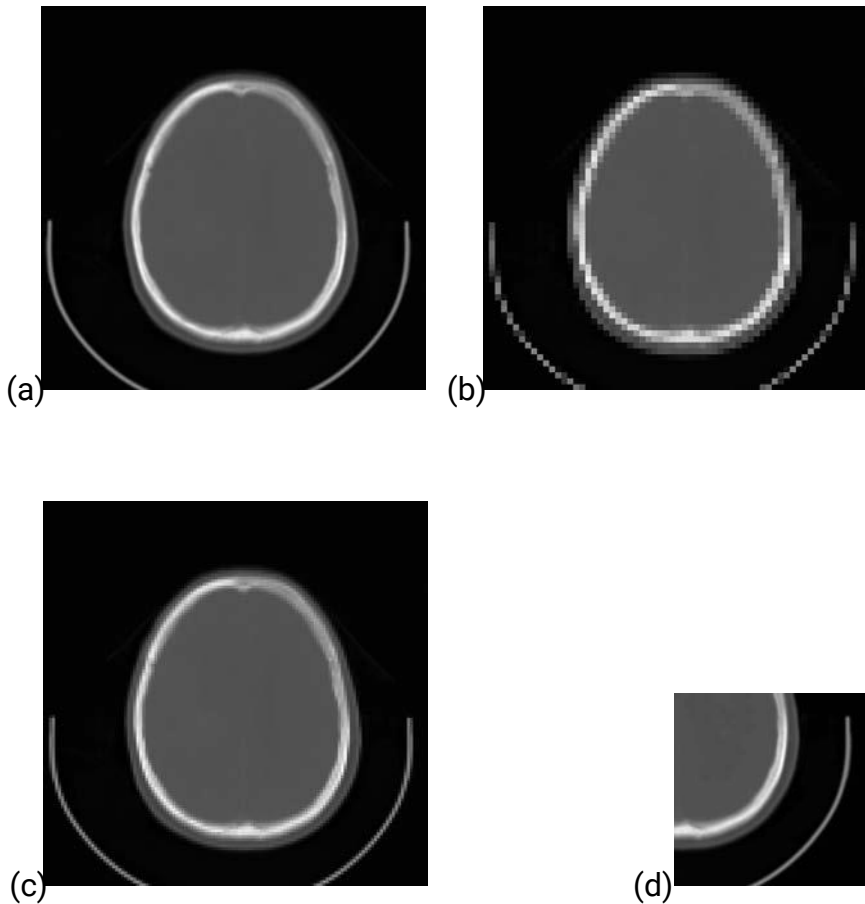


FigUrE 1.13

Images for self-assessment question 1.08. (a) 256×256 pixels, (b) 64×64 pixels, (c) 128×128 pixels, (d) 128×128 pixels.

By viewing the information in the panel above each image, it can be seen that chapter01.tif is a 256×256 pixel 16-bit image, and chapter01_c.tif is a 128×128 pixel 8-bit image. However, the two images both have the same spatial resolution, because the same number of pixels represents the same object distance in each case.

Select File | Quit to close ImageJ. You will be asked if you wish to save any open images; answer No.

1.4 Grayscale Image Processing Basics

1.4.1 Color Look-Up Tables (LUT)

In medical imaging it is common to apply false color to an image while retaining the original 8-bit scale. Instead of assigning a shade of gray to each

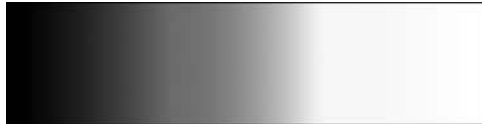


FigUrE 1.14 (Please see color insert following page 16)

The thermal color look-up table, which is a smoothly varying scale running from black (0) to white (255) through shades of red, orange and yellow.



FigUrE 1.15 (Please see color insert following page 16)

The 5-ramps color look-up table, which is a discontinuous scale with black representing five different gray values.

pixel value, a color is assigned. Some color scales are continuous scales, such as the thermal scale shown in Figure 1.14 where, just as with the gray scale, there is a smooth graduation in shade. Other scales change color abruptly, for example, with the value 101 being green and 102 being black (Figure 1.15). Abrupt changes of this kind can lead to the appearance of a sharp boundary in an image where in fact no physical feature is present. Color LUTs add impact to an image, but care is required to avoid misleading the viewer.

Activity: Look-Up Tables in ImageJ

Start ImageJ, or close any open images (by clicking on the cross at the top right of the image window) if ImageJ is already running.

Select Image | Lookup Tables > and then choose a table from the list given, for example, Fire or Spectrum.

A 256 × 32 ramp image will be created to display the LUT. An 8-bit

ramp image has pixel values from 0 to 255 placed in ascending order across the image.

If images are already open in ImageJ, the LUT is applied to the currently selected image. ImageJ allows you to have up to 1000 images open at a time, so you need to click on the image for which the LUT is required before selecting Image | Lookup Tables > .

To return the image display to its original appearance, select Image | Lookup Tables > Grays.

Sometimes the sequence of LUTs selected may result in the image appearing to have an inverted gray scale at this point (what was previously white is

displayed in black). If this happens, select Edit | Invert. Use the Invert option any time if you would prefer the gray scale to be inverted.

Close any open images and Select File | Quit to close ImageJ.

1.4.2 Image Contrast

In an image, it is possible to recognize an individual structure because it differs in brightness from its surroundings. This degree of visibility, representing the difference between light and dark regions of the image, is called the image contrast. If an image has low contrast, it means that it is difficult to distinguish different structures. The contrast in an image is affected by the image acquisition mechanism itself, as contrast between different materials relies on there being a different amount of interaction between the imaging radiation and the different materials.

Self-assessment question 1.09

In Figure 1.16, which image has the lower contrast?

There is a related quantitative parameter called *contrast*. For the two regions

S and B illustrated in Figure 1.17, contrast is defined as

$$C = \frac{(S_S - S_B)}{S_B} \quad (1.1)$$

S_B

where S_S represents the mean signal within the region and S_B is the mean signal in the background. Contrast may also be expressed as a percentage by multiplying the result by 100. Be aware that other definitions are sometimes used, for example, a simple difference in signal.

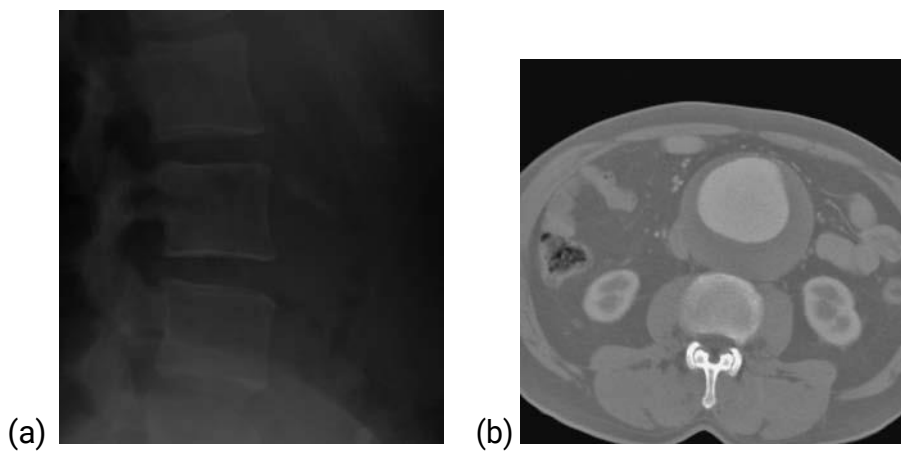


FigUrE 1.16

(a)–(b) Images for self-assessment question 1.09

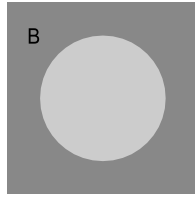


Figure 1.17

For the two regions S and B , contrast is defined as $C = \frac{S_S - S_B}{S_B}$ where S_S represents the mean signal within the region and S_B is the mean signal in the background.

Contrast to Noise Ratio (CNR) and Signal to Noise Ratio (SNR)

The contrast to noise ratio (CNR) is a more useful definition than contrast alone when considering the visibility of features in a noisy, real-life image. CNR is found by dividing the measured contrast by the background standard deviation. The background standard deviation is measured in an area of the image where the object is not present, such as the image background. In a similar way, the signal to noise ratio (SNR) is given by the mean signal divided by the measured standard deviation of the image background.

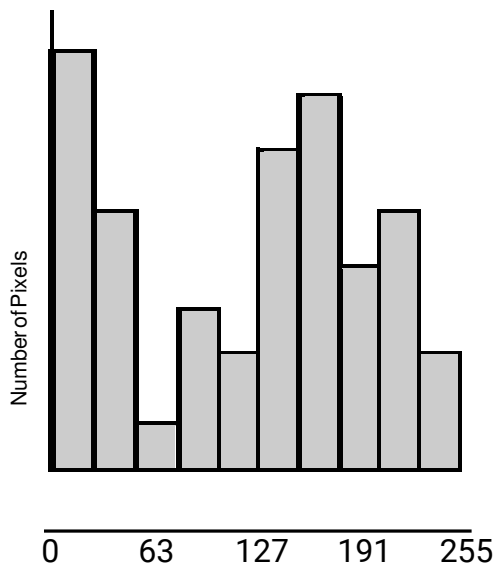
1.4.3 The Image Histogram

The grayscale image histogram is a way of illustrating the distribution of gray levels in an image. It shows how many pixels have particular gray values. The information may be displayed as a graph, or presented as a table of numbers. In the graphical representation, the horizontal axis is used to indicate the grayscale values, which may be shown individually or in ranges, and the vertical axis shows how many pixels have each gray value. An example is shown in Figure 1.18. Once the histogram

has been calculated, the underlying data may be adjusted in order to perform image enhancement. The histogram is known as a *global* histogram if it is calculated for the whole of the image. Alternatively, the histogram found using only part of the image, or *region of interest*, is called a *local* one.

1.4.3.1 *Image Contrast and the Histogram*

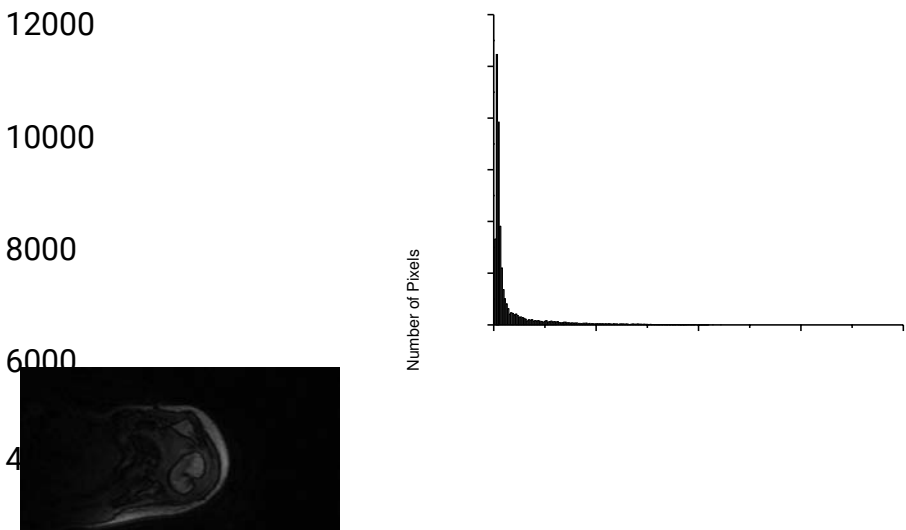
Three commonly seen types of image are those with low contrast, high contrast or with well-balanced contrast. In a typical low-contrast image (Figure 1.19a), different features in the image all have much the same gray level, so that only a few of the full range of gray levels are actually used, and these are close together. This is what is seen in a low-contrast histogram (Figure 1.19b): the pixel values are closely grouped together, and the other gray values are unoccupied or have very few pixels associated with them.



Grey Value

FigUrE 1.18

The graphical representation of an image histogram. The horizontal axis indicates the gray- scale values, and the vertical axis indicates the number of pixels with each gray value.



2000

0

0 64 128 192 256
Intensity

(a)

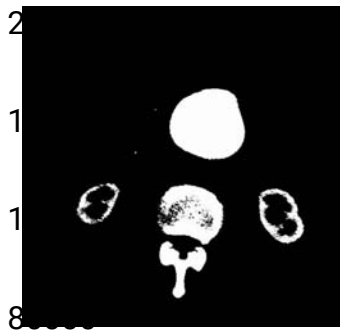
(b)

Figure 1.19

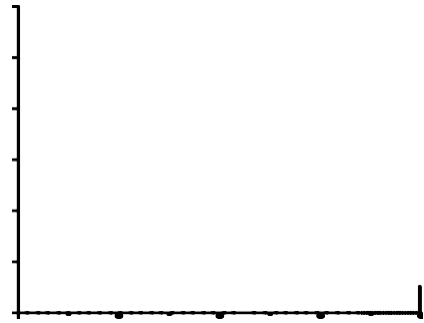
Low image contrast and the histogram. (a) A low-contrast image, (b) the associated image histogram.

On the other hand, high-contrast images have gray levels that fall into separate, very different, groups. An extreme case is shown in Figure 1.20a, where the image has pixels with only two gray levels, 0 and 255. High-contrast histograms are *bimodal*, which means that there are two well-separated peaks, with few values occupied in between (Figure 1.20b).

240000



Number of pixels



40000

0

0 64 128 192 256

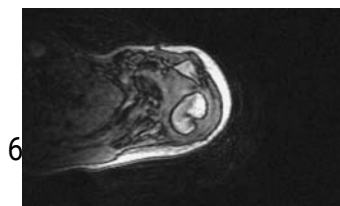
Intensity

(a)

(b)

FigUrE 1.20

High image contrast and the histogram. (a) A high-contrast image, (b) the associated image histogram; note that many pixels have an intensity value of zero.



2000

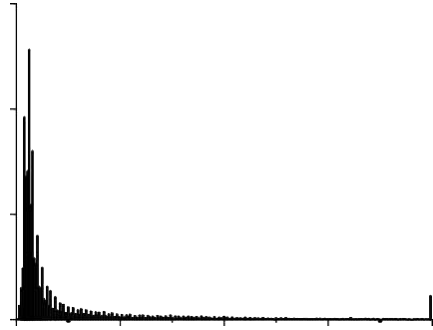
6

0

4000

Number of Pixels

0 64 128
 192 256
 Intensity



(a)

(b)

Figure 1.21

Well-balanced image contrast and the histogram. (a) An image with balanced contrast, (b) the associated image histogram. Note the high occupancy of the lowest gray values, which are associated with image background.

In an image with well-balanced contrast, gray levels throughout the range are occupied (Figure 1.21a). This property can be seen in the histogram, but care needs to be taken when considering medical images, because these often have a large number of black background pixels. The background pixels have low gray values, sometimes but not always with value 0. The eye will automatically exclude the background from its assessment of the image

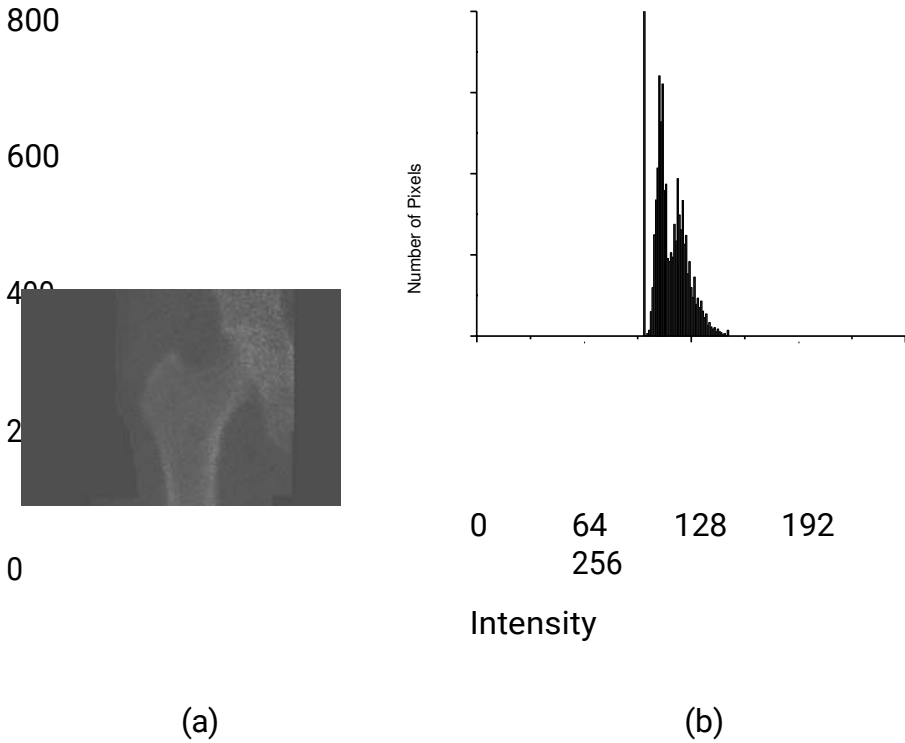


FigUrE 1.22

Although the dynamic range of an 8-bit image is 256, an 8-bit image can have a smaller actual dynamic range. (a) An image with an actual dynamic range of 50, from 10 to 150, (b) the associated image histogram.

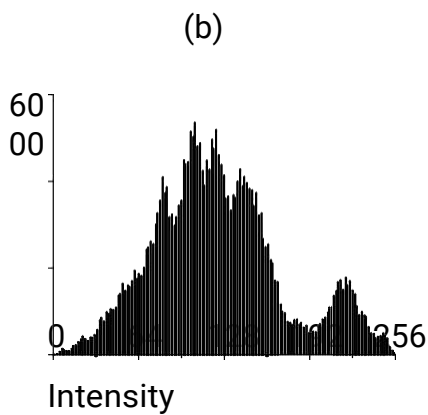
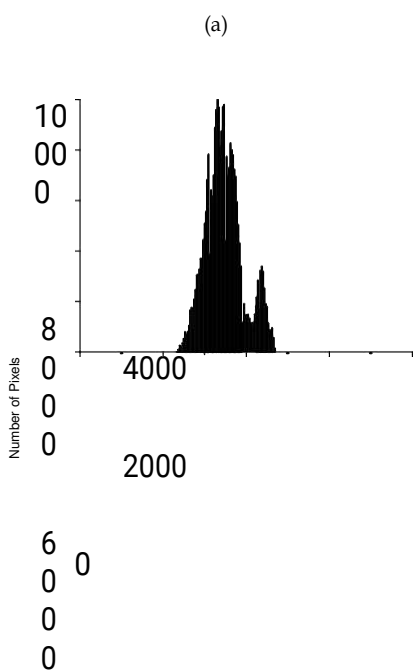
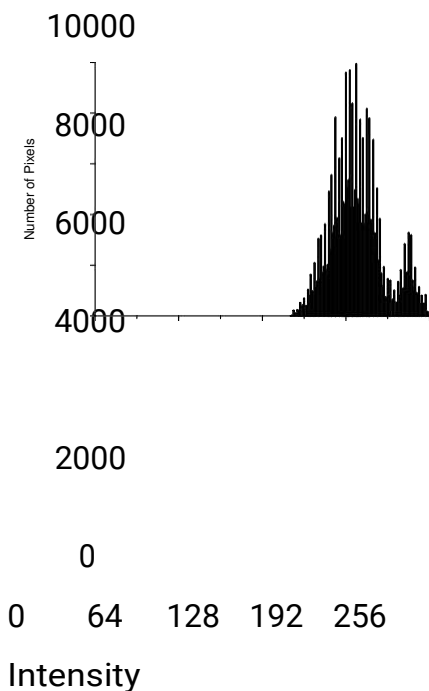
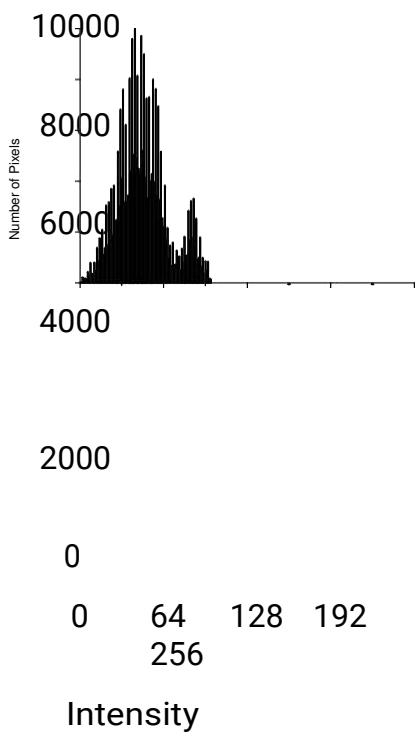
contrast, but the background pixels will be included in any analyses by a software tool unless specifically excluded. The maximum value on the vertical axis corresponds with the number of pixels with the most popular gray value, and if there is a large number of background pixels in an image, this number may be many more times the number with any other gray value. The result is that the scale of the vertical axis is such that it is very hard to see the occupancy of the gray values other than for the background regions. This effect is shown in Figure 1.21b.

1.4.3.2 ***Actual Dynamic Range***

The available dynamic range for an 8-bit image is from 0 to 255. The image histogram may be used to see how much of that range is actually occupied. For example, in Figure 1.22 the image has a small *actual dynamic range*, and there is a peak in the histogram, with all the pixels having values between 100 and 150. This is related to the earlier discussion about image contrast. An image with a small dynamic range will have low contrast and poor brightness resolution.

Self-assessment question 1.10

In the histograms in Figure 1.23, gray level 0 represents black and 255 represents white. Assign the correct description from the following list to each histogram: a predominantly light image, an image with a wide dynamic range, a well-balanced image with a large dynamic range, an image with a small dynamic range, a high-contrast image with a large dynamic range and a predominantly dark image.



4000

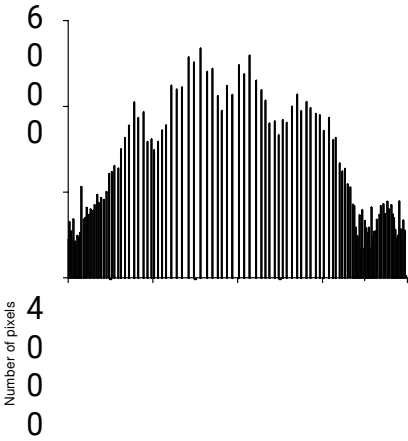
2000

0

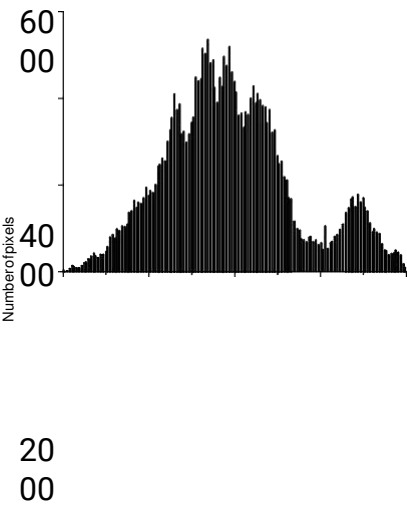
0 64 128 192 256
Intensity

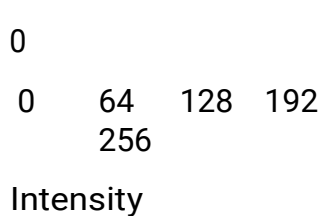
Number of Pixels

(c)

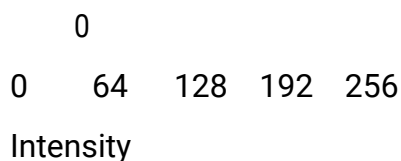


(d)





(e)



(f)

FigUrE 1.23

(a) – (f) Histograms for self-assessment question 1.10.

1.4.3.3 *Histogram Operations*

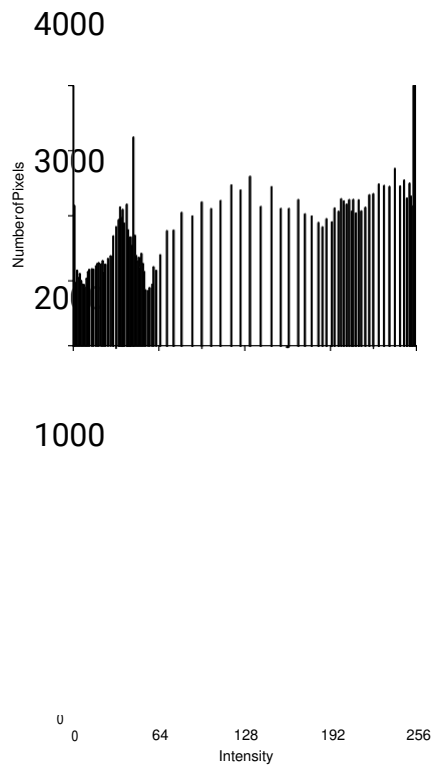
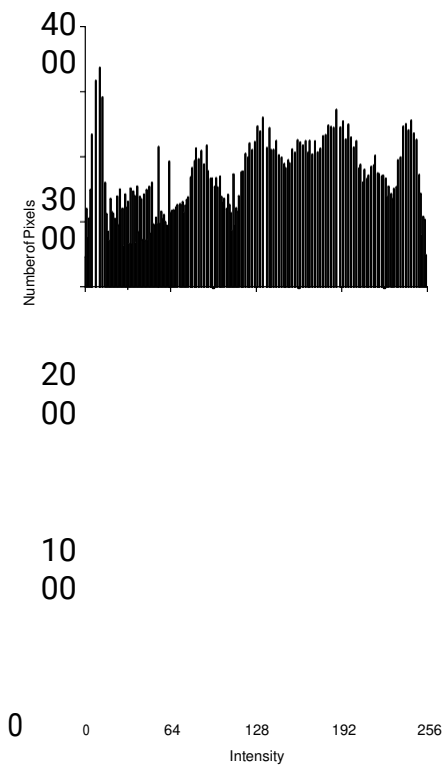
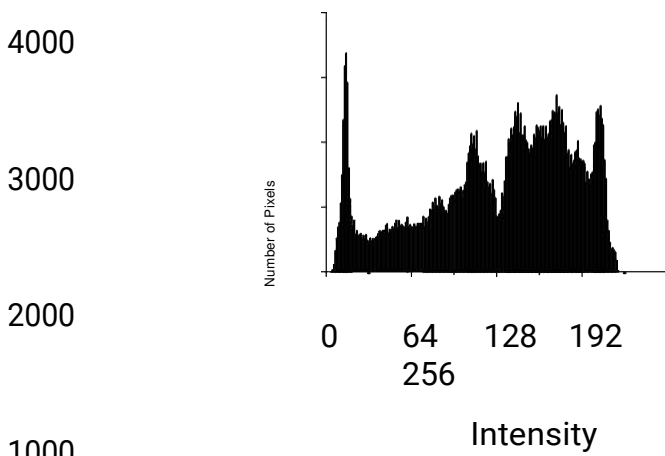
The contrast properties of an image may be changed by changing the pixel values in a way that has a particular effect on the histogram. The aim of *histogram equalization*, for example, is to spread pixel values evenly across the whole range, so that there are approximately equal numbers of pixels with each gray value.



FigUrE 1.24

Histogram equalization. (a) Original, (b) result of histogram equalization [note the enhanced image contrast in the arrowed area], (c) result of histogram equalization based on a region of interest in the femoral neck.

The effects of histogram equalization can be seen in Figure 1.24. Figure 1.24a is the original image and Figure 1.24b shows the result of histogram equalization. The enhanced image contrast is noticeable, particularly in the femoral neck (arrowed). The associated image histograms are in Figure 1.25. The equalization effect (sometimes called flattening) is evident in the reduction in the height of the peaks and the filling of the troughs in the histograms. The improved contrast in the femoral neck arises because the pixels in this area cover a greater range of values after processing than they did before.



(b)

(c)

Figure 1.25

Image histograms associated with the images in Figure 1.24. (a) Original, (b) after histogram equalization, (c) histogram equalization based on a region of interest in the femoral neck.

Because of the global nature of the operation, not all areas of the image will have greater contrast after processing. If the area of interest is known, it is possible to perform a local operation, where the equalization is based on the histogram in the selected area (Figure 1.24c and Figure 1.25c). Most pixels outside the region of interest have been set to values of 0 and 255 at the extremes of the range, and those in the region of interest are distributed evenly across the whole range.

Activity: Histogram Equalization in ImageJ

Start ImageJ and open a copy of hip.bmp. Open a second copy of hip.bmp.

Select one of the two images by clicking on the image, then select Analyze | Histogram. A histogram plot appears in its own little window (Figure 1.26). The window may be moved around the monitor by clicking and dragging.

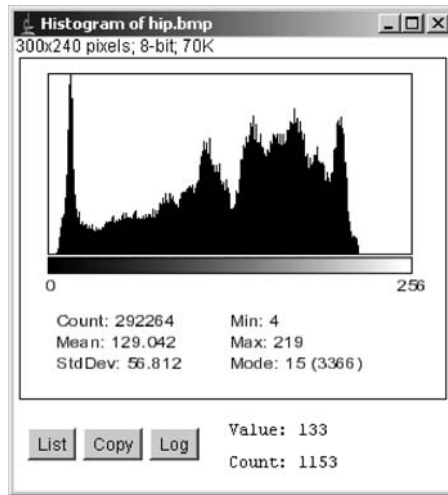


FigUrE 1.26

The ImageJ histogram window.

Make sure that one of the images is selected by clicking on it. The bar across the top will be blue, not gray, when the image is selected.

Select Process | Enhance Contrast. In the dialog box add a tick next to Equal- ize Histogram, then, while holding down the Alt key, click on OK. This dis- plays the result of histogram equalization on the image.

Do not check to see how the histogram has changed; instead, this is a good time to try out the Undo function. Select Edit | Undo. The image should revert to its previous appearance, but it may not if any other processing was performed after the histogram equalization. Repeat the histogram equaliza- tion. Visually compare the appearance of the result with the unprocessed image.

Select Analyze | Histogram to get a window similar to the one in Figure 1.27. Note the difference between the original histogram and this new, equalized one.

If the histogram equalization operation doesn't appear to be making any difference to the image, try closing the images by clicking on the cross at the top right of the image windows, and start the activity again.

More Histogram Equalization

Look in the Process Menu section of the ImageJ Documentation to see which operation is performed if the Alt key is not held down when performing histogram equalization in ImageJ. Compare the results obtained with and without use of the Alt key.

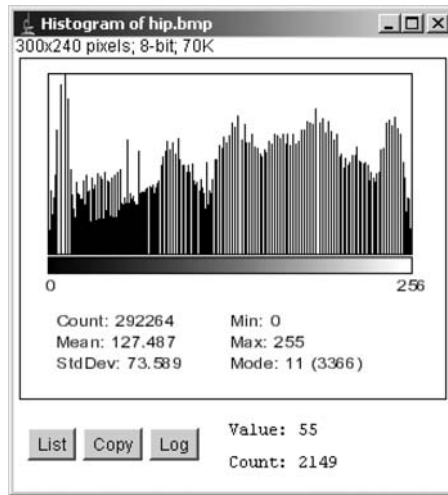


FigUrE 1.27

The ImageJ histogram window for an image after histogram equalization

Activity: Saving an Image with ImageJ

Click on the image to be saved; in this case it is the result of the histogram equalization.

Select File | Save As | BMP. Select a drive letter other than that of the CD drive, then type in the name of the file you wish to save. This should be dif- ferent from the original file name, for example "hipequal.bmp". Click the "Save" button.

Check that the operation worked as follows. Close the image window in ImageJ by clicking on the cross at the top right of the image window. Load the new file hipequal.bmp, remembering that the new file is not on the CD.

Close hipequal.bmp and Select File | Quit to close ImageJ.

Self-assessment question 1.11

In the image in Figure 1.28, there are a large number of background pix- els with values close to 0. Think about applying

the process of histogram equalization, as described above, to such an image. Describe the image that will result from applying histogram equalization to the whole image, paying particular attention to the characteristics of the background of the image and the spread of the histogram. Suggest how the histogram equalization process might be adjusted to achieve a more satisfying image.

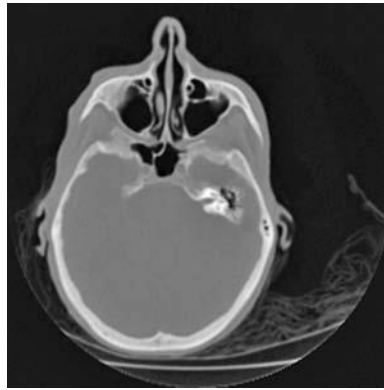
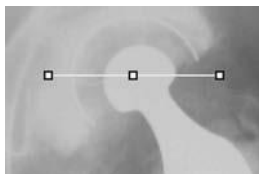
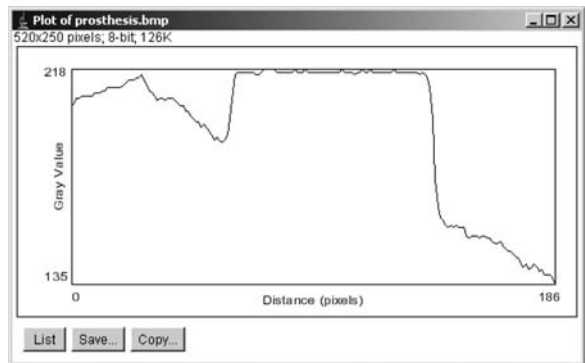


FigUrE 1.28

Image for self-assessment question 1.11. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)



(a)



(b)

FigUrE 1.29

Profile statistics. (a) A straight line profile drawn across an image, (b) graphical representation of the pixel values along the profile.

1.4.4 Pixel Statistics

1.4.4.1 *Profile Statistics*

A profile across an image is shown in Figure 1.29a. The value of each pixel along the profile is shown on the plot Figure 1.29b, and may be saved to a file for further analysis. Image processing software, such as ImageJ, will often offer options for calculating statistics from the pixel values, such as the mean gray value along the profile.



Figure 1.30

The ImageJ straight line tool icon on the ImageJ Tools menu.

Activity: Profile Statistics in ImageJ

Start ImageJ and load the image prosthesis.bmp.

Select the straight line tool icon in the ImageJ Tools menu (Figure 1.30) and click and drag on the image to draw a straight line (Figure 1.29a).

Select Analyze | Plot Profile. A profile similar to that in Figure 1.29b will be displayed.

See what happens when you click and drag on the little squares on the line. Select Analyze | Plot Profile again to draw a new profile.

To export the values in the profile (for example, to analyze the profile outside ImageJ, or to use the data to create a plot suitable for publication), use the “Save” button in the plot window. Choose a folder and file name, using perhaps a .txt extension, and click on Save. If familiar with Excel®, and with importing text files, try importing the profile into Excel now.

Select File | Quit to close ImageJ. You will be asked if you wish to save any open images.

1.4.4.2 *Region of Interest Statistics*

A region of interest is an area (or a volume in 3-D) within which measurements of pixel statistics are made. The region may be drawn interactively, or could have been defined by previous image processing operations. The measured statistics might be incorporated into further processing (for example, a measurement of mean and standard deviation might be used as

the basis for the choice of a threshold gray level) or may themselves be the values that are analyzed in a large study.

Activity: gray Level Measurements in ImageJ

Start ImageJ and open the image prosthesis.bmp

* Registered trademark of Microsoft Corporation, Redmond, Washington, USA.

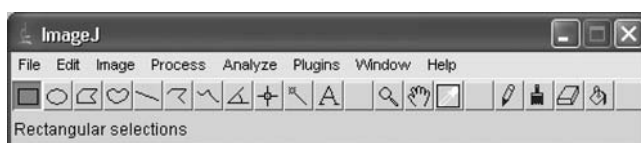


FigUrE 1.31

The ImageJ rectangular selections icon in the ImageJ Tools menu.

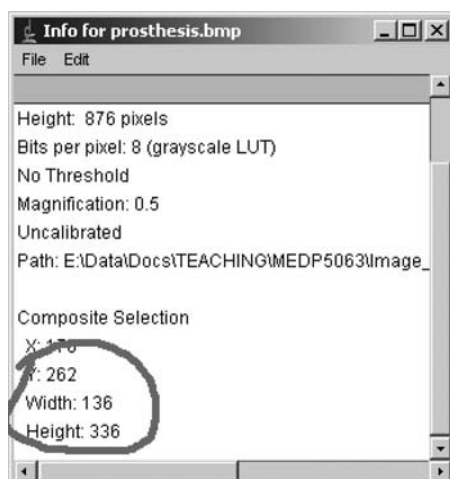


FigUrE 1.32

The ImageJ Info window.

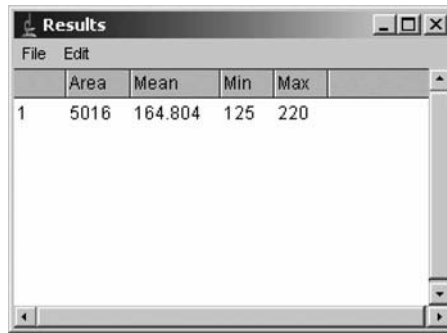
Select the rectangular selections icon in the ImageJ Tools menu (Figure 1.31), and click and drag on the image to draw a box.

Select Image | Show Info. Look in the Info Window, where information on the width and height of the box is displayed (Figure 1.32). The selection box can be dragged around the image by clicking inside it. To delete the box, click somewhere else in the image. To resize the box, delete the box and start drawing again.

Select Analyze | Measure. Look in the Window entitled “Results,” where statistics are displayed (Figure 1.33).

To include other statistics in the list of those to be measured, select Analyze

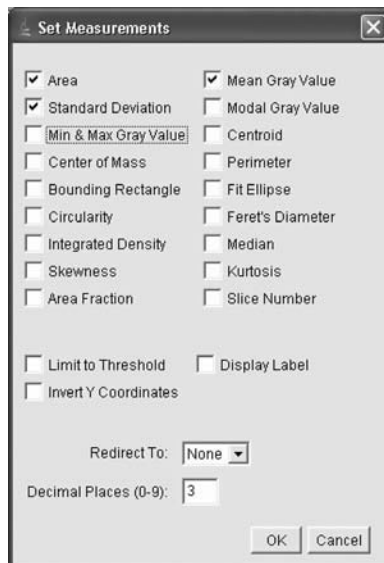
| Set Measurements. A box appears listing all the measurements that can be requested (Figure 1.34). An obvious addition would be standard deviation. Ensure there is a tick beside the options you require, then click the “OK” button.



	Area	Mean	Min	Max
1	5016	164.804	125	220

FigUrE 1.33

The ImageJ Results window.



Set Measurements

☒ Area ☒ Mean Gray Value
☒ Standard Deviation ☐ Modal Gray Value
☐ Min & Max Gray Value ☐ Centroid
☐ Center of Mass ☐ Perimeter
☐ Bounding Rectangle ☐ Fit Ellipse
☐ Circularity ☐ Feret's Diameter
☐ Integrated Density ☐ Median
☐ Skewness ☐ Kurtosis
☐ Area Fraction ☐ Slice Number

☐ Limit to Threshold ☐ Display Label
☐ Invert Y Coordinates

Redirect To: None

Decimal Places (0-9): 3

OK Cancel

FigUrE 1.34

The ImageJ Set Measurements dialog.

Position a 20×20 square ROI in the bright region below the tip of the prosthesis in prosthesis.bmp. Watch the main ImageJ window to check on the size of the region while drawing. Measure the mean and standard deviation of the gray values in this ROI. The ROIs may not be exactly in the same place, so the

results will probably be a little different from those shown in Figure 1.35.

Close any open images and Select File | Quit to close ImageJ.

Self-assessment question 1.12

Self-assessment question 1.11 was a thought experiment about the effect on histogram equalization of the presence of a large proportion of low pixel

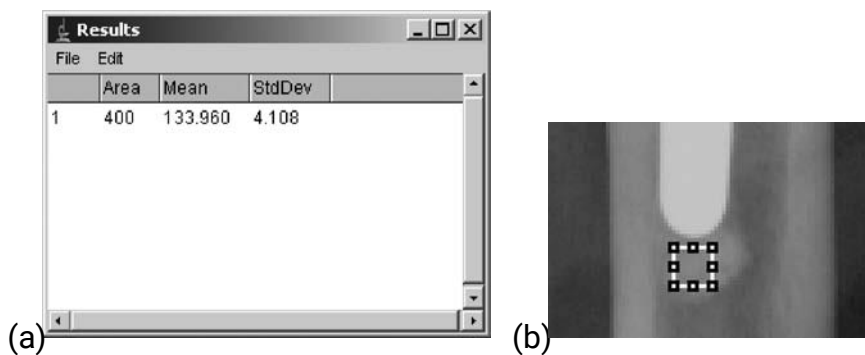


FigUrE 1.35

Measurement of statistics within a region of interest. (a) The ImageJ Results window, (b) the image selection for which the statistics were measured.

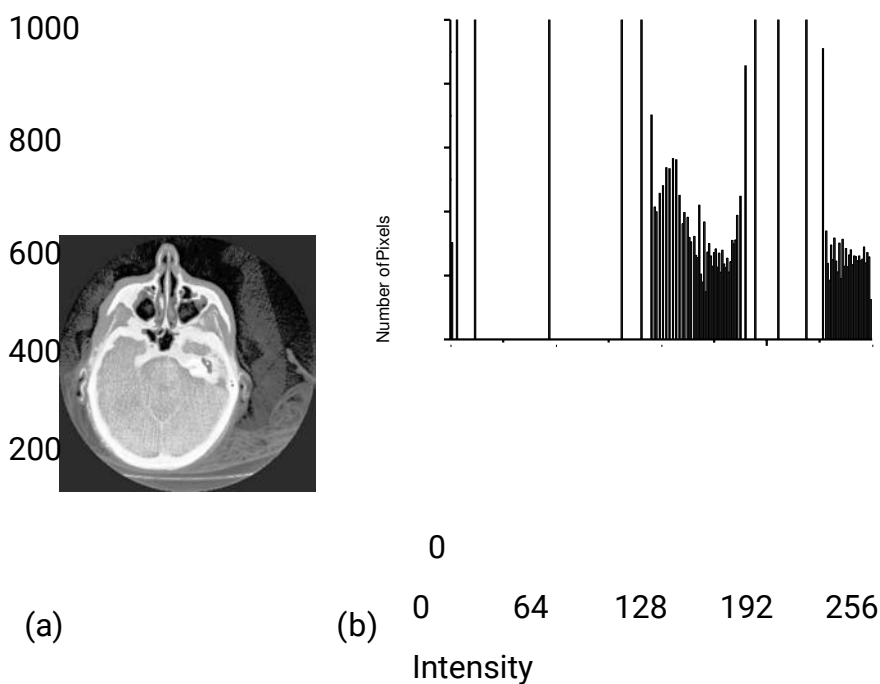


FigUrE 1.36

(a) and (b). Images for self-assessment question 1.12. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

value background pixels. In ImageJ, if there is no region of interest defined, then histogram equalization is a global operation. However, if a region of interest has first been defined on the image, any subsequent histogram equalization will be based on the pixel values within that region. Load two copies of the image *cthead.tif** from the CD and perform a global histogram equalization operation on one, and a local histogram equalization operation on the other. The aim is to achieve results similar to those in Figure 1.36 and Figure 1.37.

* Image data from the *Chapel Hill Volume Rendering Test Data Set*, Volume I. [1] With permission.

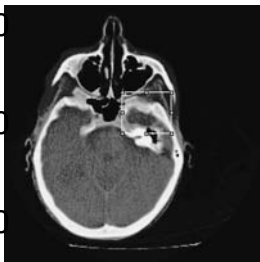
1000

800

600

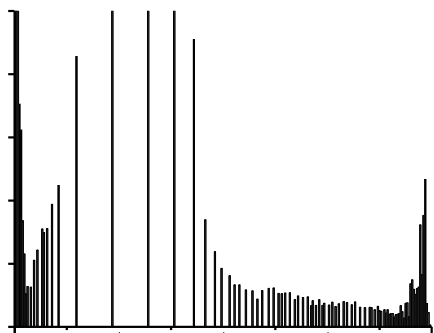
400

200



(a)

Number of Pixels



0

0 64 128 192 256

Intensity

(b)

FigUrE 1.37

(a) and (b). Images for self-assessment question 1.12. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

References

1. The BrainWeb Simulated Brain Database.
www.bic.mni.mcgill.ca/brainweb/
2. Collins, D.L. et. al., Design and construction of a realistic digital brain phantom, *IEEE Trans. Med. Imag.*, 17, 463, 1998.

Spatial Domain Filtering

3.1 Introduction

The operations in this chapter are sometimes termed neighborhood operations because the value of a pixel is changed according to calculations involving the value of the pixel itself and the values of nearby pixels. The operations fall into the image enhancement category of image processing, and are also important as preliminary steps, or preprocessing operations, in image analysis.

3.1.1 Learning Objectives

When you have completed this chapter, you should be able to

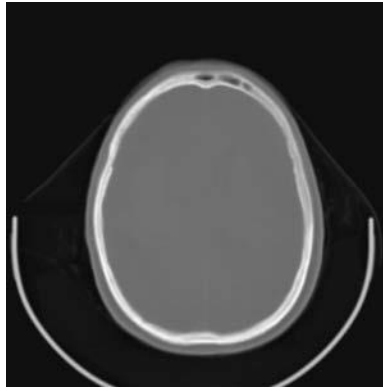
- Define rank filtering
- Define convolution filtering
- Give examples of simple rank and convolution kernels
- Discuss the effect of the size and shape of the neighborhood used for filtering
- Use ImageJ to perform a range of spatial filtering operations
- Recognize the need to choose operations and parameter

values in a justifiable way

3.1.2 Example of an Image Used in This Chapter

Self-assessment question 3.01

Figure 3.1 is an x-ray computed tomography image of the head. Give two ways in which a transverse T2-weighted magnetic resonance image of the same slice would differ.



FlgUrE 3.1

Image for self-assessment question 3.01 showing an x-ray computed tomography image of the head.

3.2 Spatial Filtering Operations

The neighborhood spatial filtering operations fall into two categories: *rank* filtering and *convolution* filtering. A third *hybrid* category involves a combination of operations.

3.2.1 rank Filtering

In rank, or ordered, filtering the gray values of pixels within a defined neighborhood around the pixel of interest are simply arranged in a list in ascending order. The new value for the pixel of interest is the value at the required rank position in this list; for example, the largest value would be chosen if maximum filtering were being performed. The defined neighborhood may be square, as illustrated in Figure 3.2, but other shapes may be chosen too.

Four commonly available rank filters are the median, maximum, minimum and range filters. Median filtering is valuable when an image is corrupted by noise characterized by noise pixels having a very much higher or lower value than the rest of the image. This is sometimes termed impulse noise, where noise pixels

have values from the extremes of the range, e.g., 0 or 255 for an 8-bit image. A median filter will replace any value that is extreme for its neighborhood by the median value in the ranked list, thus removing this kind of noise pixel without excessive blurring, as illustrated in Figure 3.3.

The maximum and minimum filters are easy to understand: each pixel in the image is replaced by the largest, or smallest, value in its neighborhood. The effect on dark and bright areas is illustrated in Figure 3.4. The original image is the same noisy image of Figure 3.3a. The minimum filter enlarges the size of dark areas, while the maximum filter enlarges light areas. The images are also slightly blurred.

	A	B	C	D	E
F	G	H	I	J	
K	L	M	N	O	
P	Q	R	S	T	
U	V	W	X	Y	

FigUrE 3.2

A square 3×3 neighborhood for rank filtering. The result calculated from the pixel values within the square will replace the value M.

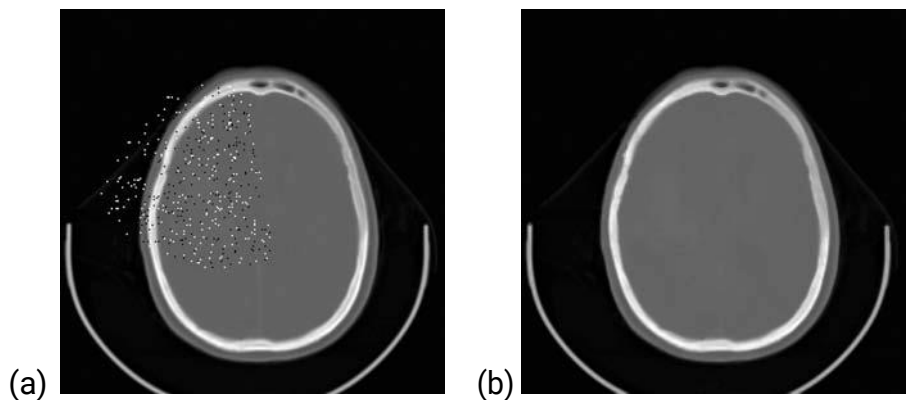


FigUrE 3.3

(a) Original image affected by impulse noise, (b) result of applying a 3×3 square median filter.

The range filter acts as an edge detector. Each pixel is replaced by range of the gray values in the neighborhood, that is, the difference between maximum and minimum values. Near the edge of an object, the range in the neighborhood will be larger than inside an object, hence the edge detection characteristic of the filter. An example is shown in Figure 3.5.

Self-assessment question 3.02

The pixel values for a 5×5 portion of an image are shown in Figure 3.6. Four pixels have been marked with the letters a–d. If a square 3×3 neighborhood is used, what is the result of applying the maximum and the minimum filter to each marked pixel?

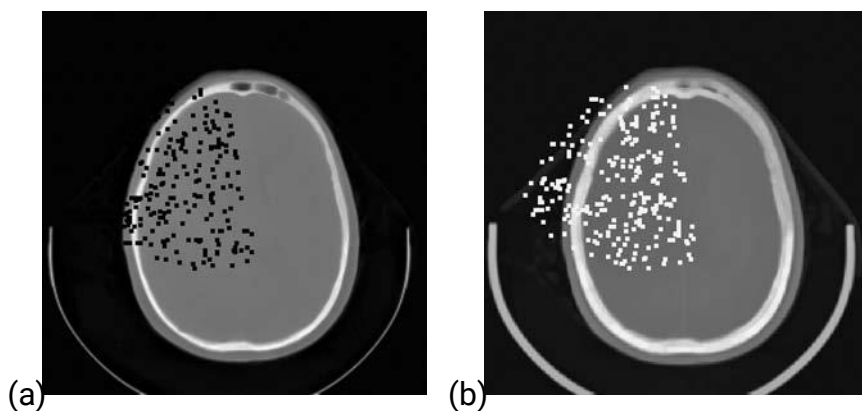


Figure 3.4

Result of applying rank filters to the original image of Figure 3.3a.
 (a) 3×3 square minimum filter, (b) 3×3 square maximum filter.

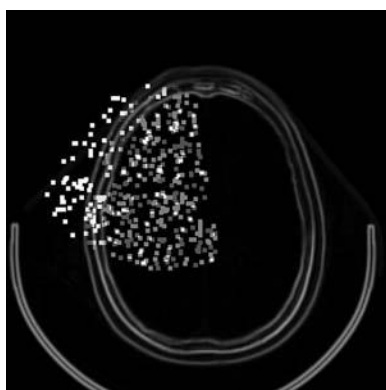


Figure 3.5

Result of applying a 3×3 square range filter to the original image of Figure 3.3a.

9	11	13	15	16
8	2	4	4	9
8	^a 89	^b 16	16	16
9		9	9	9

			9	
8 9	89 ^c	89	16 9	16 9
8 9	d 89	89	89	89
8 9	89	89	89	89

FigUrE 3.6

Image for self-assessment question 3.02.

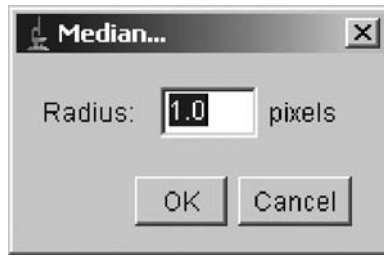


Figure 3.7

The ImageJ Median Filter dialog.

Activity: Median Filtering in ImageJ

Start ImageJ and load the image `dusty.bmp` from the CD. You will see that the image has a lot of dust on it (it was digitized from a dirty 35-mm slide). The appearance of the image can be improved using the median filter.

Select `Process | Filters | Median`. A dialog window (Figure 3.7) will appear. Choose a radius of 1 or 2 pixels, then click on the OK button. The image should now look a lot less dusty.

Load any new image of your choice.

Select `Process | Noise | Salt and Pepper` to add noise from the extremes of the gray range to this image.

Repeat if desired to get more dots.

Select `Process | Filters | Median`. Choose a radius of 1 pixel, then click on the OK button. Providing you did not add too many dots, this operation should have removed them. The median filter works well on impulse noise because the noise pixels are always at the extremes of the ranked list and will be replaced by the median value, which can be assumed to be representative of the underlying image and not noise.

Load the image `PET_Scan_256.tif` from the CD. This is also a

noisy image, but in this case the noise pattern does not consist of single pixels of impulse noise. It is not expected that the effect of median filtering will be so impressive here, because, in contrast to the situation with impulse noise, the median pixel in the ranked list may itself contribute to the noise. Use ImageJ to apply median filtering to this image. The image will be blurred by the median filter, and may indeed look a little smoother, but the effect is much less striking than the effect on impulse noise. Convolution or hybrid filtering strategies are commonly employed to reduce non-impulse image noise, and these are covered later in this chapter.

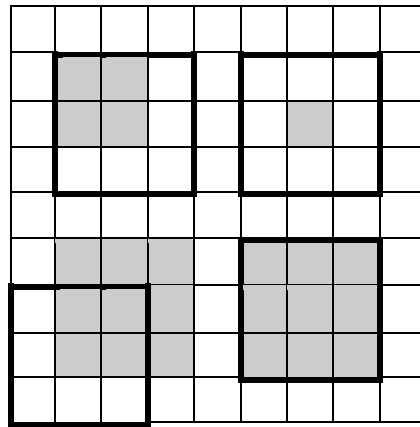


Figure 3.8

Median filtering. In each of the four examples, the 3×3 neighborhood is indicated by the black square overlying the image. The pixel value centered under the 3×3 neighborhood will be changed from gray to a white background pixel in all but the bottom right example, because fewer than half of the pixels in the neighborhood share a similar gray value to the pixel of interest.

3.2.1.1 *Effect of Neighborhood Size and Shape*

Larger filters change the image more, because pixels from further away from the pixel of interest are included in the calculations. Additionally, the nature of the median filter means that if fewer than half of the pixels in the neighborhood share a similar gray value to the pixel of interest, then the feature they represent will be removed from the image (Figure 3.8). The effect is also mediated by the shape chosen for the neighborhood, as this can determine whether or not half of the pixels in the neighborhood share a similar gray value to the pixel of interest.

The first six shapes and sizes of rank filtering neighborhoods available in the program ImageJ are shown in Figure 3.9.

Self-assessment question 3.03

Consider the six neighborhoods shown in Figure 3.10a–f. Each neighborhood is shown outlined in black and overlying a binary image, which is a triangular object on a background. The pixel of interest is indicated by a black dot.

- A. Neighborhood (a) has 9 pixels, which other neighborhood also has 9 pixels?
- B. Which neighborhood is the same size as neighborhood (c), but has a different shape?
- C. In (a) the pixel of interest will be replaced, for median filtering, with a pixel with the background value, because the neighborhood contains

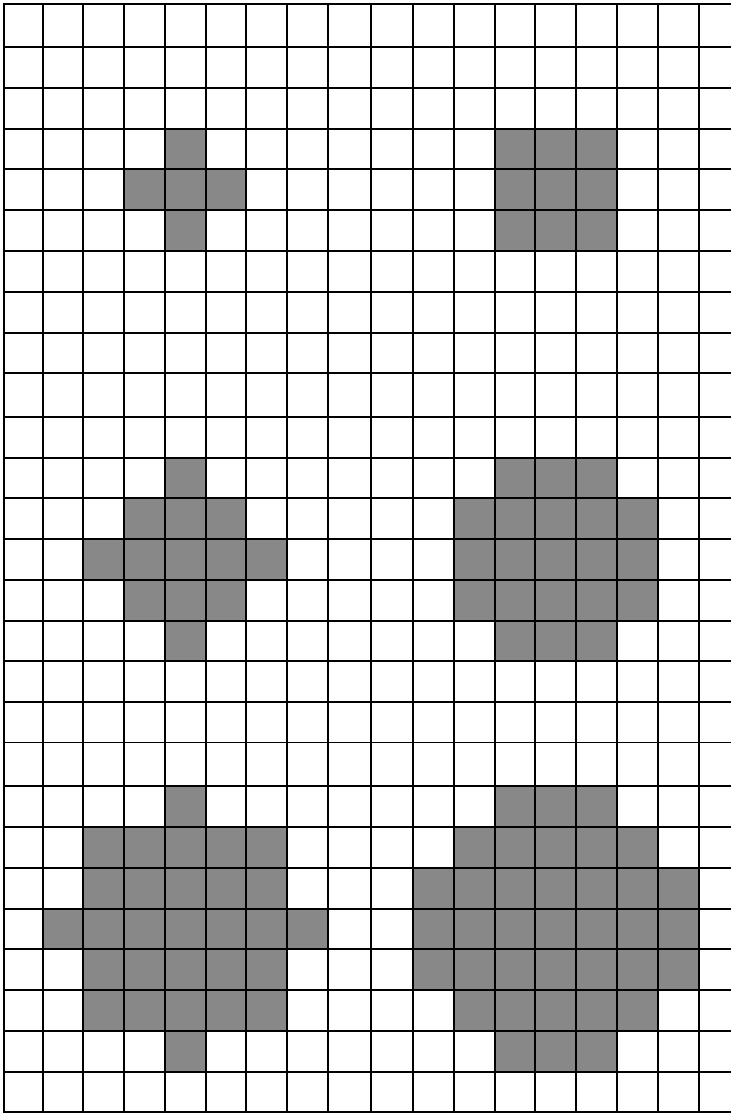


FigUrE 3.9

The first six shapes and sizes for rank filtering neighborhoods in the program ImageJ, indicated by the shaded shapes. Selection of a different shape can change the filtering result, as the shape can affect whether or not half of the pixels in the neighborhood share a similar gray value to the pixel of interest.

five background pixels and only four object pixels. For (b)–(f), will the pixel of interest be an object or a background pixel following median filtering?

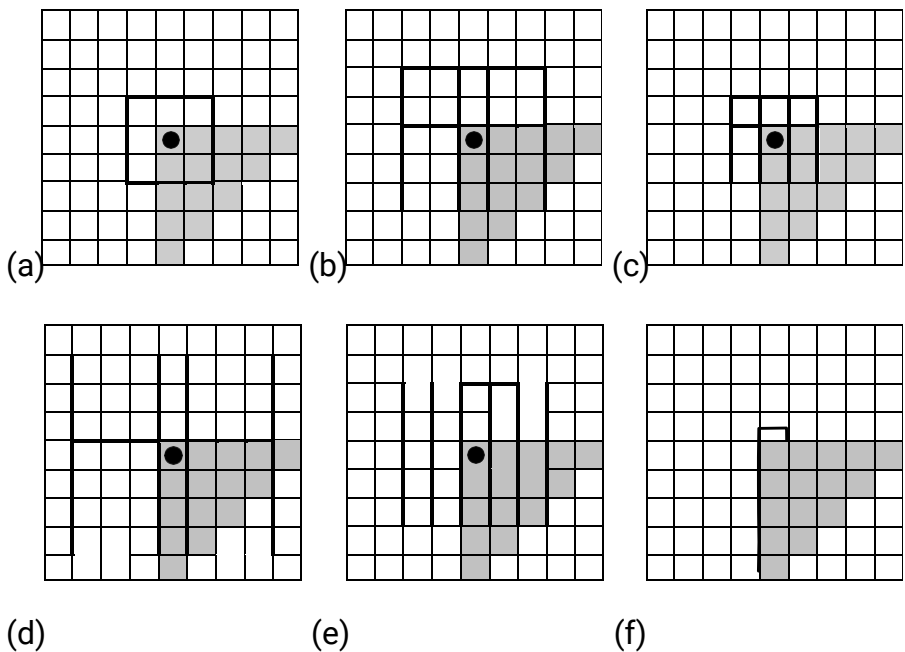


FigUrE 3.10

(a)–(f) Images for self-assessment question 3.03. Six neighborhoods shown outlined in black and overlying a binary image, which is a triangular object on a background. The pixel of inter- est is indicated by a black dot.

3.2.2 Convolution Filtering

Like rank filtering, convolution filtering is concerned with replacing a pixel value with a new value found from the values of its neighbors, but there are a few more calculations involved. A square kernel is defined to represent the neighborhood around the pixel. Each location in the kernel is assigned a numerical value, known as a weight. In Figure 3.11a, these weights are given by the letters a to i. The kernel is moved across the image, and the pixel value under the center of the kernel is replaced by the weighted sum of the sur- rounding pixels. In the example of a section of image in Figure 3.11b, where the pixel values are

represented by upper case letters, the pixel M will be replaced by M , where

$$M = aG + bH + cI + dL + eM + fN + gQ + hR + iS \quad (3.1)$$

This summation of the results of a series of multiplications is closely related to the mathematical operation called convolution, which is indicated using the symbol “*” or a star in a circle, and this is why these filters are called convolution filters. Convolution filtering may also be called linear filtering.

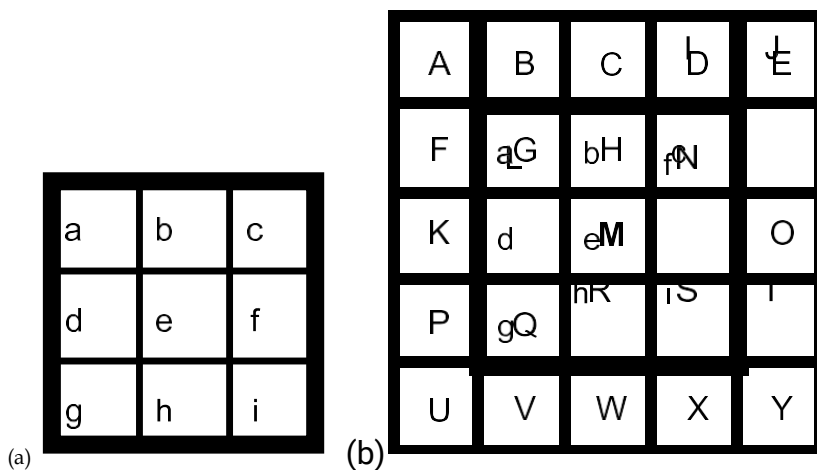


Figure 3.11

Convolution filtering. (a) The weights in a 3×3 convolution kernel are indicated by the letters a to i, (b) the 3×3 convolution kernel overlying a section of an image, with pixel values indicated by upper-case letters. The pixel value M will be replaced by $\hat{M}$ as indicated in Equation (3.1).

Convolution and Correlation

The operation illustrated in Figure 3.11 is strictly the mathematical correlation operation. The convolution operation is the same but with the kernel rotated through 180° . However, as many of the kernels used in image processing are rotationally symmetric, the results from correlation and convolution come out the same. Indeed, in some image processing programs it is assumed that all kernels are rotationally symmetrical, and convolution filtering is actually implemented using the correlation operation. It is worth checking to be sure what a program is doing.

What would be the effect of using the 3×3 convolution kernel:

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$0$$

$$0$$

$$h = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 \end{bmatrix}$$

(3.2)

$$\begin{bmatrix} 0 & 0 & 0 \end{bmatrix}$$

Answer this without using a calculator.

Commonly available convolution filters are the average or mean filters, and Gaussian filters used to smooth and blur the image, the sharpening filter and edge enhancement filters.

The averaging filter is used to reduce noise in an image, and it will also cause blurring. This is an appropriate filter to use when the noise is not

limited to extreme values, unlike the impulse noise that was successfully removed using the median filter. A typical averaging kernel is given in Equation (3.3).

$$h = \begin{bmatrix} 1/9 & 1/9 & 1/9 \\ 1/9 & 1/9 & 1/9 \\ 1/9 & 1/9 & 1/9 \end{bmatrix} \quad \text{or} \quad h = \frac{1}{9} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad (3.3)$$

The kernel weights are normalized so that their sum is 1 and the overall brightness of the image is left unchanged in the result. The result of applying this averaging filter is shown in Figure 3.12b, and the result for a similar but larger 7x7 kernel in Figure 3.12c. The Gaussian filter also has a blurring effect, but the weights at the edges of the kernel are smaller than those in the center to reduce the effect of pixels further away from the pixel of interest. The result of applying the 3x3 Gaussian filter of Equation (3.4) is shown in Figure 3.12d.

$$h = \begin{bmatrix} 0.2098 & 0.458 & 0.2098 \\ 0.458 & 1 & 0.458 \\ 0.2098 & 0.458 & 0.2098 \end{bmatrix} \quad (3.4)$$

The sharpening filter increases gray level contrast and accentuates detail in an image. It will also accentuate noise. The sharpening filter in ImageJ uses the kernel given in Equation (3.5). The result of applying this 3x3 sharpening filter is shown in Figure 3.12e.

$$h = \begin{bmatrix} -1 & 12 & -1 \\ -1 & 12 & -1 \\ -1 & 12 & -1 \end{bmatrix} \quad (3.5)$$

$$\begin{bmatrix} -1 & -1 & -1 \end{bmatrix}$$

For performing edge enhancement, the kernel weights are chosen to give a different result depending on the direction of the underlying edge in the image. For example, the kernels in Equations (3.6) and (3.7) emphasize edges that run vertically and horizontally, respectively. Results on a test image are shown in Figure 3.13.

$$h_1 = \begin{bmatrix} -1 & 0 & 1 \end{bmatrix} \tag{3.6}$$

$$\begin{bmatrix} -1 & 0 & 1 \end{bmatrix}$$

$$h_2 = \begin{bmatrix} -1 & -1 & -1 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{bmatrix} \tag{3.7}$$

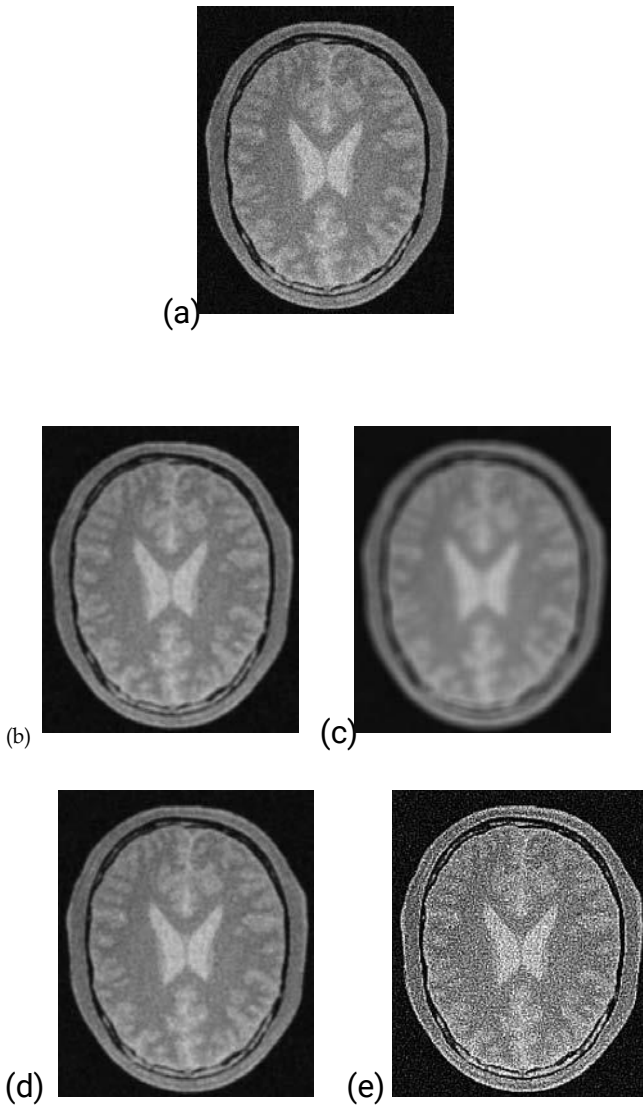


FigUrE 3.12

Results of applying various convolution filters. (a) Original noisy image, (b) result of applying a 3×3 averaging filter, (c) result of applying a 7×7 averaging filter, (d) result of applying a 3×3 Gaussian filter, (e) result of applying a 3×3 sharpening filter. (Image data from the BrainWeb Simulated Brain Database [1,2]. With permission.)

Self-assessment question 3.05

Figure 3.14 shows the pixel values for a section of an image with a 3x3 convolution kernel overlaid at the top left. Find the new value for the central pixel under the kernel, currently with value 89, for each of the convolution kernels h_a and h_b in Equation (3.8).

$$\begin{aligned}
 & \begin{bmatrix} 1/9 & 1/9 & 1/9 \\ 1/9 & 1/9 & 1/9 \\ 1/9 & 1/9 & 1/9 \end{bmatrix} \quad \begin{bmatrix} -1 & -1 & -1 \\ -1 & -1 & -1 \\ -1 & -1 & -1 \end{bmatrix} \\
 h_a = & \begin{bmatrix} 1/9 & 1/9 & 1/9 \\ 1/9 & 1/9 & 1/9 \\ 1/9 & 1/9 & 1/9 \end{bmatrix} \quad h_b = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad (3.8)
 \end{aligned}$$

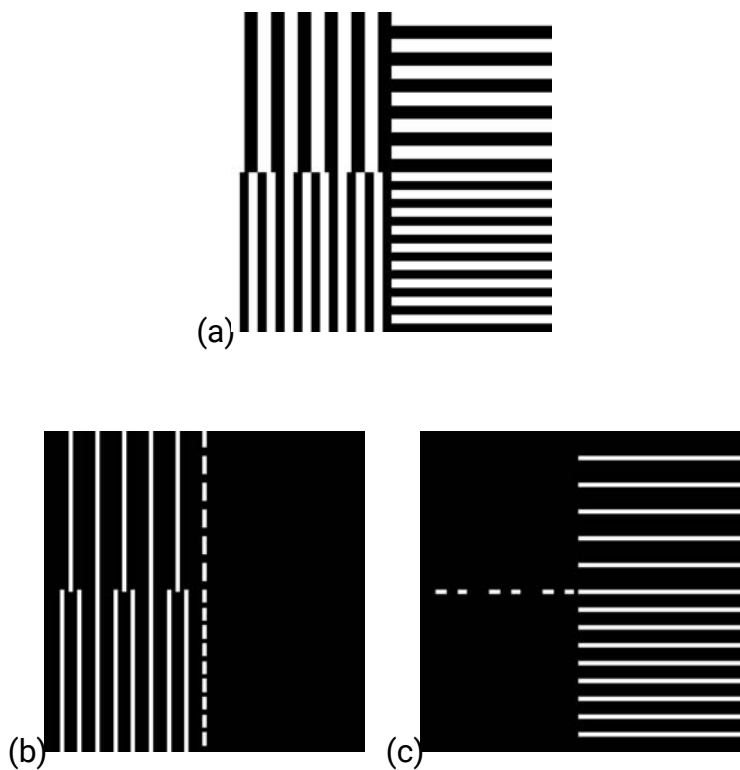


FigUrE 3.13

Edge enhancement by convolution filtering. (a) Original image, (b) result of applying kernel in Equation (3.6), (c) result of applying kernel in Equation (3.7).

98	11 2	13 4	15 4	16 9
89	89	16 9	16 9	16 9

89	89	89	16 9	16 9
89	89	8 9	8 9	89
89	89	8 9	8 9	89

FigUrE 3.14

Image for self-assessment question 3.05, showing the pixel values for a 5×5 section of an image, with a 3×3 convolution kernel outlined in black at the top left of the section.

Activity: Convolution Filtering in ImageJ

Start ImageJ and load the image tip.bmp from the CD. Repeat, so that you have two windows labeled tip.bmp.

Click on one of the two images to select it, then select Process | Smooth.

Visually compare the smoothed image with the unprocessed version in the other window.

Use the Edit | Undo function to undo the smoothing operation, watching closely to see how the image changes. You may not see very much as the smoothing filter is not a very strong filter. To get a stronger effect, perform the operation repeatedly on the same image, and you should eventually be able to see the difference.

Close the open images.

Load the image tip.bmp from the CD. Use Image | Duplicate to create another copy of it. Click on one of the two images to select it, then select Process | Find Edges. This convolution filtering operation highlights sharp changes in gray level in the image.

More Convolution Filtering in ImageJ

The kernels used for the Smoothing and Find Edges operations are described in the Process Menu section of the ImageJ Documentation. It is also possible to filter using a custom convolution kernel. This option is also described in the Process Menu section of the ImageJ Documentation and is included as an activity in Chapter 4.

3.2.2.1 *Effect of Kernel Size*

Larger filters change the image more, because pixels from further away from the pixel of interest are included in the

calculations. Images produced using large convolution kernels are generally not helpful for visual assessment, but large kernels may be useful as part of a series of operations.

Activity: Processing Time for Different Convolution Kernel Sizes in ImageJ

Start ImageJ and select File | New | Image

Set values for a single 512×512 8-bit image filled with a ramp.

Select Process | Filters | Gaussian Blur ... and set the radius to 1 pixel and click on OK.

Make a note of the time taken for the operation, which is shown at the bottom left of the ImageJ menu (e.g., 0.157 seconds).

Select Edit | Undo.

Select Process | Filters | Gaussian Blur ... and set the radius to 128 pixels and click on OK.

Make a note of the time taken for the operation, which is shown at the bottom left of the ImageJ menu (e.g., 2.375 seconds).

Close open images and exit from ImageJ.

3.2.3 Hybrid Filtering

Hybrid filters may include both rank and convolution steps, or may involve an additional image processing operation. A hybrid filter that performs a rank filtering operation and a convolution smoothing operation is a good choice where both impulse and Gaussian noise are present. A widely used hybrid filter is the *unsharp mask*. This is a filter that sharpens and enhances edges, and it involves the subtraction of a weighted copy of a smoothed version of the image from the original image. Both the degree of smoothing and the value of the weighting affect the result (Figure 3.15). The unsharp mask filter can be found in the Process | Filters menu in ImageJ.

3.3 Adaptive Filtering

Adaptive filters perform a different operation depending on the image content in the region in which they are being applied. The filters discussed in this chapter were assumed to perform in exactly the same way across the whole image, but an adaptive filter can be designed, for example, to blur only those parts of an image that do not contain edges.

3.4 Good Practice Considerations

In common with other image processing operations, when used as part of a quantitative protocol, spatial domain filters should not be applied in an ad hoc manner:

- The justification for the choice of kernel size, neighborhood size and shape, and values of other parameters should be recorded and reported.
- The filtering should be applied consistently to images that are to be compared.

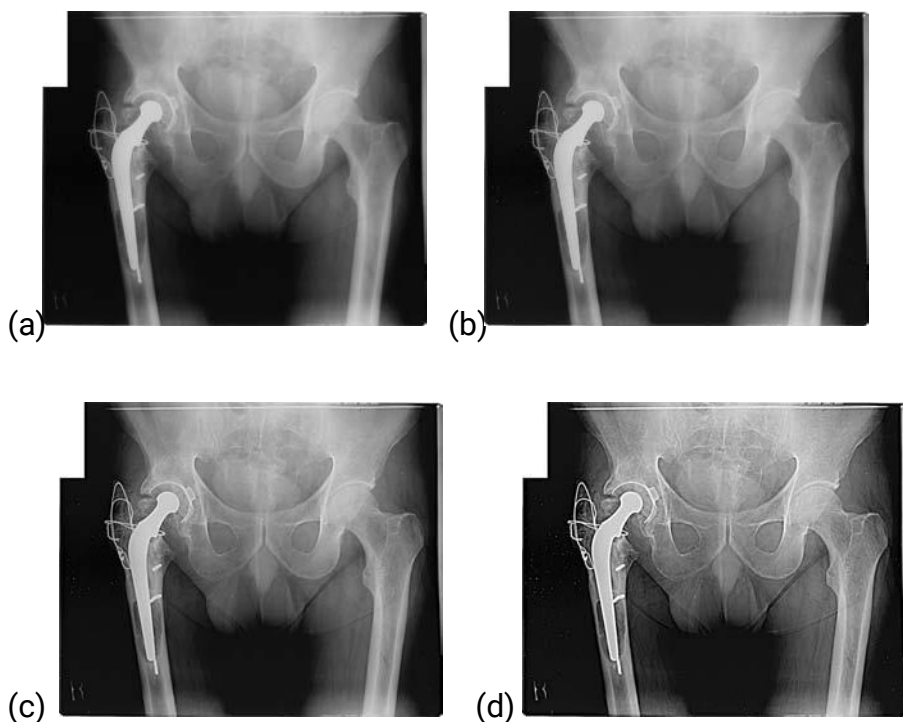


FigUrE 3.15

Effect of the choice of parameters on unsharp mask filtering. (a) Original image, (b) result of unsharp mask filtering with smoothing radius 2 and mask weight 0.6, (c) result of unsharp mask filtering with smoothing radius 10 and mask weight 0.6, (d) result of unsharp mask filtering with smoothing radius 10 and mask weight 0.8.

Observers should always be told what filtering has been applied and have access to the original image data, even for qualitative assessment. This is because there are pitfalls when the results of image processing mimic clinical conditions.

3.5 Chapter Summary

Spatial domain filtering was covered in this chapter. The emphasis was on rank and convolution filtering, and examples

were given of the key convolution kernels. Hybrid methods and adaptive filtering were also described briefly. ImageJ activities were included to allow the reader to perform filtering using some of the spatial domain filters built into the program.

3.6 Feedback on the Self-Assessment Questions

Self-assessment question 3.01

A transverse T2-weighted magnetic resonance (MR) image of the same slice would not have a strong signal from the bone of the skull, whereas the skull

is clearly shown on the computed tomography (CT) image in Figure 3.1. The MR image would show more detail within the soft tissue of the brain, with gray matter and white matter differentiated. Any fluid-filled areas would have a high signal in the MR image.

Self-assessment question 3.02

The results of the maximum filter for a 3×3 square neighborhood: a) 169, b) 169, c) 169, d) 89.

The results of the minimum filter for a 3×3 square neighborhood: a) 89, b) 89, c) 89, d) 89.

Self-assessment question 3.03

- A. Neighborhood (b) also has 9 pixels.
- B. Neighborhood (c) has 5 pixels; the other neighborhood of the same size is (f).
- C. After median filtering, the pixel of interest will be an object pixel for (b), (c), (d), and (f) and a background pixel for (e). From these examples, it can be seen that the shape of the neighborhood is important as well as its size.

Self-assessment question 3.04

This kernel would not change the image at all, as the only pixel value not multiplied by zero is the pixel of interest.

Self-assessment question 3.05

Convolution kernel h_a is an averaging kernel and the value 89 would be replaced by 106.

Convolution kernel h_b is an edge detecting kernel and the value 89 would be replaced by -77.

References

1. The BrainWeb Simulated Brain Database.
www.bic.mni.mcgill.ca/brainweb/
2. Collins, D.L. et. al., Design and construction of a realistic digital brain phantom,
IEEE Trans. Med. Imag., 17, 463, 1998.

Frequency Domain Filtering

4.1 Introduction

Frequency domain filtering has an effect equivalent to convolution filtering, which was covered in Chapter 3. The way in which the result is achieved is, however, different. Like convolution filtering, the operations fall into the image enhancement category, and the results may also be used for prepro- cessing in image analysis protocols. With frequency domain processing, it is easier to understand the relation between the filter parameters and their effect on the image than when using spatial domain methods, and this means that it is a good choice for quantitative image analysis. Furthermore, the time taken for computation is less for all but the simplest of operations.

4.1.1 Learning Objectives

When you have completed this chapter, you should be able to

- Recognize when images have undergone low-pass or high-pass filtering
- Understand the relationship between filtering in the spatial and fre- quency domains
- List the advantages of filtering in the frequency domain
- Recognize different applications of the word “convolution”
- Use ImageJ to perform frequency domain filtering

4.1.2 Example of an Image Used in this Chapter

Self-assessment question 4.01

Which part of the body appears in the image in Figure 4.1? Which

imaging modality has been used?

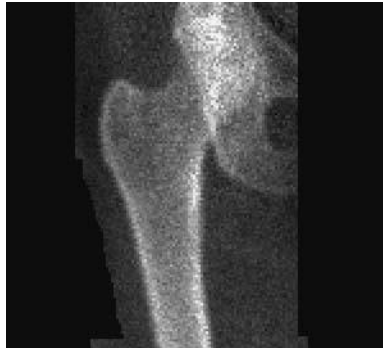


FigUrE 4.1

Image for self-assessment question 4.01.

4.1.3 Convolution Filtering: A reminder

In Chapter 3, several convolution filters were introduced. The important points are summarized in the following list:

- Convolution is a mathematical operation, indicated using the symbol “ $\ast$ ” or a star in a circle.
- Convolution involves the summation of the results of a series of multiplications
- In convolution filtering, the convolution kernel defines the factors by which pixel values are multiplied
- Examples of convolution filters include the sharpening kernel and the averaging kernel

In this chapter, an alternative way of performing convolution filtering is introduced. To understand this, it is necessary first to spend a little time getting reacquainted with the idea of spatial frequency, which was covered in Chapter 1.

4.2 The Spatial Domain and the Frequency Domain

Shapes in images are made up of changes in gray level across

the image, from dark to light to dark. The rate of this change is called the spatial frequency. In each of the images in Figure 4.2, there is just one spatial frequency. That spatial frequency is different in each image.

Self-assessment question 4.02

Put the images (a), (b) and (c) of Figure 4.2 in order of increasing spatial frequency, starting with the image with the lowest spatial frequency

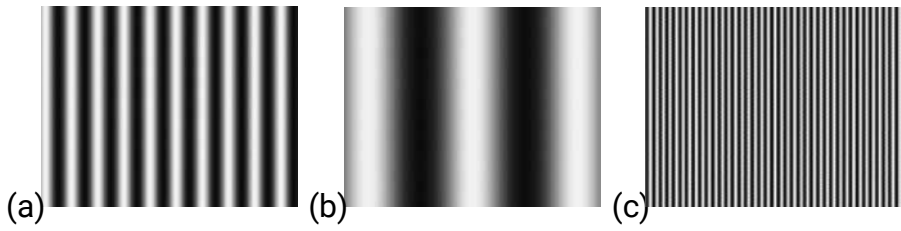


FigUrE 4.2

(a) – (c) Images for self-assessment question 4.02, illustrating the concept of spatial frequency in images. Each image contains a different, single spatial frequency.

A real image will be much more complex and will contain many different spatial frequencies. However, we can say that:

- High spatial frequencies correspond with fine detail, such as noise and edge features.
- Low spatial frequencies correspond with larger objects that have a fairly uniform gray level within the object.

These two properties mean that it is possible to describe the spatial frequency content of an image in very broad terms, from observation of the image. This is illustrated in self-assessment question 4.03.

Self-assessment question 4.03

Figure 4.3a has a slightly noisy appearance, with square pixels visible in some areas. The appearance of the noise has been reduced in Figure 4.3b by applying a 7×7 Gaussian convolution filter. Using knowledge about which features are represented by low and high spatial frequencies, would you expect the filtered image (b) to have:

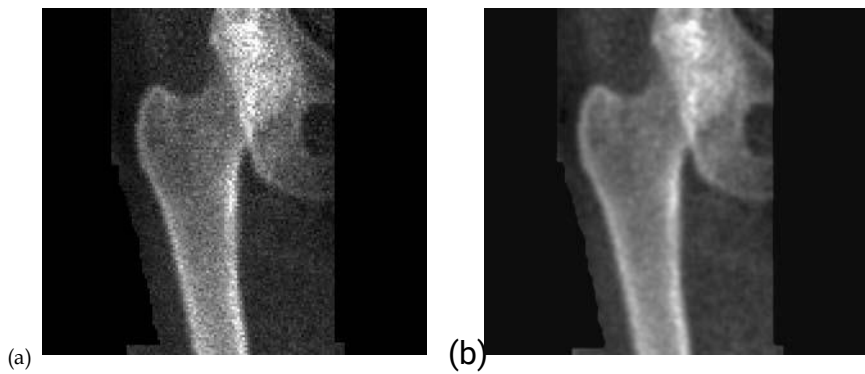


FigUrE 4.3

Images for self-assessment question 4.03. (a) Original image. (b) Image after application of a 7×7 Gaussian convolution filter.

- more high spatial frequencies than the unprocessed image?
 - fewer high spatial frequencies than the unprocessed image?
 - the same quantity of high spatial frequencies as the unprocessed image?
-

4.3 Frequency Domain Filtering

This spatial frequency viewpoint leads to an alternative way of considering the filtering process, one where filtering is considered in terms of the spatial frequencies. The filter that was used in self-assessment question 4.03 was one that preserves only the low spatial frequencies in an image. This type of filter is often described as a *low-pass* filter. Naturally there is also such a thing as a *high-pass* filter: one that preserves high spatial frequencies but removes the low. A *band-pass* or notch filter preserves a particular band, or range, of frequencies. One can imagine the high-pass filter to act like a garden riddle or a kitchen sieve. All the fine details (i.e., high spatial frequencies) get through the mesh, but the larger features cannot pass.

Self-assessment question 4.04

Which of the two filtered images in Figure 4.4, (b) or (c), represents the result of applying a high-pass filter to the original image in Figure 4.4a?

Clearly some of the spatial domain filters introduced in Chapter 3 can be considered in terms of their effect on the spatial frequencies in the image. It is also possible to generate the same effects that can be achieved by spatial domain filtering, but by working directly with the spatial frequencies. In general terms, the procedure is as follows:

- Generate a representation to show which spatial frequencies are present in the image
- Remove selected spatial frequencies from the representation

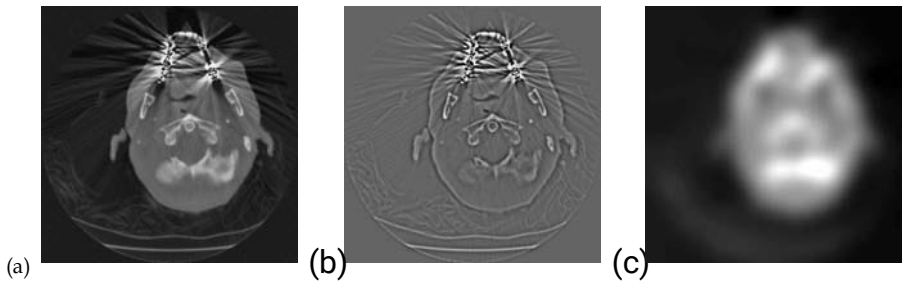


FigUrE 4.4

Images for self-assessment question 4.04. (a) Original image. (b)–(c) Images after application of different frequency domain filters. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

- Reverse the process to get back to an image. The new image is filtered because some spatial frequencies necessary to reproduce the original image are no longer present.

A standard mathematical technique can be used to implement the procedure. The representation showing which spatial frequencies are present in the image is called a *spectrum*, and it is obtained using Fourier transformation. Specific spatial frequencies are removed from the spectrum by filtering it; the mechanism for filtering will be described later. To distinguish this method from filtering in the spatial domain, the process is called filtering in the frequency domain, or in frequency space. Finally, the Inverse Fourier transform is applied to the filtered spectrum to give the filtered image.

Fourier Analysis

Those with a mathematical background will know that Fourier theory states that any waveform can be expressed as a number of sine and cosine terms, each with a different frequency, amplitude and phase. Fourier analysis breaks down a signal into these component functions. If the waveform is rebuilt, but some of the frequency components are omitted, then the result differs from the original waveform. For example, if the high-frequency components are omitted, then edges and corners are not well represented in the result.

4.3.1 Advantages of Filtering in the Frequency Domain

Why filter in the frequency domain, when spatial domain convolution filtering works so well? There are three situations in which it is preferred over spatial domain convolution filtering:

- It is possible to perform operations that are difficult in the spatial domain, such as removing, or enhancing, only

specific frequencies in the image.

- Periodic patterns can be selectively removed or enhanced (e.g., scanning lines).
- For operations that require large kernel sizes in the spatial domain, frequency domain filtering is computationally faster.

These points are considered in more detail in the following sections.

4.3.2 The FFT and the Spectrum

The Fourier transform, and its inverse, can be applied using many image processing packages, including ImageJ. In most cases, a particular method of calculating the Fourier transform is used. This is the Fast Fourier Transform,

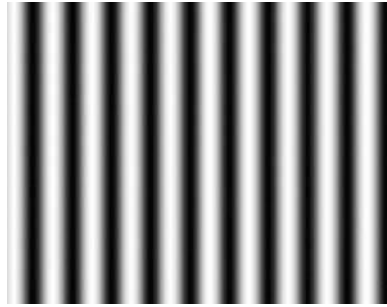


FigUrE 4.5

An image containing a single dominant spatial frequency.

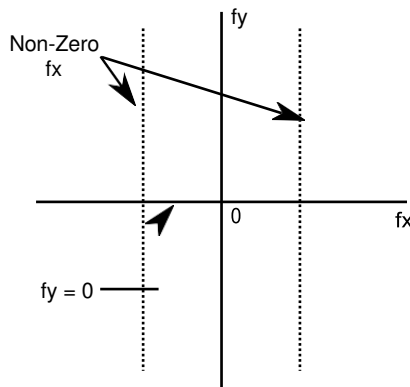


FigUrE 4.6

Sketch of the spectrum expected from Fourier transformation of the image in Figure 4.5.

which is abbreviated to FFT. Some examples follow of spectra produced by applying the FFT.

One of the simplest images to consider is one with a single dominant spatial frequency, such as the striped image of Figure 4.5. In this image, the following points may be noted:

- The stripes are vertical stripes. This means that the changes in intensity run in the horizontal (x) direction.
- There is one dominant spatial frequency present in the x

direction, with a non-zero value.

- In the y direction, the intensity is uniform, so the frequency of intensity changes is zero. That is, the dominant frequency in the y direction has a frequency of zero.

From these observations, it is possible roughly to sketch the form of the spectrum (Figure 4.6). Note that

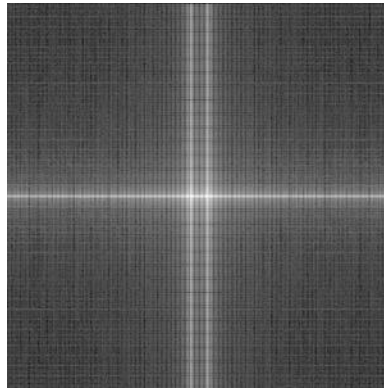


Figure 4.7

Spectrum obtained from Fourier transformation of the image in Figure 4.5.

- The spectrum includes both positive and negative frequencies for both x and y. This means that although there is only one dominant frequency in the x direction, the graph contains two lines, one each for both positive and negative values.
- The origin of the graph (0,0) is at the center.

When the FFT is applied to the striped image of Figure 4.5 in ImageJ, the result is as shown in Figure 4.7.

Self-assessment question 4.05

Sketch your own copy of the result of the FFT (Figure 4.7), and identify on it:

- The feature that represents the zero frequency y component
- The feature that represents the dominant x component

The next stage in frequency domain filtering is to ensure that areas of the spectrum that are not required are set to zero (black in the examples here) before an inverse FFT is performed

(Figure 4.8).

Self-assessment question 4.06

What do you expect to see in the final image if the spectrum in Figure 4.7 is altered to appear as in Figure 4.8? Will the image still contain stripes? Will the noise in the image be increased or decreased?

In the example for Figure 4.8, the pattern used to set parts of the spectrum to zero was not symmetrical in the x and y directions. Higher x frequencies were blocked, but some high y frequencies were not. More typically, the distribution of areas set to zero (called the *frequency domain filter*) is often symmetrical in the x and y directions.

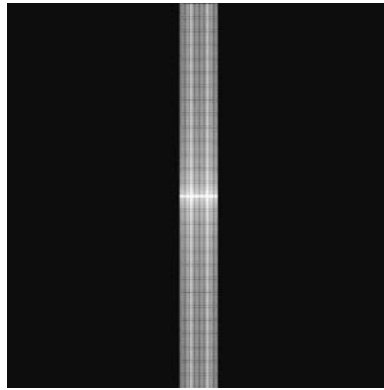


FigUrE 4.8

A filtered version of the spectrum in Figure 4.7. Areas representing frequencies that are not desired in the filtered image have been set to zero (black).

Two examples of frequency domain filters are shown in Figure 4.9b–c. In both cases the filter is symmetrical about the origin of the spectrum, meaning that the x and y frequencies are affected in the same way. As before, black areas set the spectrum to zero while the spectrum is unchanged by white.

Self-assessment question 4.07

The two example filters in Figure 4.9b and Figure 4.9c were applied to the FFT of the head image shown in Figure 4.9a. After inverse transformation, the results in Figure 4.9d and e were obtained. Which of the two filters (b) and (c) goes with which output image (d) and (e)?

4.3.3 Application of the Filter to the Spectrum

Filtering is achieved by setting unwanted parts of the spectrum to zero, while leaving other areas unchanged. In the filters shown in Figure 4.9, black has a value of 0 and white has value 1. If a spectrum were multiplied by such a filter, then the desired effect will be achieved.

In summary, the steps involved to filter in the frequency domain are:

- Calculate the FFT of the image.
- Design a frequency domain filter to be applied to that FFT. This has value 0 for the spatial frequencies to be removed, 1 for those to be retained.
- Multiply the FFT of the image by the frequency domain filter.
- Calculate the inverse FFT of the filtered spectrum.

The discussion so far has concentrated on the removal of specific features in the spectrum, but it is also possible selectively to enhance features, or to reduce their effect without removing them completely.

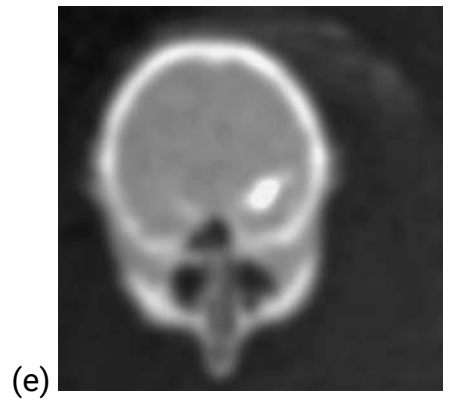
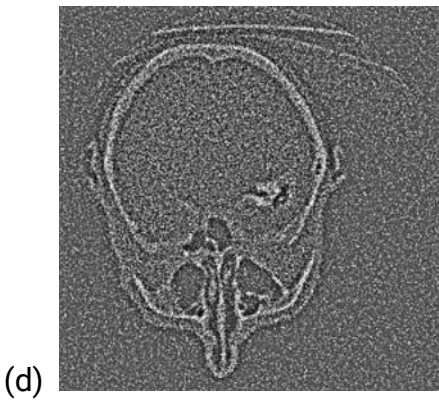
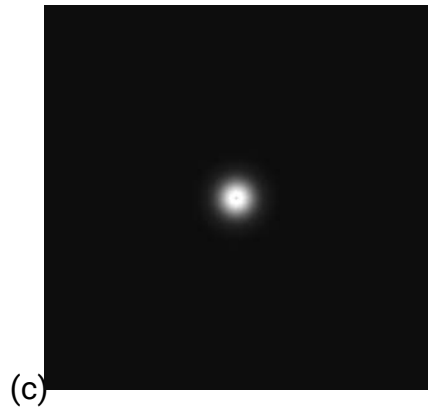
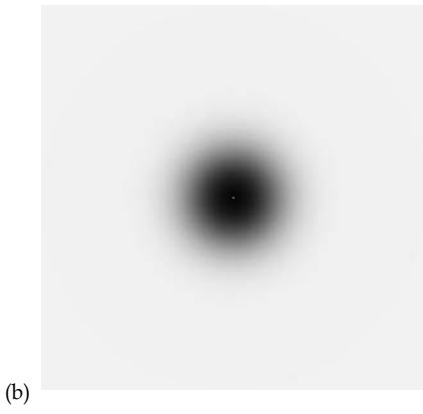
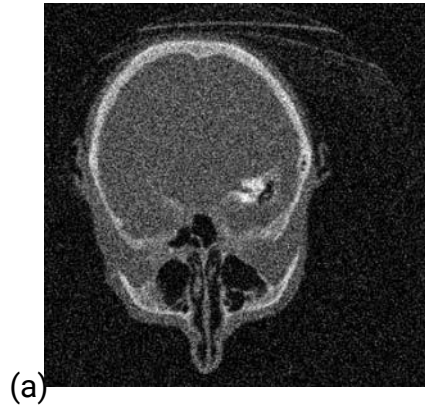


FigUrE 4.9

Frequency domain filtering. (a) Original image, (b)–(c) examples of frequency domain filters, (d)–(e) images for self-assessment question 4.07, obtained by filtering the spectrum of the original image with the frequency domain filters. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

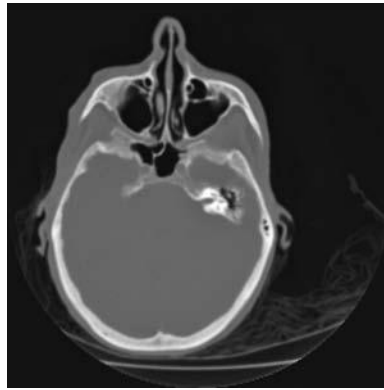


Figure 4.10

The image CThead.tif, which may be found on the CD. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

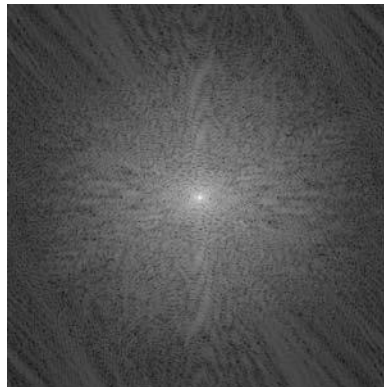


Figure 4.11

The result of applying the FFT operation to the image CThead.tif.

Activity: Low-pass Frequency Domain Filtering Using ImageJ

Select File | Open and load the image CThead.tif* from the CD (Figure 4.10).

Select Process | FFT | FFT. The result should appear as Figure 4.11.

Select the Rectangular selections option from the ImageJ tools

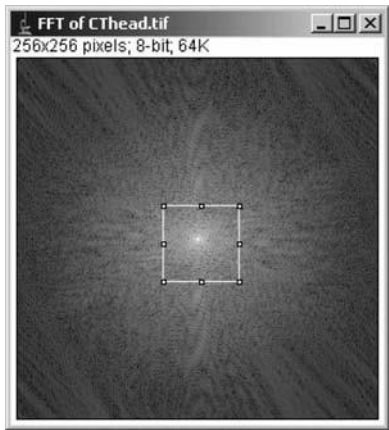
(Figure 4.12) and draw a square on the FFT, centered on the zero frequency point at the center of the image (Figure 4.13).

Low-pass filtering is required. This means that the high spatial frequency areas of the spectrum should be set to zero. Select Edit | Clear Outside (Figure 4.14)

* Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.

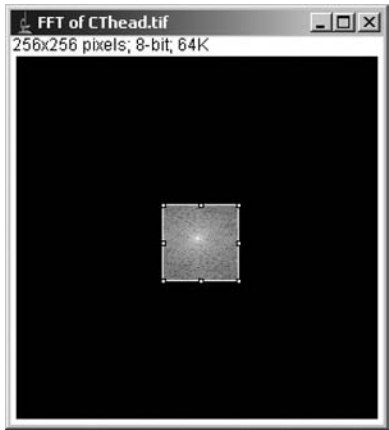
FlgUrE 4.12

The ImageJ rectangular selections icon in the ImageJ Tools menu.



FlgUrE 4.13

A rectangular selection drawn on the spectrum of the original image.



FlgUrE 4.14

The spectrum edited so that high spatial frequency areas (outside the selected square region of interest) are set to zero.

Select Edit | Selection | Select None (this simply removes the square that was drawn).

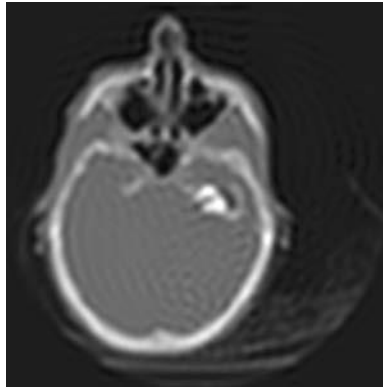


FigUrE 4.15

The result of applying the inverse FFT operation to the filtered spectrum shown in Figure 4.14. The original image has undergone low-pass filtering. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

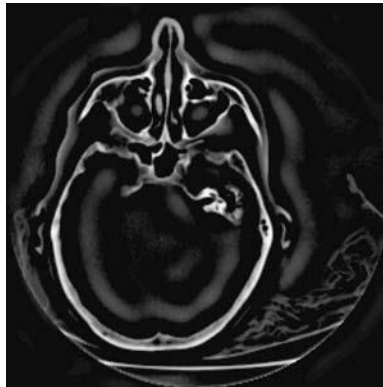


FigUrE 4.16

An example of the result expected for the activity on High-Pass Frequency Domain Filtering Using ImageJ; this is a high-pass filtered image. The image is shown here with additional contrast enhancement. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume

I. [1] With permission.)

Select Process | FFT | Inverse FFT (Figure 4.15). This displays the low-pass filtered result. When compared with the original image, the image has less detail and looks blurred. The wavy patterns arise because of the sharp edges of the filter that was used.

Activity: High-Pass Frequency Domain Filtering Using ImageJ

Repeat the last Activity, but use Edit | Clear instead of Edit | Clear Outside, so that high-pass filtering is performed. A typical result, using a much smaller square than for the low-pass filter, is shown in Figure 4.16.

FigUrE 4.17

The ImageJ elliptical selections icon in the ImageJ Tools menu.

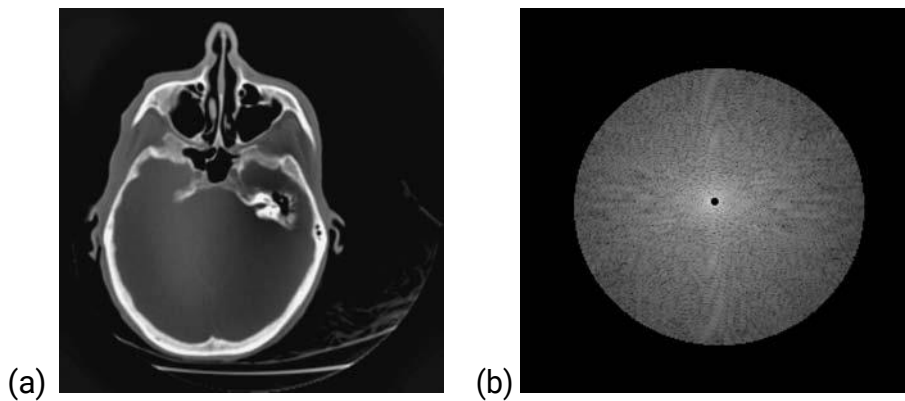


FigUrE 4.18

(a) The image CThead.tif after band-pass filtering, (b) the edited spectrum associated with the band-pass filtered image. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

Activity: Band-Pass Frequency Domain Filtering Using ImageJ

Repeat the activity again, this time performing band-pass filtering by center- ing a small circle on the spectrum and using Clear to set the inside to zero. Then center a larger circle and use Clear Outside to set the outermost fre- quencies to zero. Remember that you will need to change from Rectangular Selections to Elliptical Selections in order to draw a circle (Figure 4.17).

The result in Figure 4.18a was obtained by editing the spectrum as shown in Figure 4.18b. Image | Adjust | Brightness/Contrast was used to make the result display more clearly.

Self-assessment question 4.08

A real example of the usefulness of frequency domain filtering is described at <http://rsb.info.nih.gov/ij/docs/examples/FFT/>. Frequency domain filtering was used to remove horizontal lines on a scanning laser confocal microscope image. Adapt the technique used in the earlier activities to remove the horizontal lines from the image `confocalimage.gif`,* which is on the CD.

* From <http://rsb.info.nih.gov/ij/docs/examples/FFT/>. With permission.

4.3.4 Why Filtering in the Frequency Domain Is the Same as Convolution Filtering in the Spatial Domain

It was hinted earlier in this chapter that filtering in the frequency domain would give the same results as convolution filtering in the spatial domain. The results of the two methods are indeed the same, and this can be explained using the *convolution theorem*. The convolution theorem states that the result of the convolution operation between two functions in the spatial domain is equal to the inverse Fourier transform of the result of multiplying together the Fourier transforms of the two functions. For those happy with mathematics, this is expressed using the mathematical notation below.

The Convolution Theorem

The convolution theorem can be expressed as

$$f * h \Leftrightarrow FH$$

The left-hand side of the expression represents the convolution of an image, f , with a kernel h . F is the Fourier transform of the image and H is the Fourier transform of the kernel, so the right-hand side of the expression is the product of these two. The symbol $\Leftrightarrow$ indicates Fourier transformation from left to right, and inverse Fourier transformation from right to left.

At first glance, because of the need to perform the Fourier transforms, it looks as if performing frequency domain filtering is a lot more complicated than the equivalent operation in the spatial domain. However, convolution involves many multiplication operations, and the number of multiplications gets bigger as the size of the kernel is increased. In contrast, although two forward transforms and one inverse transform are required for the frequency domain operation, these take the same time to compute whatever filter is in use. Furthermore, there is only the one multiplication to be performed. The reduction in the number of multiplications means that filtering in the frequency domain is computationally faster than filtering

in the spatial domain, in spite of the need to perform the Fourier transforms.

The images in Figure 4.19 demonstrate how the results of filtering are the same via the two alternative routes. Figure 4.19a shows the original image, and the two filtered images are in Figure 4.19b and Figure 4.19c.

Activity: Comparison of Frequency Domain and Convolution Filtering Using ImageJ

This activity also introduces two useful features in ImageJ: the ability to perform convolution filtering with a kernel of one's own design, and the capacity for frequency domain calculations.

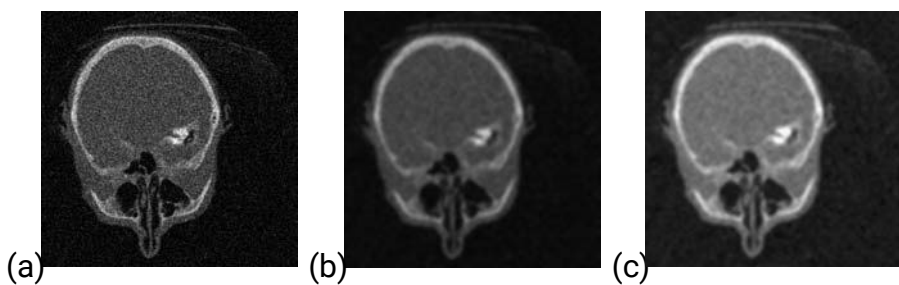


FigUrE 4.19

A comparison of filtering in the spatial and frequency domains. (a) Original image. (b) Result of spatial domain filtering. (c) Result of frequency domain filtering. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

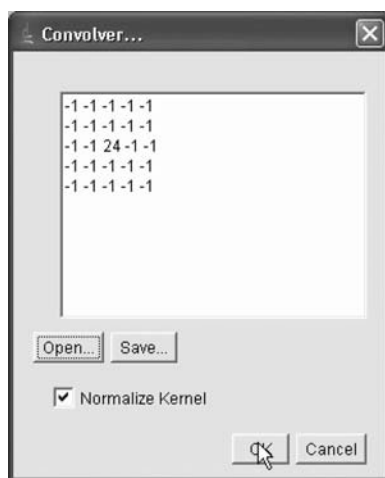


FigUrE 4.20

The ImageJ Convolver dialog for convolution filtering.

Select File | Open and load the image CThead.tif* from the CD.

Select Image | Type | 32-bit. This converts the image to the 32-bit data type, which is necessary correctly to cope with negative

pixel values.

Select Process | Filters | Convolve. The ImageJ dialog window entitled “Con- volver” will open. The default convolution kernel will probably be displayed (Figure 4.20). If it is not, type the kernel in (it consists of five rows and five columns. All the values are -1 except the central value, which is 24).

* Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.

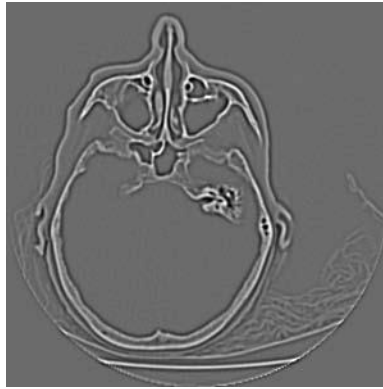


Figure 4.21

The result of convolution with a 5×5 edge-enhancement kernel. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

Ensure there is a tick beside “Normalize Kernel,” then click OK. The result of filtering is an edge-enhanced image (Figure 4.21).

It was emphasized earlier that convolution filtering is computationally slow, but the preceding operation was probably achieved almost instantly. This is because a 5×5 kernel is a relatively small one. In the next few steps of the activity, the 5×5 kernel will be made larger by using ImageJ to surround the central values with zeroes. Large kernels can also be generated outside ImageJ, for example, using Microsoft Excel®*.

Select Process | Filters | Convolve. Ensure that the correct kernel is displayed, then click the Save button. Save the file as defaultkernel.txt. Click Cancel to exit the Convolver window.

Select File | Import | Text Image and import defaultkernel.txt.

Select Image | Adjust | Canvas Size. Set the Width and Height to 63, Position to Center and place a tick next to Zero Fill. Click OK.

Select File | Save As | Text Image and save as

defaultkernel63x63.txt. Close the kernel image.

Load a new copy of CThead.tif from the CD and convert it to a 32-bit image.

Select Process | Filters | Convolve to apply defaultkernel63x63.txt – use the Open button to open the file and import the numbers into the box, rather than accepting the default kernel or typing in values.

* Registered trademark of Microsoft Corporation, Redmond, Washington, USA.

This time, the convolution processing takes much longer. The word “Convolve” will be shown at the bottom left of the ImageJ window, and a thermometer display will appear at the right. When the processing is complete, the number of seconds taken will be displayed. The resulting image should be the same as before, because the same non-zero values are at the center of the kernel. The point of the exercise was to show how the size of the kernel affected the processing time. If the resulting image is black and white, with no grays, it is likely that the conversion of the original image to 32 bits was omitted.

In the next steps the same filtering is done in the frequency domain.

Close any open images.

Load CThead.tif from the CD.

Import the file defaultkernel.txt as a Text Image. Set the Image Type for CThead.tif to 32-bit.

For the FD Math operation that follows, the image sizes must match, so change the canvas size for defaultkernel.txt to 256×256, with the Center and Zero Fill options selected.

Select Process | FFT | FD Math. The ImageJ dialog window entitled “FFT Math” will appear (Figure 4.22). Ensure that the two different image names appear for Image1 and Image2, set the operation to “Convolve,” leave the name “Result” in the result box and ensure that there is a tick beside “Do Inverse Transform.” Click on OK.

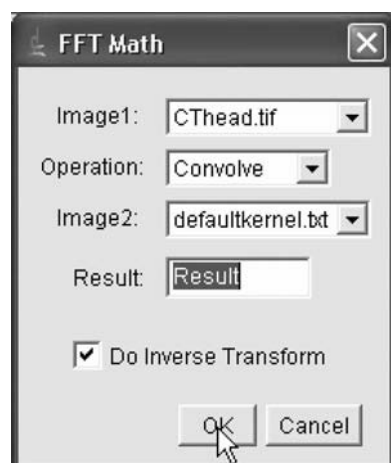


FigUrE 4.22

The ImageJ frequency domain mathematics dialog.

ImageJ now performs an FFT on both the images, multiplies these transformed images together and performs an inverse transform. In other words, it performs frequency domain filtering using the same kernel as was used for convolution filtering. The result should be visually identical to those generated in previous steps. If not, check that the change from 8- to 32-bit data type was performed.

Note that the operation was performed quickly. Frequency domain filtering is much faster than spatial convolution when the convolution kernel is larger than a few values.

4.3.5 Use of the Word Convolution

The word convolution refers to a specific mathematical operation (Chapter 3). It is true that one method of image enhancement is convolution filtering, but remember that not all spatial domain image enhancement filters are convolution filters. For example, the median filter is a rank filter, which does not involve the convolution operation. Sometimes, rather loosely, people will use the term image convolution to refer to all image enhancement operations. This is incorrect, because convolution is not a synonym for image enhancement.

The other reason for taking care with the word is that confusion can arise when discussing *image deconvolution*. Deconvolution is, as you might expect, a reverse convolution operation. However, in image processing it has a particular meaning: deconvolution is a process that is designed to remove the specific effects of the imaging process from an acquired image or signal. Deconvolution falls into the image restoration category of image processing, and it is considered alongside other methods of image restoration in Chapter 7.

Self-assessment question 4.09

Which of the following five options correctly describes a step in frequency domain filtering?

- a) The FFT of the image is added to the frequency domain filter
- b) The FFT of the image is subtracted from the frequency domain filter
- c) The FFT of the image is multiplied by the frequency domain filter

- d) The FFT of the frequency domain filter is divided by the image
- e) The FFT of the frequency domain filter is added to the FFT of the image

Self-assessment question 4.10

Which of the following are advantages of frequency domain filtering over spatial domain convolution filtering?

- a) Ability selectively to remove periodic patterns in an image
- b) Ability selectively to enhance periodic patterns in an image



Figure 4.23

Image with stripes for self-assessment question 4.11. (Image data from the Chapel Hill Volume Rendering Test Data Set, Volume I. [1] With permission.)

- c) Faster to compute when large kernels would be involved
- d) Ability selectively to remove details of a particular size from the image
- e) Ability selectively to enhance details of a particular size from the image

Self-assessment question 4.11

A copy of the image in Figure 4.23 is on the CD, named `ctandstripes05.tif`. Use ImageJ to produce a new image which has the stripes removed, and note the key steps in the processing that was undertaken to produce the final image.

4.4 Good Practice Considerations

Exactly the same considerations apply to frequency domain filtering as to spatial domain operations (Chapter 3). In particular, there is a need to justify both the use of a particular type of filter and the choice of parameters. Examples of the kind of question to address are given here:

- Why was this particular range of frequencies chosen for filtering? This choice will probably be related to the scale of an image feature to be removed or enhanced, and knowledge of the spatial resolution of the images must be included.
- Have steps been taken to ensure that the choice of parameters is equally valid for all images processed? It may be necessary to describe the scale of a feature as a proportion of the size of a large feature, and not in absolute terms.

Always be aware of the possibility of introducing features that are not present in the original data; such artifacts are considered in the image enhancement case study in Chapter 11.

If filtering is used to make cosmetic improvements in images for publication, then report this.

Reference

- 1 The Chapel Hill Volume Rendering Test Data Set, Volume I, Department of Computer Science, University of North Carolina. Available at <http://education.siggraph.org/resources/cgsource/instructional-materials/volume-visualization-data-sets>

Part 5 Research Analysis

Introduction

Considerations in Patients with Comorbidities, Pregnant and Pediatric Patients

Shilpadevi Patil, Michael Franklin, Yury Rapoport, Elyse M. Cornett,
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problematic in obese patients, who have increased

Endoscopic procedures have been described in the literature for over 200 years [1]. The first known case was performed in veterinary medicine in 1805 [2]. These procedures were performed infrequently until the early 1980s when the first laparoscopic appendectomy was performed in 1982. In the 1990s, laparoscopic procedures such as appendectomy, cholecystectomy, and hysterectomy became routine, and more difficult procedures were attempted occasionally [2]. Since then, the demand for minimally invasive techniques has grown, citing possible benefits such as smaller incisions, fewer wound complications, reduced post-operative pain, faster recovery, and shorter hospital stays [3,4].

The latest addition to laparoscopic surgery has been robot-assisted surgery, which has become increasingly more common since the da Vinci Surgical System received FDA approval in 2000 [3–5]. In 2012, there were more than 400,000 da Vinci robotic-assisted surgical procedures performed in the United States, covering a variety of surgical subspecialties, such as urology, otolaryngology, gynecology, cardiothoracic, and others, in addition to general surgery [3,6]. Like other laparoscopic surgical techniques, robot-assisted laparoscopic surgery requires insufflation of the abdomen, which provides room for the surgeon to work and have a better view of anatomic structures [2,7]. Insufflation is achieved by pumping carbon dioxide (CO₂) into the abdomen through a port, inflating the abdomen to a desired pressure. While it is effective, rare complications can arise as the increased intra-abdominal pressure and CO₂ may alter the patient's physiology [8]. The anesthesia provider and surgeon should be cognizant of these possibilities.

Metabolic complications related to insufflation include acidosis secondary to absorption of CO₂, which can theoretically affect the fetus in pregnant patients [7–9]. Increased intraabdominal pressure is a consequence of insufflation; however, this is more intraabdominal pressure at baseline. Furthermore, this procedure can have adverse effects on airway pressure during positive pressure ventilation, as well as the cardiovascular circulation [10,11]. The effects of insufflation on pediatric patients are similar, but are generally well tolerated [12]. Patients with known medical comorbidities (especially ASA classes III and IV) are at additional risks of developing intraoperative complication during robotic cases, due to distorted physiology. Preoperative counseling along with thorough evaluation is prudent in this group. In addition, pediatric and pregnant patients exhibit unique features that may make robotic surgery challenging. These features are discussed later in the chapter.

General Concerns and Regulations in Robotic-Assisted Surgery

Each patient must have a thorough history and physical examination before robotic surgery. Many medical conditions require unique implications for preoperative screening, optimization, and intraoperative anesthetic management. Cardiac conditions (systolic and diastolic failure, valve regurgitation, dilated cardiomyopathy, coronary artery disease), pulmonary pathology, renal insufficiency, mesenteric ischemia, intracranial pathology, ocular pathology, and glaucoma can be impacted by robotic procedures.

Step Trendelenburg positioning can cause significant dependent edema, so the preanesthetic evaluation should primarily address potential problems that may occur with intraocular pressure, intracranial pressure, hemodynamics, ventilation, or volume loading as a result of positioning. Since postoperative edema of the face, eyes, and larynx might delay extubation or necessitate reintubation, any known or suspected preoperative airway

challenges will be magnified in the postoperative period. Hence, a good preoperative airway exam is of paramount importance. A thorough preoperative neurological evaluation is paramount

because preexisting undiagnosed peripheral nerve injuries are not unusual. The patient should be thoroughly examined and all preexisting deficits should be documented. Electrophysiological and imaging studies may be indicated for further evaluation prior to surgery.

Age

Age has not affected the adult population outcomes for robotic surgery. Robotic surgery can be performed in the elderly population with low mortality, acceptable morbidity, and short hospital stay. Age should not be a contraindication to robotic surgery [13].

Lung Pathology

The synergistic effect of CO₂ pneumoperitoneum and steep Trendelenburg position, especially during pelvic procedures, can affect patients with virtually any thoracic cavity pathology. The diaphragm is pushed cephalad, which decreases lung compliance, thoracic volume, and functional residual capacity (FRC), while increasing work of breathing and peak inspiratory pressure. Normal lungs have a remarkable capacity to withstand the aforementioned changes and maintain adequate oxygenation, but any underlying lung pathology can distort adaptation mechanisms and lead to atelectasis and pulmonary interstitial edema. This may result in respiratory failure and hypoxia. A routine preoperative pulmonary function testing is advised if a patient shows signs of chronic lung pathology. The risks of developing hypercarbia and acidosis are significantly higher while undergoing robot-assisted procedures if compromised pulmonary function exists. For these cases, an arterial line should be placed prior to the start of the surgical procedure for frequent blood gas monitoring. Patients with COPD, reactive airway disease, and OSA must be counseled for postoperative recovery, CPAP, or ICU ventilation.

Musculoskeletal

Cervical spine disease and limited range of motion may be a factor if the patient is in the lateral position with flexion. This position may cause lateral displacement of the cervical spine with potential stretch of the brachial plexus or exacerbation of spinal stenosis. Lateral flexion of the lumbar spine might exacerbate foraminal stenosis, back pain, or radiculopathy. Any calf pain, myopathies, or use of statin drugs should be considered whenever the legs are elevated and compressed in leg holders.

Morbid Obesity

Patients who are morbidly obese are at increased risk of sleep apnea, restrictive lung disease, difficult intubation, delayed gastric emptying, difficult vascular access, cardiovascular disease, diabetes mellitus, degenerative joint disease, thromboembolic events, and reduced wound healing. Lastly, they are at increased risk for conversion to open or aborted procedures.

The multiple airway changes due to obesity are the first and foremost concern of the anesthesiologist. They may be difficult to ventilate and intubate. Morbidly obese patients have reduced vital capacity, functional residual capacity, and forced expiratory volume at 1 second, together with increased closing capacity leading to increased shunting. The

introduction of anesthesia and steep Trendelenburg positioning negatively impacts the respiratory physiology and, when combined with obesity, profoundly affects their pulmonary physiology. Because of these respiratory issues, they desaturate quickly and are more prone to atelectasis. Pressure control mode of ventilation might be helpful to prevent barotrauma from high peak pressures [14].

Peripheral Neuropathy

All patients undergoing robotic surgery should be evaluated for preexisting neurological abnormalities. Acquired peripheral nerve damage is a well-documented complication after robotic surgery, particularly in patients with increased BMI or severe comorbidities (ASA class IV, including diabetes, vascular diseases, or anatomic anomalies). Of note, positioning and increased operative duration are the major contributing factors for developing postoperative neurologic injuries. A recent study assessing the rate of neurologic complications following robotic-assisted urological surgeries found that 6.6 percent of patients experienced a nerve injury due to improper positioning, and 23 percent of these nerve injuries persisted for longer than 6 months [15].

Anesthesiologists may lessen the incidence of brachial plexus injury, a debilitating neurological complication of robotic procedures, by proper positioning. Lateral flexion and dorsal extension of the head, along with abduction, external rotation, or extension of the arms, should be avoided during robotic cases. Straps placed across the chest secure the patient's position and prevent sliding. This method is preferred. The use of shoulder braces may increase the rate of brachial plexus injury.

Cardiovascular Pathology

Preexisting cardiovascular abnormalities may be exaggerated during robotic surgery. Steep Trendelenburg position increases preload due to facilitated venous return from gravity effects. This position along with pneumoperitoneum can cause concomitant aortic compression and increase in SVR (afterload). Therefore, the overall effects on circulation are reduced cardiac output and increases in myocardial oxygen demand and mean arterial pressure.

Patients with CAD, heart failure, and/or valve dysfunction may have difficulties after positioning. Because of this, preoperative cardiovascular risk should be meticulously assessed. The patient's cardiac symptoms, medications, studies, and exercise tolerance must be identified before surgery. Current American Heart Association/American College of Cardiology (AHA/ACC) guidelines should be followed when determining whether a patient has been optimized for surgery [16]. Beta-blocker medication should be continued perioperatively. Echo or stress testing in high-risk patients helps the anesthesiologist to select optimal drug combinations in the light of SVR and PVR effects of pneumoperitoneum and Trendelenburg position. It is also helpful in evaluating cardiac valvular dysfunction since it may profoundly alter hemodynamics. Furthermore, attention should be paid to patients presenting with anticoagulation therapy. The risks and benefits must be weighed against the possibility of intraoperative stent thrombosis and the challenge of management during robotic surgery [17].

Diabetes

Diabetic patients must get a preoperative blood glucose level before robotic surgery.

Intraoperative glucose monitoring might be necessary in insulin- dependent diabetics especially in robotic cases of lengthy duration. These patients are at increased risk for nerve injury, so a preoperative neurological exam documenting preexisting abnormalities is critical.

Cancer

Cancer patients may experience certain unique issues while undergoing robotic surgery. Patients with renal cell carcinoma have a 10–40 percent chance of para- neoplastic syndromes. If a patient has a paraneoplastic syndrome, the tumor may secrete ectopic hormones such as erythropoietin, renin, insulin, or glucose during surgery. Cancer patients previously treated with radiation therapy may experience more difficul- ties during surgical resection. Fibrosis of tissue from radiation therapy may prolong surgical dissection and ultimately increase surgical bleeding and incidence of other complications.

Chemotherapy can result in a number of systemic complications that affect intraoperative planning. Patients may have significant weight loss, anemia, and a predisposition to clot formation resulting in elec- trolyte abnormalities, hypothermia risk, decreased protein, malnutrition, and embolism. Anesthetic planning should account for decreased protein bind- ing and volume of distribution for medications; these changes may significantly alter pharmacokinetics. Additionally, a history of exposure to agents such as doxorubicin (cardiomyopathy) and bleomycin (pulmonary fibrosis) necessitates further preopera- tive testing. At a minimum, preoperative studies for robotic cancer surgery should include electrocar- diogram, chest radiograph, and blood work, notably blood counts, coagulation studies, renal function and basic electrolytes, and blood type and screen. Reflux, infection, and deep vein thrombosis prophylaxis should be considered with nonparticulate antacid, antibiotics (within 1 hour of surgical incision), subcu- taneous heparin, and sequential compression devices, respectively.

Pregnant Patients

A slightly less steep Trendelenburg position, as opposed to 30° lithotomy position required during urologic procedures, is acceptable for gynecologi- cal robotic surgeries [18]. While most concerns are somewhat similar to other robotic procedures, oper- ating on pregnant patients poses additional risks for mother and fetus and deserves further attention. While there are some surgical procedures that must be performed urgently or emergently, regardless of whether or not the patient is pregnant, it is recom- mended that all elective surgeries should be post- poned until after delivery, and all other procedures should be postponed until the second trimester, if possible, as the risk of teratogenicity and miscarriage is lower at this point[19].

The risk of developmental abnormalities is highest in the first trimester, and the risk of spontaneous abortion is highest in the third trimester [20]. It is also advisable to consult the OB/GYN service prior to proceeding to the operating room to discuss the possibility of fetal monitoring, which should be at least considered [19,21]. Laparoscopic surgery, both conventional and robotic-assisted, has been performed safely in pregnant patients. Some advantages to performing procedures laparoscopically, as opposed to open (i.e., laparotomy), include less need for narcotic analgesics, which can affect the fetus as well as the mother, shorter hospital stay, lower risk of thromboembolism, less manipulation of gravid uterus, and fewer wound infections. However, it should also be noted that uterine perforation is a significant risk, particularly while placing the trocar for the surgical port. Labor and preterm birth can also be induced if the uterus is accidentally insufflated, rather than the abdomen. The risk of miscarriage may also be higher than with open procedures.

In addition to anesthetic and surgical management of the mother, there is a second patient to keep in mind as well, and potential effects on the fetus must be considered. To ensure a favorable outcome, one must be diligent to maintain adequate oxygenation and uteroplacental perfusion, as well as avoiding teratogenic medications or medications that may otherwise negatively affect the fetus in the anesthetic plan. Maternal hyperventilation should be avoided as it can decrease venous return, which can lead to decreased uterine blood flow. When treating hypotension, short-acting ephedrine and phenylephrine are agents of choice, whereas other agents such as epinephrine may reduce uterine blood flow [22]. It has been suggested that, with CO₂ insufflation that is used for laparoscopic procedures, fetal acidosis secondary to CO₂ absorption and hypoxia may occur [7,9]. However, while this has been described in sheep models, the same results have not been found in humans [9,23].

The robotic-assisted surgical system provides several advantages over conventional laparoscopic surgery. The operator will be able to utilize superior camera magnification and visualization, as well as more precise movements with the camera and instruments. This could potentially lead to less inadvertent manipulation of gravid uterus, which could potentially decrease risk to the fetus. While there are also disadvantages, such as higher cost and a greater time commitment for training physicians to safely and effectively operate the equipment, robotic surgery does appear to be as safe as conventional laparoscopy, both for the mother and the fetus. However, the number of cases described in the literature is small [24].

Pediatric Patients

With the number of robotic-assisted surgeries growing exponentially, they are gaining more popularity among pediatric surgeons as well, and there has been a recent trend to that effect [25]. Robotic approach has been utilized extensively by pediatric surgeons in a variety of specialties, including general surgery, urology, and thoracic surgery, safely and successfully, and surgeons are performing procedures with a progressively increasing complicity as time passes [26]. However, it still remains somewhat less common as in adult patients, and choosing the best modality is sometimes a subject for debate [27]. As with adult patients, the robot offers potentially greater dexterity, visualization, and ability to operate in difficult spaces, and this may be of even greater benefit in pediatric patients, given their relatively small abdominal cavity [26,28,29]. However, the major challenge lies in

the light of inability to change patient's position or even get any access to the patient until the robot is fully detached. As with any laparoscopic surgical technique, there are metabolic, respiratory, and hemodynamic concerns in children with the only difference that children have limited physiologic reserve and timing is usually crucial as delay may result in critical complications. Hemodynamic changes that have been reported secondary to pneumoperitoneum include intraoperative tachycardia and hypertension, with a decrease in cardiac index and aortic blood flow. It has also been demonstrated that, by maintaining intraabdominal pressures at 5 mmHg or below, these effects may be less significant [30].

The alterations to respiratory mechanics with abdominal insufflation may be considerable. Increased intraabdominal pressure, in the similar fashion as in adult patients, may restrict the movement of diaphragm, causing increased airway resistance and a reduction in tidal volume and overall minute ventilation. This can ultimately lead to decreased oxygenation and even hypoxemia. Additionally, pediatric patients may have an increased rate of bronchospasm during pneumoperitoneum secondary to insufflation [31]. Early recognition of the problems intraoperatively by an anesthesiologist along with adequate surgical

team training for fast de-docking of the robotic system is required, should the necessity for emergent intervention ensue.

Conclusion

Clearly, the application of robot-assisted technics will continue its integration into the majority of surgical subspecialties, increasing the number of patients requiring this approach, including vulnerable and high-risk patient populations. Anesthesiologists should be alongside with this tendency and be ready to provide better care for patients undergoing robot-assisted surgery. As this modality poses unique risks intraoperatively, a careful patient selection and thorough preoperative assessment should be employed in identifying patients in whom risks of robot-assisted surgical approach may outweigh the benefits of the procedure, or who may require optimization of the medical status prior to the procedure. Common considerations include the following complications: positioning nerve injuries, especially in obese and patients with diabetes or vascular diseases, cardiopulmonary compromise in patients with preexisting heart failure, coronary artery disease, or lung pathology. Patients with decreased functional reserve including pediatric population should be monitored closely as robot needs to be fully detached before any action or repositioning could be implemented. Pregnant patients may safely undergo robot-assisted procedures; however, elective procedure should be postponed at least until second trimester. Finally, good communication and teamwork among the medical staff are essential in providing patient safety and preventing intraoperative complications.

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Chapter

6

Anesthetic Considerations

for Robotic-Assisted Surgery

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Introduction

Robotic-assisted surgery has gained popularity as demand for minimally invasive surgeries continues to grow. Robotic-assisted surgery offers the patient smaller surgical incisions and minimally invasive instrumentation, as well as less surgical blood loss and presumably less postoperative pain. Shorter recovery room times and hospital stays are also beneficial for most patients.^{1,2} Robotic-assisted surgeries offer the surgeon a unique, magnified, three-dimensional view of the operative field with degrees of motion and maneuverability not offered with conventional laparoscopy.³ Areas of concern for the anesthesiologist specific to robotic-assisted surgery are many and are equally applicable to most types of operations utilizing robotic assistance. These include all phases of the perioperative period from patient selection and screening to intraoperative considerations and postoperative care. Prolonged surgical time with restricted access to the patient, extremes of patient positioning combined with insufflation and the resultant physiologic and hemodynamic disturbances during robotic-assisted surgery present unique anesthetic management challenges for the anesthesiologist. Anticipation, recognition, and prompt management of the more common complications associated with robotic-assisted surgery is a must. Subcutaneous emphysema, venous gas embolism, airway edema, nerve injury, and hypothermia are a few of the complications related to robotic-assisted surgery.

Anesthetic Management

Preoperative Considerations

Careful patient selection and preoperative assessment is crucial to minimizing perioperative complications in patients scheduled to undergo robotic-assisted surgery.⁴ A systematic and thorough review of the patient's history and physical, medications, allergies, surgical, and anesthetic history is required prior to robotic-assisted surgery. Risk factors to be considered are patient co-morbidities and the complexity of the surgical case.^{5,6} Specific factors that may increase patient's risk associated with prolonged pneumoperitoneum and/or extremes of position need to be elicited. Patients with significant cardiovascular and/or respiratory disease should be considered for alternative surgical methods to robotic-assisted surgery.²

Patients with obesity (body mass index [BMI] over 30) may have conditions that warrant serious deliberations prior to undergoing robotic-assisted surgery. Obese patients may come with conditions such as obstructive sleep apnea and restrictive airway disease in addition to difficulties with intubation and vascular access. Decreased gastric emptying and higher risk for aspiration are real areas of concern in the obese patient. Co-morbidities such as cardiac disease and diabetes further complicate matters for the obese patient. Also, risk of conversion to an open procedure is increased for the obese patient. As the BMI approaches or surpasses 40, the above risks become even more of a concern for the anesthesiologist.¹

Patients with cardiovascular disease require further investigation prior to robotic-assisted surgery. Areas to consider in addition to history and physical examination include exercise tolerance, symptoms, medications and laboratory results, and cardiac studies. Patients with heart failure are likely to experience an exacerbation of their condition during

the extremes of position that are required during robotic-assisted surgery.¹ Patients with preexisting cardiac disease should be optimized prior to surgery. In patients with cardiac stents, a careful weighing of the risks and benefits of surgical bleeding with anticoagulation versus discontinuation of the anticoagulation and the associated risk of stent thrombosis should be considered.¹ Patients with moderate to severe mitral insufficiency are subject to worsening of the regurgitant lesions with extreme positioning and insufflation.⁷

Patients with pulmonary disease may not tolerate the physiologic changes associated with the extremes of position during robotic-assisted surgery.¹ History of chronic obstructive pulmonary disease, bullous emphysema, and spontaneous pneumothorax may contraindicate robotic-assisted surgery and warrant further investigation.

Patients with known intracranial lesions, increased intracranial pressure, and intraocular pressure (IOP) are at risk for exacerbation of their underlying condition with positioning during robotic-assisted surgery.¹ History of cerebrovascular accident, presence of cerebral aneurysm, elevated intracranial pressure, or glaucoma require further investigation prior to robotic-assisted surgery. Patients with preexisting ocular problems are at risk for retinal detachment and periorbital edema and development of dangerous ocular pressures due to the prolonged extremes of position associated with robotic-assisted surgery.¹

Patients with a history of cancer and radiation therapy are at higher risk for difficult surgical resection due to fibrosis and increased bleeding. History of chemotherapy may present with weight loss and anemia and a predisposition to hypothermia and clot formation. Other considerations in patients with cancer history and chemotherapy include electrolyte abnormalities, malnutrition, and risk of embolism. Certain chemotherapy agents such as doxorubicin and bleomycin put the patient at risk for cardiomyopathy and pulmonary fibrosis, respectively. History of exposure to chemotherapy agents warrants further investigation prior to robotic-assisted surgery.¹

Patients with renal insufficiency require optimization prior to robotic-assisted surgery. Positioning, fluid restriction, and mechanical obstruction put patients with renal dysfunction at high risk for exacerbation of their underlying condition. Risks and benefits of robotic-assisted surgery in patients with renal insufficiency deserve careful consideration prior to proceeding to the operating room.¹ Renal protective strategies, such as avoidance of nephrotoxic drugs and renal hypoperfusion, should be employed.

Intraoperative Considerations

Spatial limitations, intraoperative monitoring, and intravenous access as well as prolonged length of surgery require special consideration in preparation for robotic-assisted surgery. The physical space required for the robotic equipment and the orientation of this bulky equipment in the operating room may compromise movement of personnel and visualization of placement sites of intravenous lines, monitors, and the endotracheal tube.¹ Standard ASA monitors are indicated as well as additional monitoring and intravenous lines depending on the patient's comorbidities, complexity of surgery, risks of bleeding, and the surgeon's level of experience with robotic-assisted surgery. It is important to reliably secure the endotracheal tube and all

monitors and intravenous lines as visual inspection may be unavailable once the robot is locked into place. Furthermore, intravenous lines should have sufficient length to provide access far from the insertion site.

Standard intravenous induction of anesthesia and intubation is acceptable with adjustments as needed for a patient's medical condition. As indicated above, the endotracheal tube should be secured properly keeping in mind limitations of access once surgery is underway and the risk of tube migration with extremes of patient positioning. In addition, robotic equipment presents a risk of accidental dislodgement of the endotracheal tube, making meticulous attention to securing the tube even more important. Mechanical ventilation to manage hypercarbia and muscle relaxation to prevent patient movement is utilized throughout robotic-assisted surgery. It is imperative the patient remain immobile throughout the procedure until the robot is undocked.¹ Securing the eyelids closed with a film dressing and ointment helps protect the patient from corneal injury and desiccation. Gastric decompression helps to reduce the risk of facial and ocular burns from passive regurgitation of stomach contents. Since the surgery is typically prolonged, use of a volatile agent such as Desflurane with a shorter half-life should be considered. An adjunct opioid, such as a remifentanyl infusion, provides a balanced anesthetic technique and is well tolerated during robotic-assisted surgery.

Patients are at risk for nerve injury from stretching and compression. Meticulous attention to patient positioning, padding, and protection from movement is required due to positioning needs to optimize surgical views. Ventilation is complicated by decreased compliance and changes in lung volumes due to extremes of patient position used in robotic-assisted surgery. Further discussion of physiologic and hemodynamic perturbations encountered during robotic-assisted surgery is covered later in this chapter. Fluid management is important to minimize facial and airway edema. Temperature monitoring and management are required to avoid hypothermia.

Emergence from anesthesia should be timed correctly. It is recommended to maintain anesthetic levels and muscle relaxation until the robot is undocked. Reversal of neuromuscular blockade, emergence from anesthesia, and extubation can then proceed as appropriate. Special attention should be paid to the possibility of residual hypercarbia and delayed emergence, atelectasis, and airway edema.

Surgical injury and occult blood loss are a concern and should be anticipated. In addition, robotic malfunction and/or failure have occurred. Use of checklists is recommended to prevent equipment malfunction.¹

Postoperative Considerations

Being cognizant of the possible need for postoperative reintubation and providing adequate pain control are priorities in the postoperative period.¹ Standard monitoring techniques following general anesthesia apply. Following robotic-assisted surgery, specific considerations include management of pain, evaluation and management of cardiopulmonary complications, and treatment of hypothermia and oliguria. Mental status should return to baseline prior to

discharging to the next phase of care. Furthermore, a preliminary evaluation for nerve injury should be performed. Occult injury and/or blood loss should be suspected if patients complain of significant postsurgical pain unrelieved with typical pain medications or if vital signs suggest hemodynamic decompensation.

Specific Anesthetic Considerations Associated with Robotic-Assisted Surgery

Robotic-assisted surgery offers a means to provide minimally invasive surgical intervention by way of robotic technology. Robotic-assisted surgery allows the surgeon to maneuver in small, enclosed spaces with precision accuracy. The surgeon operates from a distance with three extra degrees of motion that are lost during conventional laparoscopy. The surgeon has a three-dimensional stereoscopic view of the operative field with adjustable magnification and a controlled camera platform.³ Surgical specialties such as urology, gynecology, cardiac and thoracic, abdominal, and head and neck surgery all have procedures that

Box 6.1 Major Concerns for the Anesthesiologist during Robotic-Assisted Surgery
Limitation of access
Length of surgical case
Inexperience of surgeon, surgical assistants, and/or team
Extremes of patient positioning
Cardiopulmonary effects of extremes of position and pneumoperitoneum
Fluid management
Temperature control
Occult surgical injury
Occult blood loss

utilize robotic-assisted surgery. Reduced pain, shorter hospital stay, and smaller surgical incision sites are potential advantages associated with robotic-assisted surgery.² Potential disadvantages include extremes of patient positioning, perturbations in normal physiology, limitation of access, longer surgical times, and inexperience of the surgical team.

Restricted Access to the Patient

During robotic-assisted surgery, access to the patient is limited. Once the robot has been docked, the patients' position cannot be easily or quickly modified. The robotic arms

and platform are locked in a fixed position.⁸ Overall arrangement of the operative equipment and personnel during robotic-assisted surgery conflicts with the conservative basis of anesthesia care. Spatial restrictions due to bulky equipment requiring excessive space are another key consideration. Once the robot is docked, the anesthesiologist cannot readily access the patient. All lines, monitors, and patient positioning and protective devices must be functional and secured. If changes to the above are necessary, the robot must be detached first, which may result in related delays and complications. Early detection of any problems and/or complications is imperative since robotic detachment takes time. Emergency situations require advanced training of the entire surgical and anesthesia team to ensure quick detachment of the robotic system.⁸ Certain robotic-assisted surgeries require the patient head, and airway, be situated away from the anesthesiologist. Upper abdominal, thoracic, and head and neck robotic-assisted surgeries require the patients' head be situated away from the anesthesia workstation.^{8,9} Mediastinal procedures require the operating table to be rotated 90 degrees away from the anesthesiologist. During these types of surgeries, access to the airway is almost impossible and field avoidance methods must be implemented.⁹

Patient Positioning

Patient positioning is of critical importance in robotic-assisted surgery. Patient outcomes and surgical conditions rely on proper patient positioning and port placement. The crucial nature of proper positioning stems from the reality that once surgery begins, the patient cannot be moved to any other position throughout the robot portion of the procedure. Once the robotic trocars and instruments are fixed, movement of the patient in any way could be catastrophic. To avoid having to repeat the positioning process multiple times, it is recommended to standardize the positioning process. Intraoperative patient movement not related to positioning must be prevented by the use of muscle relaxants.¹⁰

Steep Trendelenburg

Robotic-assisted surgeries of the lower abdomen and pelvis require extremes of position for optimal surgical exposure. Proper patient positioning on the surgery table is necessary to allow for optimal surgical exposure and to prevent neuromuscular injury.¹¹ In the extreme head down position, cardiac, pulmonary, and nervous systems are affected. Steep Trendelenburg between 30 and 45 degrees for prolonged periods of time can lead to significant physiologic perturbations. Consequences of steep Trendelenburg include cephalad displacement of the diaphragm, decreased pulmonary compliance, decreased functional residual capacity (FRC), worsening of ventilation/perfusion mismatch, and pulmonary edema.¹⁰ Trendelenburg position is associated with a 30–40 percent reduction of cardiac output and elevation of pulmonary capillary wedge pressure. Patients with compromised systolic function are at risk for development of heart failure with steep Trendelenburg. Patients with coronary artery disease may develop demand ischemia due to the hemodynamic changes associated with positioning for robotic-assisted surgery. Creation of pneumoperitoneum – air within the peritoneal cavity – exacerbates the conditions described above. Furthermore, steep Trendelenburg leads to

increases in cerebral blood flow and intracranial pressure as well as decreased venous outflow.¹ Steep Trendelenburg for prolonged periods of time can result in laryngeal edema, cerebral edema, and facial swelling.^{11,12} Trendelenburg position can also lead to endobronchial intubation due to the cephalad displacement of the trachea and resultant atelectasis if uncorrected.¹²

Protecting the patient from injury requires meticulous attention to positioning. Stretching and compression along with improper padding and positioning can result in nerve injury. Common nerve injuries encountered after robotic-assisted surgery include injuries to the brachial plexus, ulnar, and lateral femoral cutaneous nerves. For robotic-assisted surgery in which the patient is in steep Trendelenburg with lithotomy, arms and hands should be padded well and tucked in the neutral position at the patient's side.¹ Degree of limb extension, stirrup location, and duration of immobility and padding of bony prominences require particular consideration. Careful attention to the function of monitors and intravenous lines is important during positioning because once the robotic part of surgery is underway, manipulation is impossible. Methods to prevent patient shifting include braces, leg suspension, iliac supports, and antiskid material. Unfortunately, any of these methods can result in nerve injury.¹⁰ To prevent upward sliding, padding with egg crate or a beanbag in the form of an "X" binds the patient's chest. Shoulder braces should be used with caution to prevent brachial plexus nerve injury during prolonged head down positioning.¹ Patient sliding risks stretching and tearing of incisions as well as risk of incisional hernia. Movement or shifting of the trunk may lead to improper positioning of the extremities, which increases the risk of nerve injury from stretching and compression. Other complications include acute compartment syndrome and rhabdomyolysis from prolonged lithotomy positioning, hypothermia, unrecognized surgical injury, and occult blood loss.¹⁰ The lower extremities are at risk for hypoperfusion in steep Trendelenburg and may result in postoperative rhabdomyolysis. Overlying tight table straps and improperly positioned leg holder straps add to the risk of rhabdomyolysis. Risk factors for developing compression injury and subsequent rhabdomyolysis include extreme patient positions, morbid obesity, hypertension, diabetes, and peripheral vascular disease.¹¹

Steep Trendelenburg causes IOP to rise to levels similar to that of untreated glaucoma.¹³ Rising IOP in addition to increased end-tidal CO₂ levels may make robotic-assisted surgery unsuitable for patients with glaucoma. Prolonged steep Trendelenburg, as used with robotic-assisted surgery, can result in posterior ischemic optic neuropathy. Increases in central venous pressure, intracranial pressure, and IOP associated with steep Trendelenburg over prolonged periods put the patient at risk for permanent blindness.¹⁴

Laryngeal edema as a result of steep Trendelenburg for prolonged periods is a major concern. Edema of the supraglottic airway structures, including the vocal cords, arytenoids, and epiglottis, may result in stridorous or no respirations after the endotracheal tube is removed. The need for emergent reintubation and swollen airway structures makes for a dangerous combination. Therefore, it is recommended to ensure the patient can breathe around the endotracheal tube with the cuff deflated prior to extubation.^{9,13}

Pneumoperitoneum

The presence of air or gas within the peritoneal cavity is known as pneumoperitoneum. CO₂ is the gas most commonly used to create pneumoperitoneum. Other gases such as oxygen, helium, argon, and nitrous oxide are problematic due to their combustible nature and/ or the possibility of intravascular embolism on insufflation.¹⁰ For pelvic and lower abdominal robotic-assisted surgery, intraperitoneal insufflation with CO₂ is performed with the patient in the Trendelenburg position. After the trocars are inserted, intraabdominal pressures are increased to 20 mmHg with CO₂ insufflation, then reduced to 12–15 mmHg after the ports are positioned.¹ Changes in respiratory mechanics and hemodynamics resulting from pneumoperitoneum present a special challenge for the anesthesia provider.

One of the main concerns during pneumoperitoneum is proper ventilation. Effects on respiratory mechanics are significant and include decreases in lung compliance, mean pulmonary arterial pressure, and pulmonary capillary wedge pressure. Increases in end-tidal CO₂ tension, peak inspiratory, and plateau pressures occur with pneumoperitoneum. Decreases in total lung capacity (TLC) and FRC create various ventilation problems. Areas of the lung in which there is perfusion but no ventilation result in decreases in both oxygenation and CO₂ exchange. Increased closing capacity and decreased FRC lead to atelectasis.¹³ To compensate for high pressures and hypercapnia, titration of respiratory rate to alter minute ventilation is preferred. It is desirable to maintain lower tidal volumes to improve surgical view.¹ Because shunting and hypoxia often occurs, it is important to attempt to improve gas exchange. Careful implementation of peak end-expiratory pressures (PEEP) should be considered as long as peak pressures remain below safe limits.¹ PEEP helps to decrease atelectasis and improve lung mechanics and oxygenation. PEEP also hinders venous blood return from the lower extremities and decreases cardiac output. However, extreme Trendelenburg mitigates these effects. PEEP also contributes to the risk of development of facial, laryngeal, and oropharyngeal edema.⁸ Risk of barotrauma and pneumothorax makes adequate ventilation of the patient a challenge. It may be difficult to control the level of CO₂ in the blood (PaCO₂) due to increases in ventilation to perfusion mismatch, decreased lung volumes, and restrictions on tidal volumes in the presence of high peak airway pressures. Respiratory acidosis results in a host of hemodynamic changes. These include sympathetic nervous system stimulation, myocardial depression, increases in cerebral blood flow, and intracranial pressure.¹³ Exogenous CO₂ in addition to the patients' own CO₂ production may pose a problem in the postoperative period for patient with certain co-morbidities. Patients with chronic obstructive pulmonary disease (COPD) are unable to eliminate excessive CO₂ and may require prolonged postoperative mechanical ventilation due to respiratory hypercarbia and acidosis.¹⁰

Pneumoperitoneum results in hemodynamic changes as a result of increased intraabdominal pressure. These changes include increased systemic vascular resistance (SVR), increased mean arterial pressures (MAP), increased filling pressures, and a 50 percent decrease in cardiac index (CI). Increase in heart rate can also occur. After about 10 minutes, SVR and CI normalize. Pneumoperitoneum in addition to steep Trendelenburg can

decrease cardiac output by 10–30 percent.¹ Increases in intraabdominal pressure activates the renin-angiotensin system, which results in increased SVR and increased blood pressure. Decreased urine output aids in increasing intravascular volume. Pneumoperitoneum causes decreased splanchnic blood flow, which also augments increases in intravascular volume and blood pressure. However, intraabdominal pressures over 15 mmHg results in the compression of inferior vena cava and decreases in MAP by way of decreased venous return, preload, and cardiac output.¹³ Blood flow to intraabdominal organs such as liver, kidneys, and intestines is decreased due

to decrease in flow to portal and systemic circulation as a result of pneumoperitoneum.¹

Risk of venous gas embolism is present immediately upon insufflation. Gas emboli risk is minimized by the use of CO₂, which has a high diffusion coefficient. While rare, the consequences of venous gas embolism are catastrophic and include severe cardiovascular failure, reduction in pulmonary blood flow, and death. The mechanism of venous gas embolism upon insufflation is thought to be infiltration of insufflated CO₂ into the venous/lymphatic channels. Clinical manifestations are a sudden increase, then a rapid fall in end-tidal CO₂ level, hypotension, tachycardia, localized diminished breath sounds, cyanosis, and a “mill-wheel” murmur associated with gas embolization. Should venous gas embolism occur, treatment involves rapid deflation of pneumoperitoneum, hyperventilation with 100 percent oxygen, left lateral decubitus and Trendelenburg, cardiopulmonary resuscitation followed by attempted aspiration of the embolism through a multiport central venous catheter in the right atrium.^{1,10} Other potential complications include cardiac arrhythmias and vagal reactions as a result of insufflation and peritoneal distension or viscus manipulation. Asystole cardiac arrest can result from vena cava compression and subsequent diminished cardiac preload. Cardiac arrhythmias may result from hypercapnia or hypoxia.

Pneumoperitoneum, in addition to steep Trendelenburg, presents even more of a challenge to the anesthesiologist, more so than each individual maneuver. The risks to the patient undergoing robotic-assisted surgery involved with positioning and hemodynamic perturbations as discussed above are magnified when insufflation and steep Trendelenburg (25–40 degrees) are combined. Significant hypercapnia (ET-CO₂ >45 mmHg) and significant intraoperative hypoxemia (SpO₂ <90 percent) can occur.¹³ Atelectasis and ventilation/perfusion mismatch is exacerbated by steep Trendelenburg with pneumoperitoneum. Decreased pulmonary compliance, decreased FRC, and increases in peak airway pressures are more pronounced with insufflation in the steep Trendelenburg position. Subcutaneous emphysema occurs frequently in the steep Trendelenburg position, resulting in significant amounts of CO₂ absorption.^{8,10} An increase in end-tidal CO₂ levels larger than 25 percent or if occurring 30 minutes after insufflation suggests the development subcutaneous emphysema.¹⁵ Hyperventilation to decrease the levels of CO₂ in blood and resultant respiratory acidosis is limited due to the steep Trendelenburg position and higher ventilator inspiratory pressures during robotic-assisted surgery. In addition, diaphragmatic excursion is limited by abdominal CO₂ insufflation. Therefore, increased airway pressures are primarily a result of decreased thoracic compliance due to the pressure of the abdominal contents on diaphragm and

the pressure exerted with abdominal insufflation. Elevated peak and plateau inspiratory pressures are measured at the mouthpiece and do not reflect the pressure in the alveoli nor the transmural pressure across the alveoli.¹⁵ Although there is no proven superior form of ventilation in the setting of increased airway pressures, recommendations involve the use of pressure-controlled ventilation. Lower peak airway and plateau pressures with higher lung compliance and larger tidal volumes for a given inspired pressure have been reported using pressure-controlled ventilation in patients undergoing robotic-assisted surgery and in whom adequate oxygenation is difficult to achieve.^{10,16} In patients with high end-tidal CO₂ even with optimization of ventilator settings, permissive hypercapnia can be safely tolerated.⁸

Pneumoperitoneum combined with steep Trendelenburg (45 degrees) result in marked increases in MAP, right and left ventricular filling pressures, and pulmonary capillary wedge pressure (PCWP) in both healthy patients and patients with cardiac disease. Although pneumoperitoneum combined with steep Trendelenburg results in two- to three-fold increases in filling pressures, cardiac performance seems to be unaffected in ASA I and II patients.¹⁷ Further studies are needed to establish perioperative risk for patients with existing cardiac disease.¹⁷

Increased intracranial pressure is made worse by steep Trendelenburg during insufflation. The proposed mechanism is increased intraabdominal and intrathoracic pressure of the Trendelenburg position, in addition to impaired cerebral fluid absorption from insufflation inhibits lumbar venous plexus drainage. Impaired venous plexus drainage induces an increase in intracranial pressure.¹⁵ Furthermore; hypercarbia causes dilation of cerebral vessels, which also increases intracranial pressure. Despite increases of hydrostatic pressure in the cerebral vessels, an intact blood-brain barrier helps prevent interstitial edema in the central nervous system. Therefore, patients with conditions that might disrupt the blood-brain barrier (e.g., brain tumor) placed in steep Trendelenburg with insufflation carry unknown risk.¹⁸

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Box 6.2 Physiologic Effects of Steep Trendelenburg Combined with Pneumoperitoneum^{2,17}

Cardiovascular

Increased systemic vascular resistance, mean arterial pressure, central venous pressure, pulmonary capillary wedge pressure, myocardial O₂ consumption

Decreased renal perfusion, splanchnic perfusion, portal blood flow

Respiratory

Increased ventilation/perfusion mismatch, peak airway pressure

Decreased functional residual capacity, vital capacity, pulmonary compliance

Hypercarbia

Pulmonary edema

Respiratory acidosis

Central nervous system

Increased intracranial pressure, intraocular pressure, cerebral blood flow

Gastrointestinal

Increased intragastric pressure

Endocrine
Increased catecholamine release, renin-angiotensin activity

Steep Trendelenburg with increases in intraabdominal pressure from insufflation causes increased intragastric pressure. Risk of pulmonary aspiration is increased. Risk of passive regurgitation of gastric fluids may result in injury to the eyes. The risk of passive aspiration and eye injury is lessened with gastric decompression by an orogastric tube.¹³ Conjunctival edema and corneal abrasions are other potential complications. Conjunctival edema causes the upper and lower eyelids to separate and can result in corneal desiccation and abrasion even when the eyes are taped closed.¹⁹ The use of ophthalmic ointment acts as a shield protecting the

cornea and should be considered for use during robotic-assisted surgery in addition to securing the lids.¹³ In addition, a preoperative dose of ranitidine may reduce the risk of gastric reflux and should be considered for all patients.

Fluid Management

Excessive fluid administration during robotic-assisted surgery is known to be associated with facial edema and swelling of the airway and conjunctiva. Whether

or not colloids carry an advantage over crystalloids remains speculative.¹⁵ Due to the fact that edema of the face and airway is known to develop over time in the steep Trendelenburg position, it is recommended to avoid overzealous administration of fluids. It has also been suggested that a standardized, more restrictive fluid management is beneficial for patients undergoing certain types of robotic-assisted surgery.^{9,20} Because increased intraabdominal pressure such as that which occurs with insufflation leads to oliguria, urinary output is a poor indication of volume status during robotic-assisted surgery.

Hypothermia

Development of hypothermia during robotic-assisted surgery is multifactorial. Typical operating room conditions coupled with altered thermoregulatory mechanisms while under anesthesia promote heat loss. Long surgical time, CO₂ insufflation, and exposure exacerbate heat loss. Therefore, active warming techniques are of great importance. These include temperature monitoring, warm intravenous fluids, warm humidified gases, air warming device, and operating room temperature control.²¹

Pain Management

Multimodal approaches to pain management have been shown to decrease length of hospital stay and improve patient satisfaction.²² Use of acetaminophen and nonsteroidal anti-inflammatory drugs, if no contraindication exists, are recommended. As needed, opioids are acceptable if indicated. Epidural analgesia is not typically needed for robotic-assisted surgical pain.¹ Epidural analgesia is said to have no advantage for postoperative pain control following robot-assisted surgery. Epidural anesthesia should not be used intraoperatively since the steep Trendelenburg position can cause a high block and cardiovascular instability.²

The Learning Curve

While robotic-assisted surgeries have a number of technical advantages, such as favorable field of view and minimally invasive instrumentation, variable learning curves and associated risks are discussed in the literature. As surgeons pursue lengthier and more complex robotic-assisted cases, the morbidity risk to the patient becomes greater.^{5,23} In the initial phase of practice, extended surgical time required for the surgical team to use the robot is known as the "learning curve."¹ Ongoing training in robotic-assisted surgery for surgical support staff should mirror the complexity of the surgery being performed.²⁴ The number of cases required for surgical proficiency remains unclear. Most agree that the number of cases to become proficient depends on surgical skill and type of procedure performed.²⁵

Communication among Team Members

Communication among all team members, including the surgeon, anesthesiologist, nurses, and operative assistants, is imperative to establish and maintain safe and effective environment.

Ensuring quality of communication is an active process in robotic-assisted surgery. Because the surgeon sits behind a console away from the operative field, communication with the operative assistant and the anesthesia provider presents a challenge. In order to facilitate transmission of the surgeons' voice, audio speakers are added to the video tower.² Simulation environments, continuous training, and emergency drills offer opportunities to improve communication among team members and outcomes and prevent complications.²⁶

x 6.3 Complications Associated with Robotic- Assisted Surgery

Pneumoperitoneum: subcutaneous emphysema, venous gas embolism, pneumothorax, capnothorax, pneumomediastinum, endotracheal tube displacement, intraabdominal fire

Steep Trendelenburg: patient slippage, facial trauma, corneal abrasion, facial edema, laryngeal edema, rhabdomyolysis

Neurologic: cerebral hemorrhage, posterior ischemic optic neuropathy, paradoxical cerebral air embolism

Neuromuscular: peripheral nerve injury (i.e., median, radial, ulnar, brachial plexus, sciatic, obturator, peroneal, lateral femoral cutaneous), compartment syndrome

Cardiovascular: arrhythmias, congestive heart failure, myocardial infarction, refractory hypertension

Pulmonary: barotrauma, pulmonary edema, atelectasis, pneumothorax, elevated central venous pressure, respiratory acidosis

Gastrointestinal: passive regurgitation/aspiration, burns to face/eyes

Renal: rhabdomyolysis, renal dysfunction/failure

Development of a perioperative protocol for all phases of anesthetic management is

recommended for patients undergoing robotic-assisted surgery to help ensure patient safety and satisfaction as well as optimal clinical care and provider satisfaction.²⁷

Conclusion

Robotic-assisted surgery presents unique anesthetic challenges for the anesthesiologist. Despite the risks inherent to prolonged extremes of position coupled with insufflation and associated perturbations of normal physiology, robotic-assisted surgery has been successfully performed in a large number of patients. Anticipation and recognition of risks and complications unique to robotic-assisted surgery by the anesthesiologist is essential to successful perioperative management. Common complications include subcutaneous emphysema, venous gas embolism, hypothermia, facial and airway edema, cardiopulmonary compromise, and nerve injury, to name a few. Vigilance on the part of the anesthesiologist lessens the potential for these complications. Furthermore, efficient communication and teamwork between the anesthesiologist and the surgical team also minimizes development of complications, preserves patient safety, and improves surgical conditions and patient outcomes.

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Chapter

7

General and Colorectal Robotic Surgery of the Abdomen and Pelvis

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Introduction

This chapter will discuss the application of the robotic surgical platforms (RSPs) utilized today by general surgery (GS) and colon and rectal surgery (CRS) on abdominal and pelvic procedures. The chapter is divided into preoperative, intraoperative, and post-operative management of patients undergoing RSP procedures. The preoperative section will discuss pre-operative considerations of patients with comorbidities that could be exacerbated by the positioning and the effect of pneumoperitoneum on cardiovascular, pulmonary, and cerebral systems.

The intraoperative section will focus on the RSP application in hepatobiliary, pancreatic, esophageal, gastric, splenic, and colorectal diseases. The chapter will discuss RSP application in benign and malignant disease from the historical perspective to current-day procedures. It will discuss safety and feasibility and economic considerations of the application of the RSP to complex abdominal procedures.

The postoperative section will discuss the advantages of the RSP and the utilization of enhanced recovery after surgery (ERAS) protocols, including early ambulation, postoperative pain management, onset of dietary intake, and the goal of decreasing length of stay (LOS) and decreasing hospital readmission rates.

Historical Perspectives

The first application of the robot in surgery was in 1988, for CT-guided brain biopsy [1]. Since then, the field of robotic engineering for medical use has been evolving at a rapid pace. This development was in part due to the rapid utilization of minimally invasive procedures in GS and CRS. The developers of robotic engineering were aware of the limitations of minimally invasive surgical instrumentation, loss of tactile sensation, only four degrees of freedom movement, amplification of physiologic tremors of the surgeon, difficulty with suturing, and camera fatigue. Although the application of minimally invasive surgery is accepted and tremendous technological advances have been made, there are still technical and ergonomic limitations of the standard minimally invasive equipment.

As far back as the early 1980s and 1990s, there was a belief in the potential of the clinical application of robotic surgery in abdominal and pelvic surgery.

There were significant developments for the robotically assisted laparoscopic surgery era; for example, the Automated Endoscopic System for Optimal Positioning (AESOP) and the ZEUS Robotic Systems (telemanipulator system) from the American Company Computer Motion (Goleta, CA) both began to utilize robotic arms for stability and integration into imaging technology [2,3].

During this era, the da Vinci Robotic Surgical System from Intuitive Surgical (Sunnyvale, CA) was forging ahead with engineering milestones, offering surgeons seven degrees of freedom with a robotic arm that replicated the human wrist. The concept of "telerobotic" surgery was first developed with grants from the US Department of Defense. The Department of Defense hoped to develop a robotic surgical system to permit combat surgeons to operate from a remote location on wounded soldiers on the battlefield. This system represented the transition from "laparoscopic instrumentations," with lack of articulation, inadequate precision, and nonintuitive motion, to a robotic platform that electronically controls an articulating tip of an instrument, which improved range of motion

and dexterity. For the Intuitive Surgical Company, a series of licensing agreements gave them rights to patents that allowed them to develop a robotic system that is software-driven, which provides intuitive control of seven-degrees-of freedom laparoscopic instruments, stereoscopic vision system, and an architecture composed of redundant sensors to provide maximum safety during operation [4]. The Intuitive Surgical Company has continued to redesign and engineer

the most sophisticated user-friendly and patient-safe robotic platform systems, which has revolutionized its application in the clinical setting to date.

Robotic Abdominal Surgery Platforms

The evolution from standard laparoscopic abdominal surgery to Laparoendoscopic Single-Site Surgery (LESS)/ Single-Incision Laparoscopic Surgery (SILS), and the affect that this technology has had on the robotic platforms

and the development of the Robotic Laparoendoscopic Single-Site Surgery (R-LESS)/ Robotic Single-Site (RSS) platforms (RSSPs), has advanced minimally invasive surgery over a very short time. The development of LESS has reduced the number and size of incisions, which decreases postoperative pain, shortens convalescence, and improves the cosmetic outcome.

The technique of LESS is much more challenging than standard laparoscopic surgery (SLS), especially for suturing. For example, LESS requires crossing instrumentation at the abdominal wall in order to facilitate dissection, which has resulted in reverse handedness for the surgeon. Combine this with the already counterintuitive approach intrinsic to laparoscopic procedures and the LESS technique can be quite a mental strain. This problem has limited further proliferation of LESS into laparoscopic armamentarium of the laparoscopic surgeon.

Standard Robotic-Assisted Surgery (SRAS) has several advantages over SLS: improved optics, ergonomics, dexterity, and precision, which has enhanced its use in a wider patient population and more difficult procedures [5]. The early R-LESS platform did have the problem of instrument clashing due to the coaxial alignment of instruments and the current bulky robotic arms. To minimize this, Joseph et al. crossed the robotic instruments at the abdominal wall and, at the console, switched the controls so that the left actuator was directing the right robotic arm [6]. Intuitive Surgical Inc. developed a set of R-LESS-specific instruments: a multichannel access platform with four port channels and insufflation valve. Two of the ports have curved cannulas for the robotic instruments (which are also curved) and two straight ports for the endoscope and assistant instruments. These innovations have effectively minimized instrument collisions during multiple procedures. In GS, the most clinical experience with R-LESS has been with cholecystectomy. General Comments on Abdominal and Pelvic Robotic Surgery

Preoperative Management

Multiple unique considerations come into play for the anesthesiologist prior to initiation of robotic abdominopelvic and retroperitoneal surgery. Indeed, presurgical time comprises a significant portion of total operating room time in robotic surgery [7–9]. Adequate preparation can reduce the time to initiation of surgery and in turn reduce the total

anesthetic time for the patient [7].

In order to create a working space for the surgeon, current platforms in robot-assisted abdominopelvic and retroperitoneal surgery require the initiation of a pneumoperitoneum. While the choice of induction agent of general anesthetic is unimportant, adequate muscle relaxation is necessary to facilitate both pneumoperitoneum and ease of mechanical ventilation during the procedure [10,11]. In a prospective, randomized trial, Yoo et al. compared deep versus moderate neuromuscular blockade (NMB) in 67 patients undergoing robot-assisted laparoscopic prostatectomy [12]. Deep NMB was associated with successful completion of the operation under intraabdominal pressure (IAP) of 8 mmHg more often than moderate NMB (88 percent vs. 25 percent, $p < 0.001$). Madsen et al. found that the use of deep NMB and low IAP significantly decreased the incidence of postoperative shoulder pain in laparoscopic hysterectomy when compared with moderate NMB (28.6 percent vs. 60 percent, $p = 0.002$) [13]. Deep NMB has also been shown to provide superior working space for the operating surgeon in both RS and LS [12–15].

Currently available robotic platforms allow for limited access to the patient following docking. Adequate intravenous access, as well as plethysmography and blood pressure monitoring devices, should be placed prior to positioning and rechecked following positioning to ensure function before docking [8,10,16]. Additional noninvasive or invasive monitoring is left to the discretion of the anesthesiologist. However, access for intraoperative placement of invasive monitoring devices will be limited, and so consideration should take place prior to docking.

Of even greater concern, access to the airway may be limited, particularly in cases where docking positions of the robot or its arms are above the patient's head, or where the table must be repositioned with the head away from the anesthesiologist [16,17].

Positioning of the endotracheal tube should be ensured after patient positioning and following docking by auscultation. Procedures requiring the use of steep Trendelenburg position shorten the trachea, increasing the risk of endotracheal tube displacement [16]. In an emergency setting, the presence of the robot can preclude rapid evaluation of the patient and initiation of CPR. However, an experienced team can accomplish undocking quickly in order to facilitate patient access and appropriate resuscitation [16].

Following bag-mask ventilation, the patient stomach may demonstrate significant distension. A gastric tube may be placed for intraoperative decompression with particular attention toward manipulation of the tube in cases of upper GI surgery [8,18]. Patient warming devices and corneal protection (plastic goggles with a form frame) should be placed in the standard fashion to prevent intraoperative hypothermia and corneal abrasions, respectively.

Patient Positioning

Positioning the patient is critical for the completion of abdominopelvic surgery. Because the current robotic platforms do not allow the patient's position to change without undocking, this often leads to prolonged periods of pressure under moderate to deep NMB. The range of positions for robotic abdominal surgery varies considerably, from steep Trendelenburg to reverse Trendelenburg, lateral decubitus, lithotomy, supine or split-leg depending on the region of interest

[18–21]. In fact, some cases require multiple dockings with a change in position mid-way to facilitate exposure of additional quadrants of the abdomen, although newer robotic platforms are beginning to allow for up to 180-degree access within the abdomen [19,21]. With each position comes more potential for neuropathic injury. A bevy of upper and lower extremity neuropathies has been described following robotic surgery [20–23].

Safe patient positioning for robotic surgery requires a team approach to prevent position-related injuries and includes the primary surgeon, operative nursing staff, and the anesthesiologist. Positioning the patient can take a considerable amount of time, therefore, most high-volume robotic surgical centers train the nursing and anesthesiology staff in patient positioning to decrease time wasted in the OR. All patients must be well padded on major pressure points, no matter which position is required for the operation, in order to prevent position-related injury. In the past, the primary responsibility of the anesthesiologist was to secure the patient's endotracheal tube and protect the patient's eyes. They are now confronted with making sure they have "unrestricted access" to the endotracheal tube, intravenous lines, and blood pressure monitoring while being confronted with maximally protected arms and radically "fixed" patient positions. Especially during procedures that involve laparoscopic and robotic approaches requiring radical Trendelenburg positioning and the different docking positions of the robotic arms. It has become a challenge for anesthesiologists to adapt to the various "fixed" positions of patients with operations that have prolonged procedural times. They must also be ready for any adverse event that would require emergency undocking and emergency conversion to laparotomy. The vast majority of position-related injury studies have come from the urology and gynecology literature, because these specialties have the most experience with robotic surgical procedures [7,8]. The position-related injuries are classified as cutaneous, musculoskeletal, neurologic, and vascular. The goal is to eradicate or minimize all of these position-related injuries. The incidence of position-related injuries varies in the literature, but in 2014, DiPierro looked at position-related injuries in patients undergoing Robotic-assisted Radical Prostatectomy (RARP) with Extended Pelvic Lymph Node Dissection (EPLND) classifying complications using a modified Clavian–Dindo surgical grading system. The patients were placed into four groups, and the overall minor complication rate was 75 percent (86 of 115 patients). The position-related injuries in groups 1–4 were 31, 29, 29, and 7 percent, respectively. The differences were statistically significant in groups 1–3 and group 4 ($p = .023$). Overall, 24 percent of the patients showed position-related injuries: 21 percent with Clavian grade 1, 2 percent with Clavian grade 2, and 1 percent with Clavian grade 3. After 60 patients, the grade 3 position-related injuries disappeared. The only variable that was associated with positioning injuries was time ($p = .039$) and CCI ($p = .007$). The injuries were pressure skin redness and neuropathies that were all Clavian grades 1 and 2 [24].

Just as the robotic platforms have advanced, surgical industry has advanced in minimizing position-related injuries with different types of padding materials to protect the patients, for example, gel foam and eggcrate foam. There are vacuum mattresses that conform to patient position; there are many non-slip materials that prevent patient migration during procedures. Combinations of these materials are utilized by experienced robotic teams in order to prevent position-related injuries.

The Perineolithotomy Position

Placing a patient in the perineolithotomy position is the most challenging of all positions, so it deserves a separate discussion because it defines the difficulty in preventing position-related injuries and exemplifies the importance of

team approach. It begins when the patient self-transfers from the stretcher to the operating table with eggcrate foam to protect the patient's skin. Usually silk tape or a strap is then placed firmly across the surgical restraints from opposite sides of the bed. Anesthesiologist then covers the eyes with protective plastic glasses. At this point, the surgeon should reexamine the patient, ask anesthesiologist to put the patient into Trendelenburg position, and reexamine all extremities and chest restraints. Then the patient is returned to the supine position and the prep started.

Physiologic Changes in Robotic Surgery

The combined effects of positioning, increased IAP from the operating room table on one of the "nonslip" devices, which are secured to the operating room bed. The arms are raised from pneumoperitoneum, and use of CO₂ can be sig-

placed on arm boards at 60 degrees to the bed and secured with Velcro soft restraints. The patient then moves down on the bed until the sacrum is in the middle of the bed and the lower edge of the buttocks is just below the lower break in the bed. The legs are carefully transferred simultaneously and placed in the stirrup boots (Yellow Fin by Allen Medical Systems is the most commonly utilized), making sure the heel is in the base of the boot and minimal pressure is on calf muscles and lateral tibia. The ankle and knee are placed in alignment with the contralateral shoulder in order to minimize external rotation. The knee is then flexed to approximately 90 degrees. The patient is then examined to ensure symmetry and that the pelvis is level. The patient's arms are then safely placed on the operating table with the thumbs up on a gel foam pad, then either eggcrate foam or another gel foam pad is placed on lateral and medial sides of the arm, especially protecting the elbow and medial epicondyle. Prior to wrapping the arm with the top sheet, anesthesiologist will check the IV lines, blood pressure cuff, and oxygen saturation monitor. The hands are usually formed into a fist around a piece of foam, then wrapped in foam to protect them from injury. If the patient is morbidly obese and it is not possible to place the arms on the table, there are surgical arm shields that can hold the arms or they can be placed on arm boards that are angled less than 90 degrees at the patient's side.

Attention is then turned to securing the patient at the level of the thorax, in order to minimize the patient slipping toward the head of the table during the procedure while in the very radical Trendelenburg position. A soft surgical restraint is placed firmly over the significant in robotic surgery. Separating out these effects is challenging because they can act synergistically or antagonistically depending on the position and procedure, and individual measurements in vivo would prove challenging. Nevertheless, measurable physiologic effects are present during robotic surgery in numerous organ systems and should be considered by the anesthesiologist during the operation.

Pulmonary System

The initiation of CO₂ pneumoperitoneum has numerous effects on the pulmonary system. Most abdominal operations are performed with an IAP goal between 8 and 15 mmHg. The increased IAP decreases functional residual capacity (FRC) [10,11]. When combined with Trendelenburg position, the cephalad migration of intraabdominal contents combines with IAP to decrease pulmonary compliance by as much as 68 percent [10]. The associated increase in atelectasis and pulmonary dead-space can lead to associated hypoxemia [25]. Increased peak and plateau pressures are observed in the setting of pneumoperitoneum, with increases as high as 50 percent [25]. Balick-Weber et al. compared volume-controlled and pressure-controlled ventilation systems in LS and found a small but significant decrease in peak airway pressures associated with pressure-control ventilation [25]. In a similar study, Choi et al. found that pressure control ventilation was associated with lower peak airway pressures and greater dynamic compliance than volume control ventilation [26]. Despite these significant differences, both studies failed to demonstrate clinical differences or changes in patient outcome with different ventilator settings [25,26]. CO₂ remains the

most commonly used gas to generate pneumoperitoneum. It is noncombustible and is rapidly absorbed by the peritoneum, leading to shortened duration of pain associated with

pneumoperitoneum [13,17]. Excess CO_2 leads to a mild respiratory acidosis, which is countered by multiple buffering systems in the body, the largest of which is in bone. These systems have the capacity to absorb upwards of 120 L of excess CO_2 in order to maintain normal pH [27]. After the body's buffering system is saturated, hypercarbia and metabolic acidosis can worsen. Increasing minute ventilation by 10–15 percent through increases in tidal volume and respiratory rate can correct hypercarbia, and close intraoperative monitoring of end-tidal CO_2 can guide these adjustments [28].

The principle contributor to hypercarbia during CO_2 pneumoperitoneum is decreased pulmonary compliance [29]. As such, patients with comorbidities such as asthma, chronic obstructive pulmonary disease, or obesity are at greater risk of developing metabolic acidosis during robotic intraabdominal surgery. Surgical risk factors include positioning in steep Trendelenburg and prolonged operative times [10,17]. Knowledge of both patient and operative risk factors can help guide the anesthesiologist in assessing the patient pre- and intraoperatively. Retroperitoneal and extraperitoneal dissection may contribute to the absorption of CO_2 . Meininger et al. observed a significantly faster rise in PaCO_2 during extraperitoneal insufflation as compared with intraperitoneal insufflation [30]. Additionally, patients in this study had a higher plateau of PaCO_2 which suggests that the larger absorptive surface area of extraperitoneal space more readily absorbed CO_2 [30]. A subsequent comparison of transabdominal

preperitoneal (TAPP) and total extraperitoneal (TEP) herniorrhaphy by Sumpf et al. demonstrated increase rate of CO_2 uptake in extraperitoneal surgery. In this study, the degree of subcutaneous emphysema correlated with CO_2 uptake, again suggesting a contribution from the increased surface area. In addition, the authors suggest that a disruption of extraperitoneal microvasculature may contribute to more rapid CO_2 uptake and greater hypercarbia [31]. While these effects are relatively small in healthy patients, patients with underlying pulmonary disease may see greater consequences of the physiologic changes of pneumoperitoneum [17]. Decreasing the IAP associated with pneumoperitoneum can reduce the absorption of CO_2 and allow anesthesiologists time to treat and adjust for hypercarbia or reduce peak airway pressures required for ventilation to reduce these risks.

Cardiovascular System

Initiation of pneumoperitoneum for robotic surgery can have profound and immediate effects on the cardiovascular system. Hemodynamic changes can be related to increased IAP or secondary to hypercarbia of CO_2 pneumoperitoneum. Insufflation of abdomen leads to a stretch of the peritoneum, which is innervated by the vagus nerve [27]. Rapid peritoneal stretch can cause a vasovagal response, leading to bradycardia and occasionally hypotension [28]. This effect is most commonly seen with pressures above 12 mmHg and usually resolves quickly with cessation of pneumoperitoneum, with judicious application of intravenous fluids or a vagolytic agent (i.e., atropine) when necessary. The rise in IAP associated with pneumoperitoneum leads to a direct compression of intraabdominal inferior vena cava (IVC) [27]. Compression of the vena cava at IAP above 15 mmHg can lead to decreased venous return and increase the risk of cardiovascular collapse due to decreased venous return, particularly in patients who are hypovolemic preoperatively. Central venous pressure (CVP) measurement may rise due to the transmission of increased IAP

to the thoracic cavity or remain unchanged [27,32]. Lestar et al. found that while pneumoperitoneum alone did not change CVP, the combination of pneumoperitoneum and Trendelenburg position led to a greater than two-fold increase in CVP, mean pulmonary artery pressure, and pulmonary capillary wedge pressure ($p < 0.001$). These changes resolved rapidly following desufflation of the abdomen [30,32].

A secondary effect of the compression of IVC is engorgement of lower extremity and pelvic blood vessels and associated venous stasis [27]. The physiologic effect of stasis is an increased risk of venous thromboembolic disease. The use of compression stockings or sequential compression devices or administration of pharmacologic VTE prophylaxis preoperatively counteracts this effect. In fact, in a large retrospective analysis, the National Surgical Quality Improvement Program (NSQIP) has suggested that minimally invasive techniques convey lower risk of VTE than open procedures (AOR 1.33, $p < 0.01$) [33,34].

Increased IAP associated with pneumoperitoneum leads to an increase in systemic vascular resistance (SVR) due to the compression of aorta [35]. Lestar et al. observed a 20 percent rise in SVR following initiation of pneumoperitoneum in their case series ($p < 0.05$). In their case series, the initiation of steep Trendelenburg position returned SVR to basal values [32]. Hypercarbia associated with the use of CO₂ pneumoperitoneum also has an effect of increasing SVR. The increased SVR and associated rise in afterload can lead to an overall decrease in stroke volume (SV) [10,11,17].

Changes in venous return and SVR associated with pneumoperitoneum can lead to alterations in cardiac output (CO) [10,27]. Indeed, Chow et al. observed a reduction of CO by 37 percent with the combination of steep Trendelenburg and pneumoperitoneum [10]. Contrary to this, Lestar and Flabella both observed no significant change in CO on initiation of pneumoperitoneum or changes in positioning, while Haas et al. found an increase in CO of 22.5 percent ($p < 0.05$) [32,35,36]. Reverse Trendelenburg position may worsen the changes in CO and cardiac index (CI), due to worsened venous return combined with increased cardiac afterload [21,37].

The physiologic effect of pneumoperitoneum on heart rate (HR) is multifactorial, and so like CO, the resulting effect can be mixed. In addition to vagal-mediated bradycardia, the use of CO₂ can affect HR. Physiologically, hypercarbia can produce tachycardia and an associated increase in myocardial oxygen demand [27]. While this response was observed by Meininger et al., multiple studies both prior and subsequent to this failed to note a statistically significant change in HR due to either pneumoperitoneum or altered positioning [29,32,35,37].

The cardiovascular perturbations associated with robotic abdominopelvic surgery are generally well tolerated by healthy patients and by those with cardiac comorbidities. Speicher et al. examined NSQIP between 2005 and 2011, specifically evaluating patients with congestive heart failure undergoing abdominal procedures. After adjustment for

other comorbidities, logistic regression analysis found that 30-day mortality was lowered in laparoscopic versus open procedures (OR 0.45, $p = 0.038$) [38]. Extrapolating data from laparoscopy to robotics, this suggests that robotic abdominopelvic and retroperitoneal surgery is safe in patients with preexisting cardiac disease.

The effects of positioning and CO₂ pneumoperitoneum on the cerebrovascular system are intimately linked. When inspected individually, each of increased IAP, hypercarbia, and extreme positioning has an effect on cerebral perfusion and oxygenation. The combination of these effects may be enough to overcome cerebro-vascular autoregulation and alter cerebral perfusion.

CO₂ pneumoperitoneum can lead to hypercarbia, as previously described. Elevated serum CO₂ leads to cerebrovascular dilation, increasing cerebral perfusion [39,40]. The rise in IAP associated with pneumoperitoneum is transmitted across the diaphragm, increasing intrathoracic pressure. This associated increase leads to decreased venous return by the jugular venous system, increasing intracranial pressure (ICP). The rise in ICP is mitigated by reverse Trendelenburg and exacerbated by steep Trendelenburg [39,40]. In a study evaluating the effect of pneumoperitoneum and reverse Trendelenburg position, Kurukhavecioglu et al. found that cerebral oxygenation did not change significantly despite initiation of CO₂ pneumoperitoneum during laparoscopic cholecystectomy (LC) with use of reverse Trendelenburg position [35]. In addition, the use of intermittent sequential compression devices on legs increased cerebral oxygenation when compared with a control group [41]. Closhen et al. similarly measured cerebral oxygenation during robotic surgery using two different near-infrared spectroscopy monitors [40]. Neither initiation of pneumoperitoneum nor steep Trendelenburg position was found to alter cerebral oxygenation greater than 5 percent, the accepted threshold for clinical significance [40].

While measurable changes in cerebral perfusion and oxygenation occur during robotic abdominal surgery, these changes do not appear to be clinically relevant in healthy patients. Jo et al. studied cerebral oxygenation and postprocedural cognitive function after laparoscopic and open gastrectomies [42]. In their study, patients undergoing minimally invasive gastrectomy had similar cerebral oxygen saturation as compared to open surgery, and there was no difference in Mini Mental Status Exam pre- or postoperatively [42]. These data appear to demonstrate that cerebral autoregulation is able to overcome the physiologic demands of RS and LS in majority of patients.

Renal Effects

Increased IAP causes compression of renal vasculature and parenchyma [18]. This has direct and indirect effects on the kidney. Directly, there is an immediate decrease in glomerular filtration rate and urine output [43,44]. This can be exacerbated in the setting of hypovolemia associated with preoperative mechanical bowel preparation. The oliguria associated with renal compression has been linked to the degree of elevation of IAP and resolves quickly after release of pneumoperitoneum [27,43].

In a rat model, Bishara et al. found that while IAP of 7 mmHg did not alter urine output, glomerular filtration rate (GFR), or fractional excretion of sodium, all of these parameters were significantly changed by IAP of 14 mmHg. All values returned to normal 1 hour after desufflation [43]. Renal compression also has secondary neurohormonal effects [27,43,45]. Impaired renal blood flow leads to the release of vasopressin, endothelin, and activation of the renin-angiotensin-aldosterone axis [27]. Excretion of aldosterone leads to the excretion of potassium and may contribute to mild postoperative hypokalemia. While the hormonal effects continue throughout pneumoperitoneum, these resolve within hours postoperatively due to the short half-lives of

associated hormones. While caution should be exercised in patients with underlying renal dysfunction, chronic kidney disease (CKD) is not a contraindication to robotic surgery. Dolkart et al. investigated the effect of pneumoperitoneum in a previously validated rat model of CKD and in rats with acute kidney injury [44]. While creatinine and blood urea nitrogen levels did not change significantly, the CKD in rats did experience a slight decrease in creatinine clearance after pneumoperitoneum of 8 mmHg, while the acute kidney injury rats saw a small decrease in creatinine clearance following pneumoperitoneum of 5 and 8 mmHg. The authors concluded that pneumoperitoneum does not cause further dysfunction in the setting of CKD [44].

Intraoperatively, the anesthesiologist should expect mild oliguria associated with robotic surgery and avoid overcompensation with fluid administration. Insensible losses are significantly lower in robotic surgery versus open abdominal surgery, and long-term renal impairment is rare in minimally invasive surgery [27].

A rare complication associated with robot-assisted radical prostatectomy with extended pelvic LN dissection is position-related rhabdomyolysis leading to renal failure. Rhabdomyolysis is defined as elevated serum creatine kinase (CK) of >5000 IU/L. It is hypothesized that hypoperfusion of the lower extremities occurs from the radical Trendelenburg positioning, causing tissue injury. The pathophysiologic mechanism of renal insufficiency from rhabdomyolysis is renal vasoconstriction, intraluminal cast formation, and direct myoglobin toxicity. Multiple risk factors contribute to the development of rhabdomyolysis, including high BMI, long operative times, extreme Trendelenburg in the perineolithotomy position, medications, pulmonary and cardiovascular disease. Rhabdomyolysis is associated with muscular pain, functional failure, skin lesions, and is diagnosed by elevated CK. Approximately 4% of patients developed rhabdomyolysis, requiring hypervolemic/diuretic therapy, and none developed renal failure [24,46].

Complications of Pneumoperitoneum

CO₂ Embolism

CO₂ embolism is a rare but potentially devastating consequence of pneumoperitoneum. Most CO₂ emboli are subclinical and of little consequence; the reported incidence ranges from 0.001 percent to 37.5 percent in the literature. Despite its rarity, mortality from clinically identifiable CO₂ embolism is as high as 28 percent [47]. The two primary causes of CO₂ embolism are direct insufflation of CO₂ into a blood vessel or vascularized parenchyma such as the liver during entry into the abdomen, or embolization through injury or transection of a major blood vessel during surgery. In a Cochrane review of laparoscopic entry techniques, zero gas emboli were recorded among twenty-two studies evaluated, suggesting that there is no observable difference in gas embolus among abdominal entry techniques [48].

CO₂ embolism should be suspected in the setting of sudden onset of hypotension or decrease in end-tidal CO₂ during insufflation, or during transection of either vascularized parenchyma or major vessels. The diagnosis can be confirmed by either auscultation of the characteristic “mill-wheel” murmur or through transesophageal echocardiography. If gas embolism is suspected, the robot should be rapidly undocked if necessary, and the patient should be placed in the left lateral decubitus position to facilitate trapping of the gas in the

apex of the right ventricle [31]. In severe cases, rapid placement of a central venous catheter can allow aspiration of the gas. In most cases, the continued beating of the ventricle will break up the gas into small bubbles, and the solubility of CO₂ will lead to absorption.

Subcutaneous Emphysema

Insufflation of CO₂ requires intraabdominal placement of robotic ports to maintain pneumoperitoneum. Displacement of the port or increased size of the incision can lead to subcutaneous tracking of gas. In a computed tomography study of laparoscopic patients, 56 percent demonstrated subcutaneous emphysema following surgery [48]. The majority of cases of subcutaneous emphysema are clinically insignificant, but the subcutaneous space can store additional CO₂, leading to retention and hypercarbia.

Pneumomediastinum and Pneumothorax

Dissection of naturally occurring planes can lead to gas tracking. In addition, upper abdominal surgery frequently calls for mobilization of the intrathoracic esophagus [29,31]. Violation of planes can lead to pneumomediastinum, which is usually asymptomatic, or pneumothorax in the case of violation of endothoracic fascia [27]. In lower abdominal surgery, gas dissection along natural myofascial planes can lead to pleural rupture and pneumothorax.

Pneumothorax can be diagnosed by unilateral decreased breath sounds, with or without changes in spirometry [29]. Tension pneumothorax will manifest as hemodynamic instability. Communication with the surgeon for prompt management via transabdominal surgical decompression of the thoracic cavity, desufflation of pneumoperitoneum, or tube thoracostomy is critical, as untreated tension pneumothorax can lead to complete cardiovascular collapse.

Facial, Laryngeal, and Pharyngeal Edema

Robotic surgery with prolonged pneumoperitoneum decreases venous return from the upper extremities, head, and neck. This can lead to migration of fluid into the extravascular compartment of head and neck, particularly when combined with steep Trendelenburg condition. While facial edema is common and may be bothersome to patients, laryngeal edema is of much more significant clinical concern [23,29]. Laryngopharyngeal edema can manifest postoperatively as stridor or respiratory failure requiring reintubation. Patients should be clinically evaluated prior to extubation for significant facial edema that may be suggestive of laryngopharyngeal edema, and cuff leak should be evaluated. Judicious use of fluids may reduce or prevent edema and decrease the risk of reintubation [16,17,23,29].

Ocular Complications

Corneal abrasion remains the most common ocular complication of robotic abdominal surgery. In their series, Danic et al. observed corneal abrasion in 3% of patients after robotic prostatectomy despite the use of tape, but noted a decrease to 1% following routine use of eye patches [16]. Of greater concern, pneumoperitoneum can increase intraocular pressure (IOP), especially when combined with steep Trendelenburg position. This can result in ischemic optic neuropathy and postoperative vision loss, a rare but devastating complication. Molloy observed that in the setting of steep Trendelenburg position, IOP

increased significantly [41]. IOP increases further with longer duration of steep Trendelenburg, suggesting a relationship between duration of Trendelenburg and increased IOP [49]. Additionally, in 10 of 37 patients, IOP rose to levels higher than the calculated ocular perfusion pressure, suggesting poor autoregulation [49]. Yoo et al. measured intraoperative IOP during robotic prostatectomy in a randomized group of patients in deep and moderate NMB and reported a significant rise in IOP with pneumoperitoneum and steep Trendelenburg position [12]. In addition, they observed that patients with pneumoperitoneum in steep Trendelenburg had significantly higher IOP when given moderate vs. deep NMB ($p = 0.0003$). Multivariable analysis demonstrated that increased IAP was the only significant predictor of increased IOP (slope coefficient 0.5178, $p < 0.0001$) [12].

Robotic Abdominal Surgical Procedures

Robotic Hepatobiliary Surgery

Cholecystectomy

Minimally invasive cholecystectomy is the gold standard operation for people with symptomatic gallstones and cholecystitis. Professor Erich Mühe performed the first LC on September 12, 1985, and then he went on to perform over ninety such procedures [50–52]. Since then, GS and CRS have been utilizing minimally invasive techniques for a wide spectrum of procedures in the abdomen and pelvis. It is well accepted that cholecystectomy was the principal operation to begin with utilizing the robotic approach for two reasons: gallstone disease is very common and has a long accepted basis for minimally invasive technique. The first robot-assisted cholecystectomy was performed in 1998. Since then, there have been many reports comparing laparoscopic versus robotic approach to cholecystectomy [24]. The published reports have proven the safety and feasibility of robotic platforms for cholecystectomy [53,54]. In a 2004 study utilizing surgical residents with average laparoscopic expertise, the authors compared conventional laparoscopic cholecystectomy (CLC) with robot-assisted cholecystectomy (RAC) utilizing the ZEUS-AESOP surgical system. They compared total times and number of grasping and dissection actions. This very early study did indicate that RAC was feasible, but there was a longer operative time compared with CLC [54]. Over the years, the multiport robotic platform has undergone revisions from umbilical to low abdominal placement of the ports [54]. Kim et al. (2013), utilizing the four-arm da Vinci robot system, placed the trocars below the umbilicus and the other two arms laterally 7 to 10 cm from the midline camera. A fourth arm was placed in the right anterior axillary line in the upper quadrant, for more difficult dissections due to severe inflammation. A total of 83 patients had a RAC with a mean operative time of 52.4 ± 17.1 min with a setup time of 11.9 ± 5.4 (4–43) min and console time of 15.1 ± 8.0 (range 4–50) min. The conversion rate to laparoscopic or open was zero. There were no common bile duct (CBD) injuries and the overall morbidity was 0.6 percent (one patient had bleeding) [55].

In 2008, a Canadian publication examined the safety of RAC, a retrospective study of two general surgeons with advanced laparoscopic skills comparing LC with RAC, the authors indicated

that there were no major complications in either group, and in the RAC group, there were no conversions to laparoscopic approach. However, in the RAC group, the operative surgical time including docking time was statistically greater than the LC group (91 vs. 48 min, $p < 0.001$). Also postprocedure cleaning of the operative suite was significantly longer in the RAC group (14 vs. 11 min, $p = 0.015$). In the RAC group, anesthesia was also longer (23 vs. 15 min), though not statistically significant. They also “suggested” that in the RAC group there was a longer operative time, during the learning curve of the earlier RAC performed [56]. The increase in intraoperative times of RAC procedures was supported by multiple early studies [57–59].

As LC became the gold standard, utilizing various multiport placements above or below the umbilicus, then in 1997, Navarra et al. introduced the single-incision laparoscopic cholecystectomy (SILC) [60,61]. The SILC was developed for cosmetic reasons and then evolved to SILS. The SILS approach was stimulated by natural orifice transluminal endoscopy surgery (NOTES) [62].

The Robotic Single Site Platform RSSP has a special feature – the Intraoperative Firefly™ – which is a fluorescence imaging system. This imaging system allows the surgeon to visualize the biliary system during the surgery by a preoperative intravenous injection of indocyanine green (ICG), and then the near-infrared fluorescence light would help the surgeon to perform a real-time fluorescent cholangiography [63].

Initial experience with RSSP was published in 2011; all patients underwent surgery by two experienced surgeons with single-site surgery (>50 cases) and robotic surgery (>100 cases) for symptomatic cholelithiasis, excluding acute cholecystitis, a suspicion of CBD stones, pregnant patients, or severe systemic comorbidities. There were 28 patients who underwent RSSC: 22 were female, 6 men, mean age was 48 years, BMI of 26 kg/m² (18–30), and median ASA score of 2 (range 1–3). The most significant results were a median OR time of 80 min (range 45–195), a median port placement time of 3 min (range 1–8), a median docking time of 8 min (range 1–18), and a median console time of 53 min (range 23–134). There were no conversions to laparoscopic or major complications. There was a decrease in the median operative and docking time as the study progressed. The authors indicated that RSSC was safe and feasible [64].

In 2012, the first European experience with single-site robotic cholecystectomy (SSRC) versus SILC looked at and compared learning curves. It was a retrospective review of the first 25 patients who underwent SSRC for symptomatic biliary gallstones or polyposis. They excluded patients with BMI >33, acute cholecystitis, previous upper abdominal surgery, ASA >2, and age >80 years. These cases were then compared to the authors' first 25 SILC and with the literature. Both groups were similar in gender, age, and BMI. There were no major complications in either group. The results did show that operative time was longer in the SILC group compared to the SSRC group (83.2 vs. 62.7 min, $p = 0.0006$), and the SSRC did not change throughout the series. Average LOS was not statistically different in either group. The authors felt they proved the feasibility and safety of SSRC [65]. In a comparative study of first experience with RSSC versus single-site laparoscopic cholecystectomy (SSLC) in Asia, the authors found that there was no significant differences in operative outcomes regarding intraoperative blood loss, bile spillage, postoperative pain scale values, postoperative complications, and length of

hospital stay between the two groups ($p = 0.05$). However, the actual dissection time ($p = 0.003$) and total operative time ($p = 0.001$) were significantly longer in the RSSC group than the SSLC group. This team utilized the Intraoperative Firefly™ fluorescence imaging for real-time fluorescent cholangiography [66].

The ICG fluorescence imaging system was first used for sentinel LN biopsies in patients with breast and colon cancers. ICG is a vital fluorescent dye with few side effects and low toxicity and allergic reactions. It has been used for visualization of vascular anatomy, anastomotic perfusion, hepatobiliary anatomy, tattooing of gastrointestinal lesions, sentinel LN biopsy, and LN road mapping. Currently in robotic surgery, it combines a surgical endoscope capable of visible light and near-infrared imaging, a three-dimensional high-definition stereoscopic camera head that provides visible light, and near-infrared illumination through the surgical endoscope via a flexible light guide. Since ICG is exclusively excreted in the bile, this fluorescence technique allows better visualization of the liver and the extrahepatic biliary tree during open, laparoscopic, and robotic surgery [67,68]. Utilizing intraoperative fluorescence imaging can facilitate better understanding of bile duct anatomy and help in avoiding injury [68].

Even with the utilization of intraoperative fluorescence imaging, robotic surgical exploration of the CBD has had minimal acceptance. Only 15% of patients with cholelithiasis have CBD stones. The standard of care of choledocholithiasis is endoscopic retrograde cholangiopancreatography (ERCP), preceded by cholecystectomy. However, when ERCP fails, surgical exploration of the CBD is necessary. Laparoscopic CBD exploration with sphincterotomy has been shown to be superior over open CBD exploration with sphincterotomy; however, it is utilized in highly selective cases [69]. The advantage of robotic CBDE is that it combines treatment of cholelithiasis and choledocholithiasis in a one-stage minimally invasive approach, eliminating the utilization of ERCP. The utilization of robotic CBDE in patients with refractory choledocholithiasis to ERCP has been shown to be a safe and effective alternative over open CBDE. Alkhamisi et al. compared 19 robotic CBDE with 39 open CBDE for refractory choledocholithiasis to ERCP; the patient demographics and comorbidities did not differ, nor in presenting symptoms. The mean operating times for robotic CBDE were longer (220 ± 41.26 min) than for open CBDE (169 ± 65.81 min) and were statistically significant ($p = 0.01$). The robotic CBDE mean LOS was shorter as compared to open CBDE (4 vs. 11 days; $p = 0.02$). There was no difference in T-tube utilization (74 vs. 61%; $p = 0.414$) or postoperative complications ($p = 0.402$) for robotic vs. open CBDE. There is benefit for robotic CBDE when ERCP fails in highly selected patients [70,71].

Minimally invasive surgery for cholecystectomy is the “standard of care” after almost 30 years of clinical application. One of the major issues of the application of robotic platforms for cholecystectomy is the overall cost of the procedure as compared to LC. A recent study compared cost of care and reimbursement between RC and LC based on several data points: hospital charges (amount requested for reimbursement), hospital cost (dollars spent on episode of care), net revenue (money received, regardless of cost), and earnings before depreciation, interest, and taxes (EBDIT). EBDIT is defined as the net income before considerations for depreciation, interest, and income taxes. It is used to compare profitability because it excludes the effects of financing and accounting decisions. Net income is the value after hospital cost has been applied to net revenue.

The authors further subdivided the hospital costs into variable costs, fixed costs, supply costs, drug costs, equipment costs, and facility costs. Fixed costs are expenses that are not dependent on the level of care provided (e.g., employee salaries and rents per month). Variable costs are usually volume-related and unique to any episode of care, which includes many resources (e.g., some drugs not included in drug costs, CT scans, laboratory tests) and services provided or consumed (e.g., components of nursing time, recovery room time, etc.) in the episode of care of an individual patient. Facility costs are inclusive of hospital costs (e.g., maintaining the hospital, utilities used to run the hospital, etc.); these costs are allocated to all patients and adjusted for severity of intervention and illness. An analysis of operative duration (defined as the time from when the patient entered the operating room until the time he or she was transported from the operating room) was done for each patient. Thirty-one RCs were compared to 201 LCs from June 2012 to June 2013. The operative duration for RCs was 140 min (141 ± 25.38) as compared to 93 min (102 ± 32.7) for LCs ($p < 0.01$). Hospital charges for RCs were \$33,238.42 ($\$34,178.10 \pm 6,023.66$) as compared to \$25,055.85 ($\$27,020.69 \pm 8,624.90$) for LCs ($p < 0.01$). Variable costs for RCs were \$1714.30 ($\$1,786.00 \pm 449.45$), while for LCs, they were \$1,449.54 ($\$1,555.53 \pm 527.52$) ($p < 0.022$) but only for a cost of \$264.76 per case. There was no difference between either procedures as far as net revenue, EBDIT, net income, fixed costs, supply costs, drug costs, equipment costs, facility costs, and total costs [72].

This was the first study that compared RC to LC with multiple data points, and it appears to state that the only cost difference was the variable cost of \$264.76 per case.

Robotic Liver Surgery

Minimally invasive surgery of the liver has been slow to develop because of the technical challenges of liver surgery, including access to the vena cava, major hepatic veins, and difficulty in dissections of the hilum and control of bleeding. So early liver procedures were limited to staging procedures and unroofing of hepatic cysts, then progressed to easily accessible parts for wedge resection, then to major hepatectomies with increasing experience. As the technology to control bleeding and advanced robot platforms have developed, robotic liver surgery has become more common [73]. Patient positioning for robotic liver resections has also developed depending on the segment being resected, for example, the left lateral position for lesions in segment 7 or 8.

Minor hepatectomy is the most common procedure performed robotically 58% of the time, including wedge resection, segmentectomy, bisegmentectomy, and left lateral sectionectomy. A review article of 217 patients with benign and malignant disease of the liver undergoing minor hepatectomy showed that wedge resection and segmentectomy had a conversion to open rate of 4.6% and a complication rate of 20.3%. Postoperative intraabdominal fluid collection of bile or abscess was the most common complication. Reasons for conversion to open were unclear tumor margin, bleeding control, obesity, or anatomical distortion of hilum from adhesions. Operative mean times ranged from 200 to 507 min with mean operative blood loss of

60–660 ml. The mean postoperative LOS ranged from 5.5 to 11.7 days, with a mean follow-up time of 36 months for colorectal liver metastasis and

25.1 months for hepatocellular carcinoma. The studies did support that robotic liver resection was safe and feasible for experienced surgeons with advanced laparoscopic skills [74,75].

Major hepatectomy is an advanced robotic surgical procedure that requires advanced laparoscopic skills and techniques. In one of the major series of robotic liver resections, Giulianotti et al. performed 70 procedures, including 33 major resections for both benign and malignant disease: 24 right hepatectomies, 5 left hepatectomies, 2 right trisectionectomies, and 1 extended right hepatectomy and 1 right lobe donor hepatectomy. Twenty-three of the 33 major resections were for malignancy, with 13 for colorectal metastasis. The mean operative time was 313 min (range 220–480) with a mean blood loss of 300 ml (range 100–2,000). These authors did discuss the advantages of the robotic approach, especially for dissection of the hilum and hepatocaval dissection. The robotic platform with its three-dimensional magnification and endowrist functions allows for microsurgical dissection of bile ducts and major blood vessels and was especially advantageous for biliary reconstruction during liver resection [74,75].

Overall, the utilization of the robot for minor and major hepatic resections has been slow to develop but has proven feasibility, safety, and acceptable complication rate when compared to laparoscopic hepatic resections. There is not enough data to compare a cost–benefit ratio for utilization of the robot for hepatic resections, nor is there any data on long-term oncologic outcomes [76].

Robotic Pancreatic Surgery

Pancreatic surgery, both open and minimally invasive, is both technically demanding because it is a retroperitoneal organ embedded in visceral organs. The minimal invasive approach is still developing, and because the anatomic location of pancreas positioning of the patient is still in development, the standard supine position is most common, but there is an early feasibility and safety study to approach from the posterior and lateral positions and perform a retroperitoneoscopic pancreatectomy (RP). These authors utilized minimally invasive techniques for the RP procedure on 19 patients with benign and malignant disease of the pancreas. Patients had enucleations ($n = 8$), distal pancreatectomy ($n = 4$), pancreatic cyst resection ($n = 2$), and no pancreatic lesions ($n = 5$). Intraoperative complications occurred in 12.5%, including the peritoneum and splenic vein. Six cases developed pancreatic fistulas postoperatively [77].

The difficulty of laparoscopic pancreatic resection has prevented wider acceptance because of the complexity of the procedure, the accuracy required, and the steep learning curve to become proficient with the procedure. The robotic pancreatic resection has increased the acceptance of minimally invasive surgery on the pancreas, but it is also considered advanced robotic surgery. There is a retrospective review of one surgeon's experience of 134 patients in the United States and Italy from 2000 to 2007, utilizing the robot for benign (70 cases) and malignant (64) disease of the pancreas. The patient is placed in the low lithotomy position with the robot over the patient's head. The procedures were pancreaticoduodenectomy (PD) (50), distal pancreatectomy (DP) spleen preserving (23), distal

splenopancreactectomy (23), cystogastrostomy (14), middle/total pancreatectomies (4), longmire procedure (10), cystoduodenostomy (1), cystojejunostomy (3), pancreaticogastrostomy (2), pancreaticojejunostomy (1), and enucleation (3). For the Italian group (77 patients), the results for all procedures were: mean operative time, 312 min (55–660); estimated blood loss, 261 cc (100–600); and LOS for patients with perioperative complications, 21.8 days (6–85), and those without perioperative complications, 10.2 days (4–15). In the US group (57 patients), the results for all procedures were: mean operative time, 351 min (73–630); estimated blood loss, 323 cc (5–2,000); and LOS for patients with perioperative complications, 9.3 days (3–30), and those without perioperative complications, 6.4 days (3–13).

The total conversion to open rate was 18.3% (11) in the PD group and 6.5% (3) in the DP group. The reasons for conversion in the Italian group were venous tangential infiltrations, hypercapnia, malfunction of robotic system, difficulty isolating anatomical structure, positive tumor margins, and infiltration of the superior mesenteric vein.

The most common postoperative complications in the combined groups were pancreatic fistula, which occurred in 31.3% (19 of 60 patients) in the PD group and 20.9% (9 of 43 patients) in the DP group. The 30-day total mortality was 1.5% [41].

The incidence of pancreatic fistula was high in this series than in other series utilizing minimally invasive

techniques. The major question that has not been answered is whether the oncology outcome is better than or equal to open technique for pancreatic cancers [78,79].

Robotic Gastrectomy

The role of minimally invasive approaches (both laparoscopic and robotic) to gastrectomy has not been widely accepted in the United States or Europe. Laparoscopic gastrectomy (LG) was used for early gastric cancers that did not require extensive LN dissection. As the technology improved and with accumulation of surgical experience, the indications were broadened to later gastric cancers.

In 2009, a comparative study was carried out on 60 patients with gastric cancer: group 1 (initial robotic) of 20 patients underwent robot-assisted distal subtotal gastrectomy with gastroduodenostomy (RADG), group 2 (initial laparoscopic) of 20 patients underwent laparoscopic distal subtotal gastrectomy with gastroduodenostomy (LADG), and group 3 (recent laparoscopic) of 20 current patients underwent LADG. A single surgeon who had performed 177 laparoscopic gastrectomies and 100 open gastrectomies before starting robotic surgery performed all procedures. All patients were placed in supine position and reverse Trendelenburg with the surgical cart above the right side of the patients' head.

The demographics of the patients were all similar based on sex, age, BMI, and comorbidities. Operative time of the initial RADG was significantly shorter than the initial LADG group ($p = 0.003$); however, in comparison the initial RADG had a significantly longer operative time than the recent LADG group ($p < 0.001$). The initial LADG had the longest operating times (289.5 ± 59.3 min) followed by the initial RADG (230 ± 34.9 min). There was a trend in the initial RADG of decreasing time with

increasing experience.

There were no significant difference in tumor characteristics ($p = 0.399$) or difference in LN retrieval ($p = 0.080$). Stage IA was the most common for all groups. There was no statistical difference in LOS, tolerance of diet, and only four postoperative complications with zero mortality [80].

In a recent meta-analysis comparing robot-assisted gastrectomy (RAG) and laparoscopy-assisted gastrectomy (LAG), it found that RAG was acceptable than LAG when performing radical gastrectomy. The study compared 1,875 patients in eight studies.

There was no difference between RAG and LAG in LOS ($p > 0.5$), no difference in postoperative complications ($p > 0.1$), proximal margin was similar in RAG and LAG ($p > 0.05$), but the distal margin was longer in RAG than LAG ($p > 0.05$), and harvested LNs were similar in both groups ($p > 0.05$). However, in the RAG group the operative time was longer because of setting and docking. Three of the studies indicated that the operative time did decrease as the surgeons' experience increased. The da Vinci allowed for intracorporeal anastomosis in all cases. The authors concluded that long-term studies of clinical outcomes should be evaluated before final conclusions can be drawn [81].

In a retrospective review comparing RAG to LAG in short-term surgical outcomes, there were 423 patients from October 2011 to August 2014 with gastric cancer. Ninety-three patients had RAG and 330 had LAG; a comparative analysis was performed for clinicopathological characteristics and short-term surgical outcomes.

There was no significant difference in age, BMI, tumor location, TNM staging, and medical comorbidities ($p > 0.05$). The extent of resection (subtotal or total gastrectomy or distal gastrectomy) and the extent of LN dissection to achieve R0 resection was the decision of the operating surgeon. Reconstruction was either gastroduodenostomy, or gastrojejunostomy for distal gastrectomy, Roux-en-Y esophagojejunostomy for total gastrectomy, and esophagogastric anastomosis for proximal gastrectomy, and most were performed extracorporeally. Operating time was longer for RAG (257.1 ± 74.5 min) than LAG (226.2 ± 61.3 min), which was significant ($p < 0.001$). RAG (176.6 ± 212.2 ml) had less intraoperative blood loss than LAG (212.5 ± 198.8 ml), which was significant ($p = 0.001$). There was no difference between types of resections performed ($p = 0.686$). The proximal and distal margins were not significantly different in either group ($p = 0.092$ and 0.486 , respectively). The short-term outcomes – days to first flatus and days to tolerating diet – were similar in RAG and LAG groups ($p > 0.05$). Postoperative complication rates were not statistically different between RAG (9.8%) and LAG (10%) with $p = 0.927$. Hospital LOS was also similar with a $p = 0.41$.

In summary, the RAG requires a longer operative time, but over time the mean operative time does reduce. This study did demonstrate that RAG is acceptable over LAG in terms of surgical and oncologic outcomes in the short term [82].

Robotic Splenectomy

The use of minimally invasive surgery for splenectomy is an established procedure and is the standard of care for diseases of the spleen. The minimal invasive approaches are multiport laparoscopic splenectomy, hand-assisted laparoscopic splenectomy (for very large spleens), robotic splenectomy, natural orifice transluminal endoscopy, and single-port access splenectomy. LS is performed for idiopathic thrombocytopenic purpura,

hereditary spherocytosis, autoimmune hemolytic anemia, thrombocytopenic purpura, Hodgkin's and non-Hodgkin's lymphoma, chronic lymphocytic leukemia, hemangiomas, idiopathic myelofibrosis myelodysplastic syndrome, hairy cell leukemia, splenic abscess, or cyst and tuberculosis. The utilization of RShas not surpassed the level of LS. The position of the patient is the right lateral decubitus, with reverse Trendelenburg inclination and the table is flexed [83].

The use of the robot for either total or partial splenectomy has been very slow to evolve because of very few studies. In a comparative study in 2012 of 32 consecutive subtotal splenectomies, only 10 cases were performed with the robotic platform. The authors felt that the robot was superior in dissection of splenic vessels, but the effective cost-benefit ratio was not acceptable. They felt that only difficult cases be referred for robotic surgery [84]. In a review in 2015 of minimally invasive surgery comparing LPS and RPS, out of 195 publications only 33 articles were included with a total of 187 patients: the mean total operative time for LPS was between 70 and 216 min and between 108 and 120 min for RPS. The complication rate with similar: LPS 5.36% and RPS 5.56%. The authors felt that the robotic approach needed more research to prove efficacy over LS or LPS [85]. The current data for the utilization of robotic platform for diseases of the spleen is limited and indications for it are evolving. It does require a high degree of robotic and advanced laparoscopic skills before attempting to treat diseases of the spleen.

Robotic CRS

Since the first reported LC in 1991, the use of minimally invasive approaches to diseases of the colon and rectum had begun [86]. The first robot-assisted CRS in 2001 for ileocolic resections and sigmoid resections for benign disease was published [87]. Since that time, LC has become more widely utilized for benign and malignant diseases of the colon and rectum with significant short-term benefits over open colectomy, for example, reduction of postoperative pain, shorter hospital LOS, and earlier return to work. Studies have also shown no difference in LC versus open colectomy for colon cancer for short- and long-term oncologic outcomes [88–90].

The more common robotic platform utilized today is the da Vinci Si series, and the approach to the colon or rectum involves “hybrid” procedures, including laparoscopic-robotic procedures. For all left-sided colon or rectal procedures, the patient is in the perineolithotomy position with radical Trendelenburg position, with radical tilt to the right. Many sigmoid resections or low anterior resections with low pelvic anastomoses include laparoscopic mobilization (either pure laparoscopic or hand-assisted laparoscopic) of the splenic flexure and/or ligation of the inferior mesenteric artery. When performed, the inferior mesenteric vein then robotic mobilization of the rectum, with a hybrid hand-assisted colorectal anastomosis. With greater experience, there has been mobilization of the splenic flexure with one docking of the robot, then redocking in order to perform the resection of sigmoid or rectum with an intracorporeal colorectal anastomosis. Now the only disadvantage of multiple docking methods is increased operative time.

The majority of right colectomy resections are performed in the supine position tilted to the left in the Trendelenburg (some surgeons prefer the reverse Trendelenburg) utilizing robotic

mobilization of the ileum and colon with extracorporeal anastomosis, while other surgeons perform robotic high vascular ligation, with intracorporeal resection of the ileum and transverse colon, then utilizing either intracorporeal or extracorporeal anastomosis [91]. With the recent release of the da Vinci Xi platform, the entire abdominal and rectal procedure can be performed with the robotic platform.

A systematic review of articles compared robot-assisted CRS with laparoscopic and open surgery in 2014. For robot-assisted CRS studies in 69 publications, there were a total of 2,644 operations performed, and in 62 sex-reported studies, there were 1,445 males (54.7%) and 1,092 females (45.3%). In 60 age-reported studies, the average age was 60.1 ± 6.2 for 2,478 patients. In 46 BMI-reported studies, the mean BMI was $25 \pm 1.8 \text{ kg/m}^2$ for 2,269 patients. There were 499 (19.3%) procedures for benign disease and 2,089

(80.7%) for malignant diseases in 65 studies. The types of procedure reported in 66 studies were: 966 low anterior resections (37.8%), 387 (15.2%) right colectomies, 385 (15.1%) anterior resection, 170 (6.7%) sigmoid colectomies, 168 (6.6%) abdominoperineal resections, 104 (4.1%) rectopexies, 70 (2.7%) left colectomies, and 36 (1.4%) total or subtotal proctocolectomies.

In 66 studies involving RC, the mean operative time (OT) was 253.3 ± 65.8 min. When compared to laparoscopic surgery (LS) and open surgery (OS), the mean OT was significantly greater than the LS time, while RS and LS times were significantly greater than OS times. Interestingly, the average LOS, was inconsistent in the RS and LS procedures, which were statistically similar but less than OS.

Intraoperative complications in 2,391 patients (61 studies) reported a 0.8% complications, which included associated bowel or vascular injuries, intraoperative bleeding, and two ureteral injuries. There were 504 (21.1%) postoperative complications, of

which 21.4% anastomotic leaks, 20.4% ileus, 10.5% wound infection, 9.9% urinary or sexual dysfunction, 7.1% pelvic abscess, 6.9% medical problems, 4.8% bleeding, and 3.2% neurologic problems (positioning injury). Conversion from RS to OS was 2.4% (0–40%) and to LS was 0.7% (0–33%), and the most common reason was obesity (15.3%), followed by technical problems (13.9%) and difficult dissections or anatomy (9.7%). Regarding oncology pathologic outcomes when comparing RS to LS and/or OS, there was no statistical difference in harvested LN, distal resection margins (DRM), circumferential resection margins (CRM), total mesorectal excisions (TME), or mortality. With regard to oncologic outcomes comparing RS to LS and/or OS, there was no statistical significance ($p = 0.873$). This systematic review of RS as compared to LS and OS did determine that RS is safe and feasible in diseases of the colon and rectum and not inferior to LS or OS. They also stated that there is a longer OT, steeper learning curve, and a higher cost [92]. Minimally invasive rectal surgery is an advanced laparoscopic technique, and robotic platform has just started to be utilized, and whether the procedure is performed minimally invasive or by open surgery, the gold standard for rectal cancer (RC) is a TME. A 2015 meta-analysis compared outcomes in robotic TME (RTME) versus laparoscopic TME (LTME) in randomized controlled trials (RCTs) and nonrandomized controlled trials (NRCTs) to

evaluate whether RTME was as safe and efficacious as LTME. Utilizing a strict inclusion and exclusion criteria, the authors were able to find eight studies (7 NRCTs and 1 RCT) out of 192 studies. There were 1,229 patients with RC, of which 554 (45.08%) were RTME versus 675 (54.92%) who underwent LTME. When comparing the two groups, there was no statistical difference in the pooled data for LOS ($p = 0.43$), overall complications ($p = 0.23$), anastomotic leaks ($p = 0.66$), wound infection rates ($p = 0.52$), or overall pathologic data (LN $p = 0.84$, DRM $p = 0.36$, PRM $p = 0.32$, CRM $p = 0.50$). The complication of urinary and sexual function was mixed, but when looking at the pooled data, there was no statistical difference ($p = 0.72$). And there was no difference in OS or DFS in either group ($p = 0.404$ and 0.914 , respectively).

Overall, the total hospital costs for RTME (\$14,080) was higher than LTME (\$9,120) and OS (\$8,386) with $p < 0.01$. The conversion to open in the RTME (6/554) was significantly lower than the LTME (35/675), the reasons being obesity with thick mesentery, inability to identify important vascular structures, vascular injury, adhesion, and narrow pelvis. The mean operative time was longer in RTME versus LTME in most of the studies. In some of the studies with the addition of neoadjuvant chemoradiotherapy (NCRT), there was a higher anastomotic leak rate in the lower RC patients. The authors admitted that the meta-analysis has limitations; the most important issues were that the primary studies determine the quality of meta-analysis, which indicated methodological problems; only one study was RCT; and there was always heterogeneity in the patients. Overall this study did suggest that RTME is safe and feasible with lower conversion rates than LTME, but the disadvantage was higher cost [93]. The ACOSOG Z6051 randomized clinical trial determined that among patients with stage II and stage III RC, the use of laparoscopic resection as compared to open resection failed to meet the criteria for noninferiority of pathologic outcomes. The authors recommended, pending clinical oncologic outcomes, that the findings do not support the use of laparoscopic resection in these patients [94]. In the Australasian Laparoscopic Cancer of the Rectum (ALaCaRT) randomized noninferiority phase III trial with a total of 475 patients (237 open rectal resection/238 laparoscopic resections), T1–T3 RCs 15 cm from the anal verge showed that laparoscopic resection did not reach noninferiority versus open resection. The authors did not recommend a routine use of LS for RC [95].

Postoperative Management

Enhanced Recovery after Surgery

The advent of ERAS programs for perioperative care of the surgery patient has done more to foster the modern multiteam approach to patient-centered management pathways. It has been through the collective development of protocols and multidisciplinary team, including nursing and other ancillary care givers under the leadership of surgeons and anesthesia providers, that evidence-based perioperative protocols have been implemented in the management of the surgical patient, which have led to improved outcomes.

These perioperative protocols contain facets that focus on preoperative, intraoperative, and postoperative management techniques that require multidisciplinary team cooperation. These ERAS protocols developed to reduce the surgical stress response and thereby improve patient's outcomes, reduce complications, and shorten postoperative hospitalization. The proliferation of ERAS studies and resultant protocols have spawned an

Enhanced Recovery After Surgery Society, which serves as a valuable databank available at www.erassociety.org.

The predominance of medical literature on post-operative recovery pathways has been centered on the CRS patient, but there is growing evidence that other postoperative procedures, particularly other abdominal pelvic procedures, are amenable to ERAS protocols as well. The majority of this literature demonstrates a reduction in hospital stay coupled with a lack of an increase in readmission rates or mortality [96]. These advantages are not relegated to only younger, healthier patients as ERAS protocols have been safely applied to elderly patients and have been demonstrated to reduce complications and shorten length of hospital stay in those patients as well [97].

While the initial studies were actually performed on open colectomy patients by Kehlet et al., LS has predominated recently and robotic surgery is ideally suited for incorporation into these pathways as well [98]. The minimally invasive approach has been demonstrated to better preserve the immune response and enhance faster postoperative recovery [99,100]. The utilization of ERAS is obviously not unique to RS or LS, but it is particularly germane to these operative techniques and is a critical component of perioperative management of these patients. It really is not a question of whether ERAS should be done, but rather how best to develop and implement an ERAS protocol for robotic surgical patients [4].

It is critical when embarking on ERAS pathways that it is done with a multidisciplinary team and is patient-centered. Initially, it is very labor-intensive and is a significant allocation of resources [101]. There are current systems based on practice pathways and cultural barriers that can be impediments to implementing ERAS protocols. These barriers must be overcome in order to standardize care through education of staff to overcome cultural and organizational roadblocks. If an ERAS protocol is developed and instituted and the nursing personnel have not embraced it or the surgeons and anesthesiologists are not committed, then it is doomed to fail.

Protocol compliance and clinical outcomes must be continually monitored, updated, and even modified. An initial pilot study conducted by a dedicated team was able to maintain a compliance of the protocol 93% of the time with a median length of hospital stay (LOS) of 3 days and a 30-day readmission rate of 4%. However, when the protocol was implemented hospital wide, compliance fell to 74% and median LOS rose to 6 days. These results demonstrate a quicker postoperative recovery and shorter LOS compared to historical controls, but also emphasize the importance of constant vigilance and monitoring of the protocol [102].

Just as there are multiple methods for performing a given operation or providing anesthesia for a surgery, no two ERAS pathways are identical. The tenets of the protocol that is developed and instituted must be incorporated into the individual institution and eventually through the healthcare system. Since the predominance of studies involve multiple separate parameters, it is often difficult to pinpoint and then separate out the most critical components. The long-standing question of which ERAS component is the most critical for the patient with respect to postoperative recovery remains unanswered.

What follows is not an exhaustive review of literature, but rather an attempt to coalesce some of the pertinent data on ERAS and allow the practitioners to build a protocol that can be incorporated into the cultural goals of their own institution. The goal is to allow the multidisciplinary ERAS teams to examine the evidence and to use the data to develop optimal

perioperative management for their robotic surgical patients.

ERAS Protocol Overview

Since the advent of ERAS or fast-track protocols almost 20 years ago, a voluminous number of studies have been performed. The initial studies in Europe have spread to North America and throughout the world [103]. Studies demonstrate that these protocols are safe and effective and can be inculcated into any size and makeup of hospital – in both academic and private institutions [104]. There have been multiple meta-analyses studies addressing colorectal ERAS programs and a Cochrane review that has indicated enhanced patient outcomes. As with meta-analysis studies, heterogeneity of patient populations, as well as disparate protocols, there is difficulty in combining these studies to evaluate patient outcomes. In addition, most studies are compared to historical controls, which makes the outcomes even more problematic. Despite these methodology problems, all studies have demonstrated a decreased hospital LOS, without compromising patient safety. These studies uniformly indicate that complications and readmission rates are equivalent. The data on complications is less clear, with some studies showing a reduction in complications as well as some showing a savings in healthcare costs [105–112].

Applicable Robotic Surgical Procedures

Although the predominance of literature, especially the initial studies on ERAS protocols, mainly involved CRS, there are multiple other procedures that are amenable to a robotic ERAS protocol, for example, the bariatric and obstetric patients who are commonly operated using robotic technology have incorporated ERAS protocols. Due to the fact that these patients have already shorter length of hospital stays than CRS patients, it has been somewhat difficult to demonstrate improvement in LOS and less readmission rates utilizing ERAS protocols, but overall these have been shown to benefit patients [113–116].

ERAS Protocol Components

The ERAS protocols are typically divided into three components for conceptualization, but it is critical to realize that these are an organizational division only and there is significant overlap such that all the providers are involved in one aspect or another in each phase of the protocol. Anesthesiologists play perhaps the most critical role in facilitating the recovery of patients, as many of the ERAS elements are under their direct control. At least one author contends that for successful implementation of an ERAS program, anesthesiologists must become more involved in perioperative care and be more aware of the impact of anesthetic techniques on surgical outcomes and recovery [117].

The multidisciplinary protocol and team must transition the patient from one provider to the next in a smooth and consistent manner. Communication between team members during protocol development and implementation is crucial to enhance patient experience and outcomes. The three components are roughly divided into preoperative, intraoperative, and postoperative care of the surgical patient [118,119].

Preoperative ERAS Component

The preoperative care component is identifying patients who will benefit from the protocol. While most patients can garner some benefit, some may not be adequate candidates, so the ERAS protocol should not be “instituted” on every patient unless the team believes that the patient will benefit. Patients with significant comorbidities or those who cannot ambulate without assistance or lack cognitive abilities to follow instructions may be poor candidates for inclusion in the protocol. Following patient selection there is a designated team member who gives extensive preoperative counseling and coaching. It is important to understand patient’s expectations and provide counseling on the protocol and allow ample amount of time for the patient and their family members to understand the goals of the protocol and also encourage them to ask questions. Both surgical and anesthesia providers should ideally be involved in pre-operative counseling, highlighting their own respective areas. This team approach further enhances the patients “buying in” the protocol and its goals.

At preoperative assessment and testing, in addition to the standard assessment of comorbidities, nutritional concerns and smoking cessation, if applicable, should be addressed. The patients are also provided instructions on any preoperative bathing requirements and Chlorhexidine sponges or wipes, if indicated.

When a mechanical bowel preparation is to be used, a review of the prep protocol should be performed along with assurance that the patient has the necessary prescription for the mechanical prep.

Instructions should be given during preoperative assessment on the amount of time the patient is not to take any liquids or solids by mouth (NPO). A decrease in traditional NPO time is preferable, allowing clear liquids up to 2 hours prior to surgery. In addition, carbohydrate drink recommendations are supplied for carbohydrate loading on the morning of surgery.

Intraoperative ERAS Component

On the day of the procedure, it is important to identify and document any patient who will be included in the protocol. As per the protocol, initiate antibiotic prophylaxis and antithrombotic medications and apply pneumatic leg compression devices. Additional medications for the prevention of postoperative ileus such as alvimopan are also administered at this time.

The intraoperative anesthesia management of the ERAS protocol centers on not using sedative medications prior to the surgery. Typically, an epidural catheter is placed and epidural analgesia is used throughout the operative procedure, and opioids are avoided if possible. Goal-directed perioperative fluid management is also employed in an attempt to avoid giving the patient excessive crystalloid fluid, as this can contribute to postoperative ileus. In addition, antiemetic prophylaxis is typically given at the conclusion of the case in order to facilitate early resumption of oral intake.

The surgical portion of the protocol concentrates on minimally invasive surgery, with laparoscopy or robotic surgery. When laparoscopic operative principles are combined with ERAS, 60% of CRS patients can be discharged within 72 hours [120]. The incisions should be infiltrated with local anesthesia prior to making the incision. Drains should not be used routinely and any gastric tube should be removed at the conclusion of the case.

Postoperative ERAS Component

The postoperative care centers on early mobilization of the patient in an attempt to return them to a more functional status. The epidural catheter is used for postoperative analgesia, typically for at least the first 48 hours following the surgery. Intravenous ketorolac or acetaminophen is commonly used while the patient is transitioned to oral nonsteroidal antiinflammatory medications as soon as possible, again trying to avoid narcotics, in an effort to reduce postoperative ileus and postoperative nausea and vomiting (PONV). The postoperative care includes early initiation of oral feeding in conjunction with the discontinuation of routine intravenous fluids a few hours after the surgery. The patient is allowed liquids shortly after the surgery, often with protein supplementation. The IV fluids are discontinued in the recovery room or shortly after arrival to the patient floor.

Early mobilization and assisted ambulation is encouraged within 2 to 4 hours postoperatively. The first postoperative day the patient is encouraged to spend 8 hours out of bed and to begin take meals, consisting of light semisolid food seated out of bed.

The Foley catheter is typically discontinued on the first postoperative day, except in the case of low pelvic operations, when it is left in place for an additional few days. The discharge criteria are unchanged from any other

operative procedure. Patients can be safely discharged to home when they are taking oral food without nausea and their pain is controlled with oral medication.

ERSA Protocol Failure

It is obvious that whatever components make up the protocol, it may not work in every patient. Due to the number of variables, it is impossible to determine the contribution of each individual facet to either ultimate success or failure. It is possible to determine which facets are less likely to be followed and which are more likely to result in failure of the protocol.

One study looking at almost 20 facets of different ERAS protocols found that none of the published studies used the same variables. This obviously makes it difficult to establish superiority of one over another. What was found, not surprisingly, was that compliance was poorest during the postoperative period [120]. The postoperative component is the longest period and is the period that is subject to most variability, emphasizing the need for multidisciplinary team management and monitoring of protocol compliance. In a randomized trial comparing colectomy coupled with or without ERAS, the combination of LS with ERAS protocols resulted in superior results with a shorter hospital stay [121].

A study of patient postoperative needs assessment following discharge to home utilizing ERAS guidelines indicated that receiving this information was vital as patients attempted to regain control over their life after surgery during transition from hospital to home. These variables varied from hospital to site of transition. This suggests an even greater need for patients to receive information preoperatively but also reinforcement of the goals of the protocol throughout their hospital stay and the importance of monitoring their understanding of those goals [122].

Muller et al. in 2009 found that fluid administration greater than the restricted limits and a non-functioning epidural analgesia were independent predictors of postoperative complications and fast-track failure [123]. In fact, failure to follow the established protocol

rather than any patient factors was the predictor of ERAS protocol failure. Deviations of the protocol at the end of the first postoperative day – for example, continuing intravenous fluid infusion, lack of functioning epidural, inadequate mobilization and ambulation, vomiting, and/or reinsertion of a Foley catheter – are all strongly associated with a delay in discharge and an increase in LOS in several studies [124–126].

ERAS protocols are successful when adequate patient education is given, minimally invasive surgical techniques are used, postoperative nausea is prevented, and excessive intravenous fluid administration is avoided.

ERAS Prevention of Ileus and PONV

Several of the ERAS facets are designed to minimize ileus and subsequent PONV. Refraining from the routine use of nasogastric tubes, early ambulation, and avoiding narcotic analgesia are all used in an attempt to facilitate normal intestinal function. Initiation of antiemetic premedication and continued use in ERAS protocols has become standard at many institutions because of their efficacy of prevention of PONV. Despite these measures, postoperative ileus and PONV continues to be a significant problem in postoperative abdominal surgery patients [127–130].

Alvimopan

The ERAS protocols were begun well before the introduction of Alvimopan, which was approved for use in the United States in 2008. Since that time, the medication has been commonly adopted into ERAS protocols with some positive results [131]. Alvimopan is a mu-opioid receptor antagonist, which blocks the constipating effects of narcotic medication without compromising any analgesic effect. Alvimopan has been demonstrated to lower the incidence of postoperative ileus following gastrointestinal surgery. Several

studies have demonstrated that Alvimopan is useful in accelerating GI recovery and hospital discharge after laparoscopic and open abdominal surgery and may be effective in lowering hospital costs [132].

A 2015 meta-analysis of five studies indicated that the use of Alvimopan in the perioperative period showed a relative risk reduction (>75%) in postoperative ileus when compared to placebo [133]. Twelve milligrams of Alvimopan is administered to patients throughout the perioperative recovery until discharge, a component of an ERAS protocol for patients undergoing abdominal surgery [131–133].

ERAS Fluid Management

The administration of excessive amounts of crystalloid fluid both during intraoperative and postoperative periods is common in the management of patients undergoing elective abdominal surgery. Intraoperative and postoperative oliguria is common, especially in LS, and the traditionally employed monitoring of urine output has been demonstrated to be an inaccurate measurement of overall fluid status [134–136]. The goal is to have a hydrated, euvolemic patient at the beginning of the surgery in order to achieve a zero fluid balance by the end of surgery. The postoperative goal of a balanced oral intake without the addition of intravenous fluid infusions will achieve the end result of euvolemia of the patient throughout the perioperative period.

Through the use of ERAS protocols, it has been demonstrated that patients do better clinically if the goal of directed fluid management is utilized and maintained throughout the perioperative period. Fluid management begins in decreasing the time a patient is required to be NPO prior to the surgery. Most ERAS protocols decrease the time that a patient must refrain from oral intake and actually encourage patients to drink clear liquids up to 2 hours prior to the induction of anesthesia. In addition, patients are given or instructed to consume carbohydrate drinks the morning of surgery.

Carbohydrate Drinks

The addition of carbohydrate or protein supplementation on the morning of surgery has become a common component of ERAS protocols. Initial studies involving patients who were given a carbohydrate drink prior to elective surgery demonstrated a reduction in insulin sensitivity [137]. The utilization of patients taking carbohydrate drinks preoperatively led to better glucose homeostasis as well as grip strength during the postoperative period [138].

In a systemic review of 17 RCTs involving 1,445 patients, preoperative carbohydrate drinks significantly improved insulin resistance and some indices of patient comfort following surgery, including hunger, thirst, malaise, anxiety, and nausea [139]. A Cochrane review of RCTs of preoperative carbohydrate treatment did find that despite a high risk of bias due to inadequate blinding in most of the studies, there was a small reduction in hospital LOS. It also indicated that preoperative carbohydrate treatment did not increase complication rates, especially of aspiration pneumonitis [140].

Goal-Directed Fluid Therapy

There are numerous methods of perioperative fluid management and one approach is fluid-restrictive therapy. A 1 L crystalloid bolus is administered in the preoperative holding area and continues to be infused during induction. After induction the bolus injection is stopped. The remainder of the operation uses a rate of 3 mL/kg/h, using the patient's lean body weight, to a maximum of 240 mL/h.

If an esophageal Doppler is to be used, it is placed after induction, and an initial SV is calculated. After pneumoperitoneum is established, a 250 mL colloid bolus is given over 15 min. If the SV increases by >10%, then the patient is intravascularly depleted and a repeat bolus should be given. If the SV is unchanged or actually decreases, then the patient should be considered to be euvolemic, as any additional fluid does not result in an improvement in CO. There are other methods of noninvasive monitoring during surgery, but no one method has proven superiority [141].

Analgesia Management

Adequate postoperative analgesia is another critical component of ERAS protocols. While the use of an epidural catheter has demonstrated effectiveness, they can at times be difficult to place, can be time-consuming, and have variable success. It is important for the team to be familiar with and include alternative pain management techniques within any ERAS pathway.

Liposomal Bupivacaine

The introduction of bupivacaine liposome inject- able suspension has been used with some success as a component of a perioperative analgesia regimen. Patients who had liposomal bupivacaine infiltrated preoperatively in the operative sites had lower post- operative pain scores and a decreased use of opioid narcotics [142].

Transversus Adbominis Plane Block

The transversus adbominis plane (TAP) block is a peripheral nerve block, which functions to anaes- thetize the abdominal wall. There is limited evidence that TAP block reduces opioid consumption and pain scores after abdominal surgery as compared to no intervention or placebo [143]. Nine studies (including published and unpublished data), containing a total of 413 patients, indicated that cumulative morphine utilization was significantly reduced following TAP block [143]. While there are no studies that compared TAP block with epidural analgesia directly, a meta- analysis of all relevant RCTs comparing the efficacy of TAP block with local infiltration of local anesthesia was performed. The patients in the TAP block group had lower pain scores 24 hours postoperatively when compared with the local anesthesia infiltration group; at rest and with movement also, the TAP block group demonstrated better long-lasting effect [143].

Conclusion

This chapter has covered a broad topic on robotic sur- gery being utilized in the realm of abdominopelvic procedures in GS and CRS. The preoperative section discussed the importance of the physiologic effects of pneumoperitoneum and radical patient position- ing that is required in order to perform complex surgical procedures. These are difficulties that our anesthesia colleagues have had to conform and learn under a much higher level of stress in order to man- age our patients in an entirely different environment. And they have been performed at the highest level of patient management.

The chapter has pointed out the advantages of robotic platforms over laparoscopic platforms for very complex procedures. The development of a “wrist-like” motion and visual acuity of the robotic technology have stimulated surgeons to successfully incorporate complex abdominopelvic procedures into their armamentarium of techniques which has led to less complications and a comparable decrease in hospital stays in many cases as compared to other minimally invasive techniques. Then, incorporating the ERAS protocols in the postoperative management of their patients has enhanced early discharge and patient satisfaction. The ERAS protocols have shown benefit in patients undergoing abdominal surgery. These protocols can be labor-intensive, but they have a documented benefit with a reduced length of hos- pital stay without a concomitant increase in readmis- sion or complications. Minimally invasive techniques such as robotic surgery play a key role in these proto- cols. While no two protocols will be identical as each is developed within the hospital and system in which they are to function, their development requires mul- tidisciplinary input from both surgeons and anesthe- siologists using evidence-based methods.

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Part 6 Research Design

The introduction of robot assistance to the field of gynecologic surgery, specifically the da Vinci Surgical System, represents a remarkable breakthrough in minimally invasive surgery. Subsequent to the 2005 FDA approval of the da Vinci Surgical System, robotics for gynecologic surgery has been rapidly adopted nationwide as a means to improve access to minimally invasive surgery for surgeons and their patients. At centers where it is available, it has assumed an important role in the surgical armamentarium (1). The current application of robotic technology in gynecology includes hysterectomy, myomectomy, oophorectomy, ovarian cystectomy, resection of endometriosis, sacrocolpopexy, and lymphadenectomy with an increasing role of robotic surgery in gynecologic oncology. Known advantages of robotic surgery include three-dimensional visualization, improved ergonomics, reduced fatigue, decreased tension tremor, seven degrees of motion, and decreased blood loss (2).

This chapter will focus on the preoperative workup that pertains to gynecology, our surgical technique, and common intra- and postoperative complications related to the most commonly performed robotic procedures: hysterectomy, oophorectomy, ovarian cystectomy, myomectomy, and sacrocolpopexy.

Robotic-Assisted Total Hysterectomy with or without Bilateral Salpingo-Oophorectomy

In the United States, hysterectomy is the second most common surgical procedure and the most common gynecologic procedure. There has been a steadily increasing trend toward the minimally invasive approach of laparoscopic or robotically assisted hysterectomy (3,4). The number of benign hysterectomies performed via laparoscopy doubled and robotic-assisted hysterectomy increased from 0.5 percent in 2007 to 9.5 percent in 2010 (5). The American College of Obstetrics and Gynecology (ACOG) and the Society of Gynecologic Surgeons recommend surgeons should be skilled at both abdominal and laparoscopic procedures prior to the use of robotics. The selection of cases should be based on available data and expert opinion. It is also recommended that use of this technique should be driven by patient benefit and satisfaction without external commercial pressure. Furthermore, didactic and hands-on training is in development at most centers and should take place at the institutional level. In keeping with the goal of performing the least invasive procedure, ACOG continues to recommend the transvaginal route of hysterectomy whenever possible (4).

Regardless of the route of hysterectomy, the preoperative evaluation is similar for all approaches. The indication for hysterectomy should be valid and the choice to use robotic assistance should be based upon operator experience and patient benefit and safety (4). The gynecologic preoperative evaluation includes obtaining a full gynecologic and obstetrical history. This includes, but not limited to, a history of gynecologic malignancies, STDs, menstrual history, obstetrical history, familial history of breast or gynecologic malignancies (cervix, uterus, ovaries, fallopian tubes), and previous gynecologic

procedures. A thorough pelvic examination is important to assess uterine size and mobility as these attributes can significantly impact technical difficulty and ultimately the success of the procedure and potential complications. There is no agreed-upon size that precludes a minimally invasive approach. However, a wide bulky uterus with minimal mobility can be more difficult to adequately manipulate, thereby limiting exposure during surgery and significantly increasing tissue extraction time. Cervical cancer screening should

be performed according to the currently published guidelines for any woman aged 21 or older, with the exception of those infected with HIV who warrant screening at the time of diagnosis (6). Abnormal uterine bleeding and postmenopausal bleeding should be evaluated per current guidelines with ultrasound and possible endometrial biopsy as well as any other indicated testing to exclude malignancy prior to hysterectomy (7,8). Preoperative lab work should include, but not limited to, CBC, type and screen, and a pregnancy test in reproductive-aged women.

Bilateral salpingo-oophorectomy (BSO), or salpingectomy, can be performed at the time of benign hysterectomy or as an isolated procedure for the purpose of risk reduction of ovarian cancer and the treatment of benign ovarian conditions such as neoplasm, endometriosis, and pelvic pain (9). Genetic susceptibility for ovarian carcinoma is based on family history and possibly genetic testing. The presence of bilateral ovarian neoplasms, severe endometriosis, pelvic inflammatory disease, bilateral tuboovarian abscesses, or postmenopausal status favor BSO over ovarian conservation (9). The benefits of ovarian conservation, e.g., a decreased risk of cardiovascular disease, osteoporosis, and cognitive impairment, were found to decrease after the age of 65 in the Nurses' Health Study and, as such, should favor BSO (10). It is appropriate for surgeons to offer risk-reducing salpingectomy with ovarian conservation to decrease the risk of ovarian cancer at time of benign hysterectomy without the risk of ovarian compromise (10). At the same time, women should be informed of the reduction in breast and ovarian cancer associated with bilateral oophorectomy (11). The decision for BSO versus salpingectomy should be individualized and fully discussed with each patient.

Supracervical hysterectomy may be chosen based on patient or physician preference, need to decrease operative time, or to use the cervix for pelvic organ prolapse (POP) reconstruction. If a decision is made to retain the cervix, the patient will need to continue pap screening per current guidelines. She will need to be informed of the risk of continued bleeding or potential need for later trachelectomy. Removal of the uterus may be done through a mini-laparotomy with or without an extraction system or through power morcellation. If power morcellation is the mode of extraction, patients should be informed of the potential for undiagnosed gynecologic malignancy and the risk of intraperitoneal dissemination of benign or malignant disease with secondary implantation (12). Power morcellation can be performed within a containment bag creating a pseudo-peritoneum; however, this technique is currently experimental. Nongynecologic preoperative work-up includes pulmonary, cardiovascular, and other indicated assessment similar to any operative procedure and not unique to robotic-assisted hysterectomy. This should include a thorough history and physical and pertinent diagnostic testing (13,14). Patient's at high risk of postoperative venous thromboembolism should be identified preoperatively and treated according to recommended guidelines. If longer operating times or conversion to laparotomy are anticipated or pre-existing VTE risks are present, then prophylaxis is indicated (15)

Antibiotic prophylaxis is indicated for all routes of hysterectomy (3). First-generation cephalosporin is dosed appropriately for weight and considered first-line prophylaxis due to its effectiveness, low cost, and lower risk for stimulating a β -lactamase response (3). For penicillin-allergic patients, the recommendations include clindamycin or metronidazole plus gentamicin or a quinolone (16). Preoperatively the patient should also be treated for any known bacterial vaginitis or trichomoniasis to reduce the risk of vaginal cuff infection postoperatively (17).

Similar to an open approach, the possible risks of this procedure include blood loss and the need for transfusion, unplanned adnexectomy, and injury to other pelvic organs, especially bladder, ureter, and bowel. Complications related to robotic-assisted procedures include entry injury to the major vessels, bladder, and bowel. The ureters are also at greater risk during laparoscopic hysterectomy compared to other approaches (18); however, the use of ureteral catheterization to prevent such injury is of unproven benefit (19). The risk of conversion to an open procedure should also be discussed with the patient preoperatively.

Surgical Technique

Our typical setup for a robotic-assisted laparoscopic hysterectomy is the same regardless of whether we are doing a total or supracervical hysterectomy. We use monopolar scissors in the number 1 arm (right) and Maryland bipolar grasper in the number 2 arm (left). In cases that may be more technically difficult, we use a ProGrasp or Cadiere in the number 3 robotic arm. In addition, a uterine manipulator that has a cupping device is helpful for making colpotomy and for tissue extraction prior to cuff closure. If a uterine manipulator with a cupping device is not available, alternative instruments such as right-angle retractors, ring forceps with or without a sponge, and a thin malleable retractor may be used to help delineate the anterior and posterior fornices for colpotomy.

The patient is maintained in the low dorsal lithotomy position on a Pink Pad (Xodus Medical, New Kensington, PA) with the arms tucked at the side using the draw sheet. All bony prominences are padded typically with foam, and a bimanual examination is completed to determine uterine size, shape, and mobility and to determine port placement. The abdomen and vagina are surgically prepared. To avoid stomach puncture by a trocar during primary abdominal entry, an orogastric or nasogastric tube is placed to decompress the stomach. The patient is then draped and a Foley catheter is inserted via the urethra. A uterine manipulator with its attached cervical cup (VCare or KOH Cup with RUMI manipulator) is placed vaginally to assist uterine manipulation and delineate the cervicovaginal junction for colpotomy and the pneumo-occluding balloon is inflated.

Abdominal insufflation may be achieved using a Veress needle after "water drop testing" to confirm intraperitoneal entry or by direct visual entry using an optical trocar loaded with a laparoscope. The number of trocars and their caliber may vary, but in general, we use a 12-mm optical port, usually at the umbilicus, and two or three reusable robotic ports placed through the lower abdominal wall. Specifically, the two to three robotic ports are placed 9 cm from each other to avoid arm collisions during the procedure. A 5-mm assistant port is placed on the low right flank and, if necessary, a second 10-mm port is placed in the right upper quadrant to facilitate

passage of sutures and other materials such as grafts, hemostatic agents, and clips. This port also allows the assistant to retract, irrigate, and suction effectively. The pelvis and abdomen are inspected and photodocumentation or videography is initiated. At this point, adhesiolysis is performed to restore normal anatomy, if needed, prior to docking.

Docking maneuvers are initiated once the patient is placed in steep Trendelenburg and the da Vinci system is guided into place. The robot is side-docked and the instruments are inserted into the abdomen under direct visualization. Prior to making any incisions, it is important to identify the ureters. In most cases the ureters can be visualized without difficulty peristalsis beneath the peritoneum on the pelvic side walls. However, it is sometimes necessary to open the peritoneum for identification. In such situations, the peritoneum medial to the infundibulopelvic (IP) ligament is grasped and tented using atraumatic forceps and incised with scissors. The opening in the peritoneum is then extended a short distance both caudally and cephalad along the length of the ureter. Through this peritoneal window, on the medial side the ureter is identified (20). The proximal round ligament is grasped and then divided. If preservation of the ovaries is planned, the proximal portions of the fallopian tube and uteroovarian ligament are then desiccated and transected.

With this, the tube and ovary are freed from the uterus and can be placed in the ovarian fossa. If removal of the ovaries is desired, the IP ligament is grasped and pulled up and away from retroperitoneal structures. The ureter's path is once again identified. The IP ligament is isolated and dissected away from the ureter. The pedicle is subsequently coagulated, desiccated, or stapled and divided. If the fallopian tubes are to be removed, the distal attachment of the tube to the ovary (fimbria ovarica) must be removed in its entirety and the mesosalpinx is coagulated and transected in a stepwise fashion moving toward the uterus.

Following round ligament transection, the leaves of the broad ligament peritoneum are separated and the loose connective tissue is localized between these leaves. The anterior leaf is incised with the monopolar scissors. This incision is made parallel to the border of the uterus and directed caudally to the midline above the vesicouterine fold. The posterior leaf is then taken down to the uterosacral ligaments. Opening the broad ligament allows the uterine vessels to be skeletonized and clearly visualized. Once the broad ligaments are opened bilaterally, the vesicouterine fold is grasped with atraumatic forceps, elevated away from the underlying bladder, and incised transversely.

The loosely attached connections can be bluntly divided by gently pushing against the cervix in a caudal direction. This displaces the bladder away from the cervix and upper vagina. Denser tissue in the vesicouterine space may be divided sharply with the aid of monopolar energy or sharp tissue dissection. Bipolar or monopolar electrosurgery may be utilized to coagulate small bleeding vessels. It is equally important to keep cephalad traction on the uterus with the uterine



Figure 8.1 Desiccation of the uteroovarian ligament vessels. The uteroovarian ligament is desiccated with a bipolar grasper.



Figure 8.2 Creation of the bladder flap. The loosely attached connections can be bluntly divided by gently pushing against the cervix in a caudal direction. This displaces the bladder away from the cervix and upper vagina.

manipulator to assist with this dissection. Alternately, the prograsp or cadere in the third arm of the surgical assistant can grasp the fundus to maintain cephalad

traction on the uterus and improve visualization of the anterior and posterior surfaces. The mobilization of the bladder and sometimes the upper rectum is

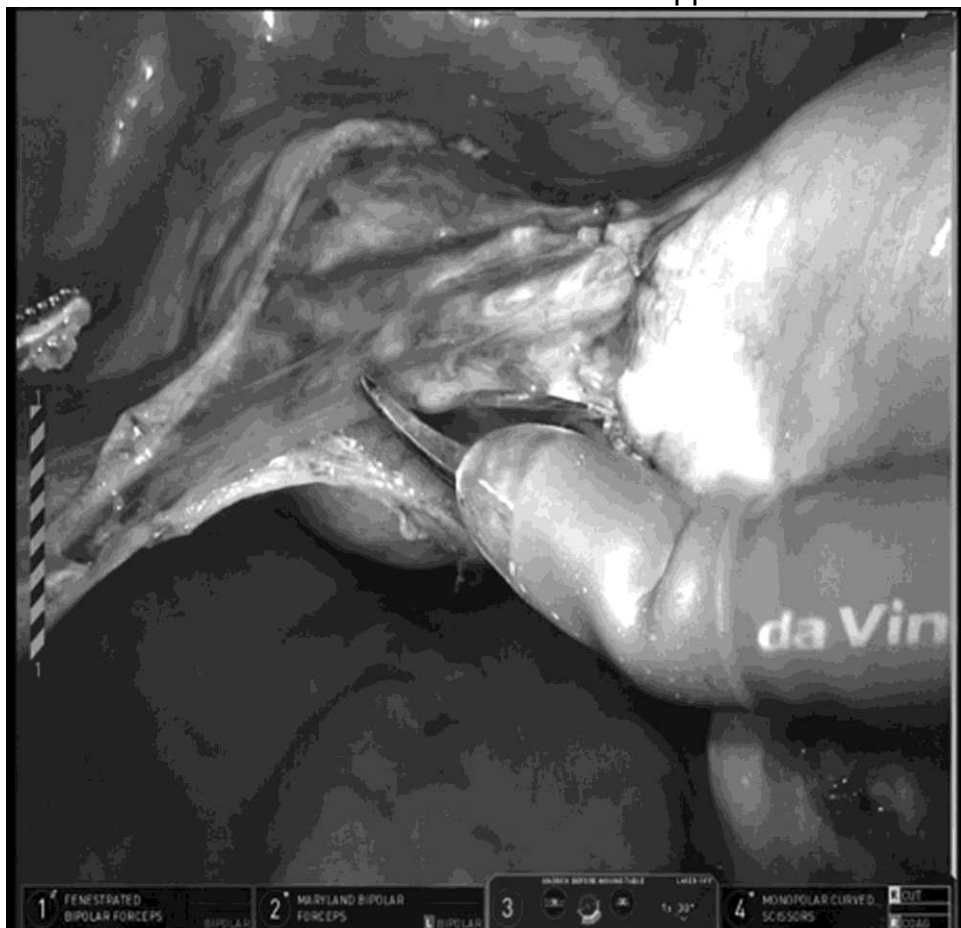


Figure 8.3 The uterine vessels are skeletonized. Skeletonizing of the vessels permits precise desiccation and transection of the uterine vessels.

necessary for the final colpotomy and removal of the uterus. Of all the hysterectomy approaches, the laparoscopic one has the highest risk of bladder injury, and when it occurs, its most frequent location is at the dome during this sharp or blunt dissection (21). The risk of bladder injury is increased when scarring from prior surgery such as cesarean delivery is present or when concomitant pelvic disease such as endometriosis exists.

After the uterine arteries are identified, the loose areolar connective tissue surrounding them is grasped and incised. This skeletonizing of vessels permits precise desiccation and transection of uterine vessels.

The lateral cardinal ligaments are then taken down to the level of uterosacral ligaments bilaterally. Prior to colpotomy incision, the uterine manipulator is pushed cephalad to allow the colpotomy cup to displace the ureters laterally and expose the optimal location for the incision. The

colpotomy can then be performed with monopolar scissors.

The colpotomy is initiated by placing the incising tool at the anterior cervicovaginal junction, which is delineated by the cervical cup. If a colpotomy cup is not used, a simple tool such as right-angle retractor or ring forcep is placed vaginally in the anterior or posterior fornix to assist with the identification of the cervicovaginal junction. The anterior vaginal wall is usually opened first followed by the posterior colpotomy. The uterosacral ligaments are then transected. To prevent thermal damage to vaginal tissues and potential later cuff dehiscence, surgeons should use the minimum amount of energy needed to incise vaginal tissues.

Intact uterine extraction is completed through vaginal colpotomy using a manipulator or alternatively

with a transvaginally placed instrument such as a tenaculum. In cases involving large uteri, the uterus can also be transvaginally cored, bivalved, or morcelated. In some cases, the uterus can be placed in an Alexis contained extraction system (Applied Medical, Rancho Santa Margarita, CA) for intracorporeal morcellation through a slightly extended port incision.

Vaginal cuff closure can be achieved in numerous ways, including conventional laparoscopic, robotic, or vaginal suturing with or without a suture device, and laparoscopic or robotic suturing using barbed suture. We close the cuff robotically with interrupted delayed-absorbable sutures. Full-thickness closure with 1 cm depth is recommended to help prevent cuff dehiscence. To support the vaginal cuff long term, the uterosacral ligaments are incorporated into the closure as a separate step. After cuff closure, the pelvis is irrigated and hemostasis confirmed. Intraabdominal pressures are lowered to 5 mmHg during this inspection to reduce vascular compression and better identify sources of bleeding. Once completed, the robot is undocked and cystoscopy is performed to confirm ureteral patency and absence of bladder injury. The trocars are removed and the fascia is closed where trocar sites larger than 10 mm are present. The skin is closed with moncryl with or without supplemental skin adhesive.

Complications

Intraoperative and postoperative complications associated with robotic-assisted hysterectomy include genitourinary, gastrointestinal, vascular, and neurologic injury, as well as pelvic infection and vaginal cuff dehiscence.

Nerve injury during hysterectomy and BSO is rare but can occur at a rate of 0.2–2 percent during major pelvic surgery (22,23). The femoral nerve is the most common nerve injured during major pelvic surgery, usually on the anterior surface of the psoas muscle and inguinal canal. Although this injury occurs more commonly during abdominal hysterectomy due to compression from lateral retractors, it can also occur as an indirect stretch injury as it passes through the inguinal canal due to malpositioning of the legs in the stirrups. When placing patients in the dorsal lithotomy position, care must be taken not to hyperflex and externally rotate the hip to avoid this injury. The superficial branch of the peroneal nerve can also be easily injured by compression of the stirrup on the lateral edge of the fibular head during abdominopelvic procedures. The iliohypogastric and ilioinguinal nerves while rarely injured during laparoscopy can be injured during placement of lateral trocars at the location where the iliohypogastric nerve penetrates the fascia of the internal oblique and where the ilioinguinal nerve penetrates the fascia of the transverse abdominus muscles. Closure of fascial incisions and subsequent scarring are additional sources of nerve entrapment and injury (3).

Blood loss, in general, is lower in minimally invasive hysterectomy. The reported median blood loss during laparoscopic hysterectomy in randomized trials comparing two or more routes of hysterectomy is 156–660.5 mL (24). In a recent Cochrane Review, laparoscopic hysterectomy was found to have significantly lower estimated blood loss than abdominal hysterectomy but not when compared to vaginal hysterectomy (3). The loss of control of the uterine and ovarian blood supply is the most common reason for hemorrhage and increased blood loss during hysterectomy. Injury to any of the many vessels originating from the iliac arteries supplying the pelvis can significantly increase blood loss. The complex

venous plexus, which is a collateral network of veins from the external and internal iliac veins, inferior mesenteric, and ovarian veins, is yet another possible major source of bleeding. Other risk factors for bleeding include pelvic adhesive disease and malignancy.

Genitourinary tract injury is an additional complication that can be incurred at the time of hysterectomy. The reported rate of genitourinary tract injury in major gynecologic surgery is approximately 1–2 percent (25). The occurrence of bladder injury during laparoscopic hysterectomy has been estimated at

2.1 percent compared to 1 percent and 1.2 percent in abdominal and vaginal routes, respectively, in a randomized trial of 1,300 hysterectomies (26). While it is reported that bladder injuries are more common than ureteral injuries, it is also noted that two-thirds of ureteral injuries are not identified at the time of injury (25,27). The occurrence of ureteral injury is highest for laparoscopic hysterectomy as compared to other routes, but the overall incidence of ureteral injury is low at 0.05–0.5 percent (27,28). Ureteral injury most commonly occurs during dissection and ligation of the infundibulo-pelvic ligament at the pelvic brim, followed by ligation of the cardinal and uterosacral ligaments and uterine arteries at the bladder base and lower uterine segment respectively (3). Hemorrhage, Endometriosis, previous pelvic surgery, pelvic masses or fibroids, and obesity are associated with an increased risk of ureteral injury during hysterectomy and BSO (3). In addition, dissection of the prevesical plane during laparoscopic surgery is the most common source of bladder injury, especially in patients with previous cesarean delivery, endometriosis, pelvic adhesive disease, or cancer (3).

Gastrointestinal tract injury is yet another concern during robotic surgery. Injury to the vascular supply and tissues of the GI tract or bowel occurs by thermal, direct, or indirect etiologies. The reported rate of GI tract injury is 0.1–1 percent of all hysterectomies, with 0.2 percent occurring in association with the laparoscopic approach (29). The use of monopolar current during hysterectomy is a common cause of thermal bowel injury most often incurred during deep pelvic dissection in the posterior cul-de-sac when performing colpotomy. In addition, direct bowel injury can occur when placing laparoscopic trocars and when performing blunt or sharp adhesiolysis. Devascularization of the bowel is most likely to occur during dissection of the mesentery of the bowel, and is more common in surgical cancer staging procedures (3).

Surgical site infection is not an uncommon event after hysterectomy. The prevalence of infectious complications after laparoscopic hysterectomy has been estimated at 9.0 percent (29). Hysterectomy is considered to be a “clean-contaminated” procedure due to its entry into the vagina (3). Postoperative infection may occur in the form of infected pelvic hematoma, vaginal cuff abscess, wound infection, urinary tract infection, or respiratory infection. Symptoms or signs of infection should be evaluated with a thorough history and physical and indicated diagnostic laboratory and clinical tests to determine the source and differentiate infection from febrile morbidity (3).

The vaginal cuff is the primary source of postoperative complications that are unique to hysterectomy. Vaginal cuff cellulitis is found to occur in 0–8.3 percent of patients after hysterectomy (24). This typically presents within a few days after surgery with fever, purulent vaginal discharge, and pelvic pain. A pelvic examination usually confirms the diagnosis with demonstration

of cuff tenderness or induration with or without purulent discharge (3). Cuff cellulitis is commonly polymicrobial (3,16), and the type and duration of treatment should be based on current standards of care.

Another potential complication specific to hysterectomy involving the vaginal cuff is dehiscence

with or without evisceration. In a large retrospective review, Cronin et al. found the rate of dehiscence after all routes of hysterectomy to range from 0.14 to

4.1 percent. Reported rates of dehiscence after total laparoscopic and robotic hysterectomy are found to be the highest (1–4.1 percent) when compared to other routes of hysterectomy (0.14–0.27 percent) (30). The creation of colpotomy using electrocautery with the attendant thermal injury coupled with smaller tissue incorporation during cuff closure due to laparoscopic magnification has been implicated in the causation of this postoperative complication. Vaginal cuff dehiscence is a serious postoperative complication that more frequently follows laparoscopic hysterectomy as compared to vaginal or abdominal hysterectomy (30,31). In most cases, the precipitating event in premenopausal woman is sexual activity, and in postmenopausal women any increased intraabdominal pressure (e.g., constipation) exerted on a weak, atrophic vagina (32).

Robotic-Assisted Cystectomy

A robotic approach can be used to safely remove the adnexa and, in most cases, offers a faster recovery and less postoperative pain when compared to laparotomy. Indications for adnexectomy vary but may include mass, torsion, ovarian cyst rupture, suspicion of ovarian malignancy, and symptomatic ovarian remnant. Robotically assisted cystectomy accounted for 2.4 percent of minimally invasive cystectomies performed in 2009 and has increased annually thereafter to 12.9 percent currently. The minimally invasive approach can also be safely performed in pregnant women, preferably in the early second trimester (33).

Sonography is the primary perioperative tool used to evaluate ovarian pathology, and the sonographic characteristics of a cyst aid in determining the malignant potential of a given lesion. In cases in which the anatomy may be unclear, magnetic resonance imaging may add additional information. Tumor markers, such as serum cancer antigen 125 (CA125) levels, are typically drawn preoperatively in postmenopausal patients and in any woman whose tumor displays other signs consistent with ovarian epithelial cancer. In addition, serum alpha-fetoprotein (AFP), lactate dehydrogenase (LDH), inhibin, and β -hCG levels may be measured to exclude germ cell or sex cord-stromal ovarian neoplasms. As with any surgical procedure, patients should be informed of the unique complications associated with minimally invasive surgery. In particular with adnexal surgery, the risk of ureteral injury should be discussed. In some cases, unanticipated bilateral adnexectomy may be required, and the patient should be aware of the significance of hormonal deprivation. Lastly, many adnexa are removed due to concerns of potential malignancy, and the patient should be apprised of the additional procedures required for the surgical staging of ovarian cancer.

In general, robotic-assisted adnexal surgery does not require antibiotic prophylaxis. Bowel preparation is also not usually required but may be considered in addition to antibiotic prophylaxis

if extensive adhesions are suspected. Venous thromboembolism (VTE) prophylaxis is typically not recommended for robotic-assisted cystectomy. However, those with greater risk of malignancy, VTE, and conversion to laparotomy may benefit from those measures. Generally accepted guidelines for VTE prophylaxis should be applied.

Surgical Technique

For robotic-assisted ovarian cystectomy, we use monopolar scissors, a Maryland bipolar forcep, and if an additional robotic arm is required we use a pro-grasp or cadere. We also typically use a suction irrigation system and additional laparoscopic graspers and retractors through the ancillary ports. The patient is prepared and positioned for robotic surgery as previously described. The abdomen is insufflated with CO₂ to a pressure of 15 mmHg and the camera port is inserted (34). Secondary trocars are then placed. Depending on the size of the adnexa, at least one trocar should be 10 mm or larger to allow for the use of an endoscopic retrieval bag to contain the specimen at the conclusion of surgery.

Once the abdomen is entered, inspection of the pelvis and upper abdomen for signs of malignancy such as ascites and peritoneal implants is performed. Pelvic washings are obtained if malignancy is a concern. Peritoneal implants should be biopsied and sent for intraoperative frozen section. If a malignant neoplasm is found, then the cystectomy is aborted and an intraoperative consult is obtained from a gynecologic oncologist.

Adhesions are divided to restore anatomy, and the anterior and posterior surface of the ovary is carefully inspected. The ovary is then stabilized and the monopolar scissor blade is used to make an incision along the antimesenteric surface of the ovary to minimize disruption of the extensive vascular supply located at the ovarian base. The incision is extended into the ovarian stroma to the level of the cyst wall but no deeper to avoid rupturing the cyst. A space between the ovary and cyst wall is created bluntly using Maryland forceps or scissors. The grasping forceps are then used to hold the ovarian tissue, while a prograsp can be used to separate the cyst wall from the ovarian capsule. Depending on the adherence of the cyst to its surrounding ovarian tissue, sharp dissection with monopolar scissors may be required to complete the cystectomy. Following cyst removal, bleeding sites and isolated vessels may be grasped and coagulated with the bipolar grasper. Not uncommonly, during the dissection of the cyst away from the ovary, the cyst may rupture. As a result, the grasping forceps can be used to strip the cyst wall away from the underlying ovarian stroma (35). To prevent damage to the underlying healthy ovary, the dissection plane between the cyst and stroma should be clearly delineated by traction on each side to prevent laceration.

Specimen retrieval is then performed. A small excised cyst wall can be removed directly through one of the laparoscopic ports. In some cases, a posterior vaginal colpotomy is used for removal of the intact cyst or cyst wall (36). Yet another option is to place the cyst in an endoscopic retrieval bag and decompress the cyst inside the bag. This procedure significantly decreases the possibility of spilling the cyst contents into the pelvic cavity, which is important given one study reported a 7.3–8.1 percent spillage rate for laparoscopic ovarian cystectomy (37). Contained rupture and extraction is possible with even larger cysts wherein the cannula is removed, and the purse-stringed opening of the bag is drawn through the trocar incision and fanned out onto the skin surface. The

open edges of the bag are pulled upward to lift and press the cyst up against the incision. A needle tip is then directed into the incision and pierces the cyst contained within the endoscopic bag. An attached syringe is used to aspirate the contents. Alternatively, the cyst may be ruptured by an instrument such as a Kocher clamp placed through the skin incision and into the sac. The endoscopic sac and decompressed cyst wall are then removed together through the incision. During removal, care is taken to ensure that the endoscopic bag is not inadvertently punctured or torn, and all measures are used to prevent spillage of cyst contents into the abdomen or port site.

Closure of the ovarian capsule is not required following cyst removal due to the risk of adhesion formation, technical difficulty, and additional operative time required for laparoscopic suturing. Several studies have shown that leaving the capsule open does not lead to an increase in adhesion formation (38,39). Application of an adhesion barrier such as oxidized regenerated cellulose (Interceed, Ethicon, Inc., Somerville, NJ) may be considered to reduce adhesion formation (40,41). However, no substantial evidence documents that their use improves fertility, decreases pain, or prevents subsequent bowel obstruction (42).

As previously recommended, intraabdominal pressures are lowered to 5 mmHg during final pelvic inspection to identify sources of bleeding. The addition of hemostatic agents such as Surgicel Fibrillar, Evicel, Surgiflo (Ethicon Inc., Somerville, NJ), Tisseel, Floseal and Gelfoam (Baxter International, Inc., Deerfield, IL) can be used when indicated. After conclusion of the laparoscopic portion of the procedure, the robot is undocked and cystoscopy and skin closure is completed as previously described.

Complications

In women undergoing robotic-assisted cystectomy, the overall complication rate is reported to be

3.7 percent (95 percent CI, -0.8 to 8.2 percent) (33). Complications include bleeding and inadvertent cyst rupture. Bleeding can usually be controlled with a judicious use of electrocautery with or without the application of hemostatic agents previously described. Another potential complication is injury to the ovary itself, resulting in impaired function. Ovarian preservation is crucial for patients desiring future fertility, and methods of obtaining hemostasis should not be overly destructive of the ovarian parenchyma. It has been shown in some studies that ovarian cystectomy can have a negative impact on ovarian reserve as measured by serum antimüllerian hormone (AMH) (43,44).

Another crucial concern regards rupture of the cyst during resection and removal. The frequency of intraoperative cyst rupture at laparoscopic cystectomy ranges from 6 to 27 percent and occurs more frequently than when performed through a laparotomy (36,37). Depending on the type of cyst, e.g., endometrioma, teratoma, or malignancy, inadvertent spillage of the contents may result in subsequent spread to other areas of the abdomen and pelvis or severe peritoneal irritation. The rupture of a malignant cyst is more serious as it may result in tumor dissemination, advancing stage of disease, and adverse impact to patient survival (36). If spillage occurs during any cystectomy, the pelvis should be copiously irrigated.

Robotic-Assisted Myomectomy

Myomectomy involves the surgical excision of leiomyomata from the surrounding normal myometrium in an attempt to resolve abnormal uterine bleeding, pelvic pain, mass effect, and infertility. The surgical technique of abdominal myomectomy was first developed by Bonney in 1931 as a procedure for women who wish to preserve their uterus or who declined hysterectomy (45). In 1979, Semm demonstrated that this operation could be performed with laparoscopic techniques (46). Robotic myomectomy followed on the successes of endoscopic surgery with specific advantages, especially to those surgeons with limited or no laparoscopic experience. The popularity and rapid adoption of robotic technique for myomectomy is predominantly due to the ease of suturing robotically

compared to laparoscopic technique. The fact that myomectomy is a suture-intensive surgery requiring a multilayered closure only further drives the conversion to the robotic approach (1). Robotic myomectomy has been reported to be as effective as classic open myomectomy with comparable safety and acceptance (47). The pregnancy outcomes following robotic-assisted myomectomy are also comparable to open surgery (48).

Preoperative planning requires delineation of leiomyoma size, number, and location. Sonography, magnetic resonance imaging, or hysteroscopy may all be utilized to evaluate the tumors (49). Abnormal uterine bleeding commonly occurs with leiomyomata, such that the presence of anemia should be assessed preoperatively. Numerous studies have shown the benefit of the administration of a GNRH agonist preoperatively to significantly reduce uterine volume and concurrently improve blood counts (50). When myomectomy is performed for fertility, antibiotic prophylaxis is advocated to reduce the risk of tubal adhesions that can be associated with pelvic infection (49) and typically consists of a first- or second-generation cephalosporin unless penicillin-allergic (51,52). Preoperative bowel preparation has not been shown to improve visualization but may be given in patients at increased risk of bowel injury as previously described.

Surgical Technique

The patient is positioned, prepped, and draped as previously described. A Kronner uterine manipulator (Cooper Surgical, Trumbull, CT) and Foley are placed. Port placement, docking, instrumentation, and positioning of assistants were as previously described but can vary by physician preference. In particular, a robotic tenaculum and monopolar spatula are useful for the dissection and enucleation of leiomyomata. The subserosa of the myomata can be injected with dilute vasopressin to decrease bleeding. A vertical incision is made over the leiomyoma using monopolar scissors. The myoma is grasped with a single-tooth tenaculum and placed on tension, while sharp and blunt dissection of the pseudocapsule surrounding the leiomyoma frees the tumor from normal myometrium. The risk of excessive bleeding correlates with uterine size, total weight of leiomyomas removed, and operative time (53). Sequential fulguration of the vascular supply to the tumors prior to transection is preferable to reduce bleeding. Smaller internal incisions into the myometrium may be required to excise all the tumors. If the endometrial cavity is entered, it should be closed by running a 3-0 or 4-0 delayed-absorbable suture (49). The surgeon should minimize the number of incisions on the uterus to reduce the risk of postoperative adhesion formation. In addition, care must be taken to avoid disrupting the fallopian tubes during the course of dissection and enucleation.

Once all the leiomyomas have been excised, the internal myometrial incisions are closed first with 0 delayed-absorbable suture. The myometrium is then sutured in layers to prevent hematoma formation and to secure hemostasis. Closure of serosal incisions is performed with 3-0 or 4-0 delayed-absorbable suture using a locking or baseball stitch. The pneumoperitoneum is transiently reduced to 5 mmHg to check for hemostasis prior to the placement of Interceed (Ethicon, West Somerville, NJ) adhesion barrier over the hysterotomy sites. Due to the recent FDA safety communication, we no longer use power morcellation for tissue extraction (54). Alternatively, we use the Alexis Contained Extraction System (Applied Medical, Rancho Santa Margarita, CA). The large containment bag carrying leiomyomas is inserted through the 10-mm trocar and placed in the pelvis near the uterus. The robot is undocked and the Alexis Contained Extraction System (Applied Medical, Rancho Santa Margarita, CA) is then deployed through the umbilical port for contained tissue morcellation. Alternatively, tumors may be removed through a posterior colpotomy or mini-laparotomy. Fascial and skin closure proceeds as previously described.

Complications

Bleeding complications are the most commonly encountered during myomectomy. Uncontrolled hemorrhage or massive myometrial injury during tumor removal can precipitate the need for hysterectomy. If significant adhesiolysis is required during the procedure, it is important to inspect the bowel for injury. Serosal injuries can be oversewn. An incidental or intentional enterotomy should be repaired by a qualified surgeon. Other operative complications include delayed bowel or bladder injury, fistula, hematoma, and adhesion formation.

While myomectomy is often performed to preserve fertility, postoperative adhesions can jeopardize the success of the procedure. Single, vertical, anterior, and midline uterine incisions induce adhesions that are less likely to compromise fertility (55). While

several adhesion barriers are available or are under development, none of them have been shown to be completely effective in preventing postoperative adhesions (56,57). It is equally important to counsel patients regarding the risk of uterine rupture during pregnancy after myomectomy. Fortunately, this risk is low at 0.75 percent but can be associated with significant fetal and maternal mortality when it does occur (58).

Robotic-Assisted Sacrocolpopexy

Pelvic organ prolapse (POP) is a common problem among women with an increasing incidence in the aging population. It is estimated that by 2050, 43.8 million women will be affected by at least one bothersome pelvic floor disorder, including prolapse (59). Sacrocolpopexy is one of several operations for the resuspension of the vaginal apex. It is preferred over other approaches when restoration of normal vaginal anatomy and durability of the repair are primary concerns (60). Long-term success rates for sacrocolpopexy range from 78 to 100 percent when success is defined as no postoperative apical prolapse, and from 58 to 100 percent when defined as no prolapse in any compartment (60).

Sacrocolpopexy provides durable support by attaching the vaginal apex and the anterior and

posterior vaginal walls to the anterior longitudinal ligament of the spine at the level of sacrum using a bridging graft. Although grafts of autologous, cadaveric, or synthetic materials may be used, permanent synthetic mesh has the best success rate and should be used unless otherwise contraindicated (61). Prior to sacrocolpopexy, patients with symptoms of urinary incontinence may undergo simple or complex urodynamic testing to determine the need for an antiincontinence procedure (62). Similarly, women without incontinence should also undergo testing with reduction of the prolapse to assess whether the repair will unmask occult incontinence. Alternatively, an antiincontinence procedure can be performed routinely at the time of sacrocolpopexy; however, the patient needs to be counseled regarding the risks and benefits of this approach prior to surgery.

When determining the appropriate surgical intervention for a specific patient, factors that influence the decision regarding approach include overall health, body habitus, presence of intraabdominal adhesions, and surgeon preference. Minimally invasive transabdominal sacrocolpopexy may be indicated for patients who have advanced prolapse, a large anterior defect, or those with a history of failed prolapse repair. Patients with a foreshortened vagina may also benefit from this approach, as transvaginal repair can result in further decrease in vaginal length (63). It is important to counsel the patient that even if a sacrocolpopexy is performed, concomitant vaginal prolapse repair for persistent cystocele or rectocele may be required, especially in cases of advanced prolapse (60).

The preoperative evaluation includes a history that assesses the degree of prolapse symptoms, the presence of urinary incontinence, as well as any past history of urologic or gynecologic surgery. If she has not had a hysterectomy, a discussion should be held as to whether she wishes to keep her uterus in situ or undergo a supracervical hysterectomy while retaining the cervix. Cervical cancer screening should be performed according to the currently published guidelines, for any woman aged 21 or older, with the exception of those infected with HIV who warrant screening at the time of diagnosis (6). Abnormal uterine bleeding and postmenopausal bleeding should be worked up per current guidelines to exclude malignancy (7,8). A complete physical examination, including a pelvic exam with a defined measurement of the prolapse (POP-Q), should be performed. As with any surgical procedure, a preoperative risk assessment should be conducted.

Different methods for minimally invasive sacrocolpopexy have been described in the literature. However, there is no consensus on how these procedures should be performed to have optimized outcome (64). Here we describe our technique as an option for performing robotic sacrocolpopexy.

Surgical Technique

The patient is positioned, prepped, draped, and instrumented as described previously. Side or parallel docking is preferred to allow access to the vagina, bladder, and rectum intraoperatively if needed. Port placement and conduct of the initial setup for the procedure are as previously described with variations relative to surgeon preference and clinical scenario.

After any necessary adhesiolysis, the procedure starts with the dissection of sacral

promontory since the completion of this portion is essential to complete the surgery. The bowel is gently swept out of the pelvis to the left and above the pelvic brim. Not infrequently, the congenital attachments of the sigmoid colon on the left must be taken down to mobilize the bowel out of the pelvis. The aortic bifurcation and iliac vessels are identified, and the sacral promontory is visualized and delineated at the midline. We identify the ureters coursing along the pelvic side wall, especially the right ureter, which is closest to the field of dissection. Once the promontory has been identified, the peritoneum overlying it is grasped and incised vertically with monopolar scissors.

It is important to be aware of the left common iliac vein, as this structure is frequently located more medial than the artery and can be injured during exposure of the promontory. The incision is extended caudally into the cul-de-sac, creating peritoneal leaves that are later used to cover the graft.

The anterior longitudinal ligament at sacral promontory is then identified and carefully cleared, taking care to avoid any sacral vessels as these may be difficult to control if interrupted. If bleeding is encountered, it may be controlled by applying direct pressure to the area of bleeding, increasing insufflation pressures to 20 mmHg, by bipolar coagulation of discrete vessels, or oversewing the source of bleeding with absorbable sutures. Laparoscopic thumbtacks may also be used to control bleeding from the presacral region (65). Ultimately, if hemostasis cannot be controlled



Figure 8.4 Dissecting the anterior longitudinal ligament. The anterior longitudinal ligament at sacral promontory is then identified and carefully cleared, taking care to avoid any sacral vessels.

laparoscopically, then the robotic procedure should be abandoned, laparotomy performed and bleeding controlled in the traditional open fashion.

The upper vagina and vaginal apex must be elevated and distended with a vaginal stent. This permits adequate dissection and visualization of fibromuscular layers of the vaginal wall and aids graft placement. The vaginal stent may be a large end-to-end anastomosis sizer, which is present in most operating rooms, a cylindrical Lucite rod, or the Colpassist Vaginal Positioning Device (Boston Scientific, Marlborough, MA). The vaginal stent is used to elevate the vaginal apex, and the peritoneum covering it is incised transversely. Sharp and blunt dissection is used to separate the peritoneum and bladder from the anterior vaginal wall. This anterior dissection extends approximately 5 to 6 cm caudally to create an adequate surface for graft fixation. Dissection should progress at a depth above the fibromuscular layer of the vaginal wall. Entry into the proper plane above the fibromuscular layer will decrease the risk of incidental entry into the vagina. Accidental opening of the vaginal wall increases the risk of future graft exposure especially when using synthetic mesh. If the vaginal wall is opened, it should be irrigated copiously followed by a two-layered closure with 2-0 or 3-0 delayed-absorbable suture. The vaginal apex is redirected anteriorly, and the peritoneum covering the posterior vaginal wall is opened. The rectovaginal space is identified and blunt dissection further

opens this space to the level of rectal reflection for a distance of about 6 cm.

The selection of sacrocolpopexy graft is at the preference of the surgeon. In general, if using synthetic mesh it should be lightweight, flexible, and porous (66). At our institution, a prefabricated Y-shaped mesh is employed. The mesh is placed into the peritoneal cavity through the assistant's 10-mm cannula and guided into place. The graft may be secured to the anterior and posterior vaginal walls with delayed-absorbable or permanent suture or a combination of both.

Some studies have shown equivalent long-term outcomes with the use of absorbable suture compared with permanent suture for sacrocolpopexy mesh fixation (67).



Figure 8.5 Dissecting the rectovaginal space. The avascular space may be bluntly dissected.

Once the anterior and posterior arms of the mesh have been secured to the vagina, the tail is extended toward the promontory. The graft is then tensioned to replicate normal vaginal compliance, as excessive tension can result in pain or de novo stress urinary incontinence (60). Tensioning can be performed through visual or direct vaginal examination techniques depending on surgeon preference and experience. The apical suspension should reduce prolapse of the apex as well as the apical segments of the anterior and posterior vaginal walls.

The apical tail of the graft is sutured to the anterior longitudinal ligament at the level selected by the surgeon. Traditionally suture placement is at S3 or S4 to recreate the normal axis of vagina; however, that approach increases the risk of injury to presacral venous plexus. Alternatively, placement of sutures at S1 or sacral promontory risks laceration of the middle sacral vessels or the left common iliac vein (68). The middle sacral vessels, however, are readily visible and can be isolated and avoided. Additionally, at S1 the anterior longitudinal ligament is thicker, which minimizes the risk of suture avulsion. For these reasons, many surgeons currently choose to fix the graft at S1, the level of sacral promontory (60).

The peritoneum is closed over the vaginal apex with 2-0 delayed-absorbable suture in a running fashion.

Cystoscopy is performed to rule out thermal or mechanical bladder injury, intravesical suture or mesh perforation, and to confirm ureteral patency. The robot is then undocked and port sites are closed as previously described.

Complications

Several important perioperative complications are inherent to both minimally invasive as well as open sacrocolpopexy. These include the risk of vaginotomy, cystostomy, ureteral injury, enterotomy, as well as



Figure 8.6 Suturing the graft to the anterior vagina. The mesh is sutured to the vagina with 2-0 delayed-absorbable suture.

mesh extrusion or perforation (69). Significant hemorrhage can develop during dissection and suture placement at the anterior longitudinal ligament. A thorough knowledge of pelvic anatomy is essential to prevent and manage intraoperative hemorrhage. The most common vessels lacerated during sacrocolpopexy are presacral venous plexus and middle sacral vessels. To control acute hemorrhage, several steps are critical. First, pressure is applied immediately and held for several minutes. This is particularly effective for venous bleeding. Sutures and clips may be employed, but injury of small veins traversing the sacrum frequently worsens with suturing. Additionally, as vessels retract into the foramina, isolation and ligation become difficult if not impossible. Although no studies have compared these agents for use in urogynecologic procedures, animal and vascular studies have shown FloSeal Matrix (Baxter International, Inc., Deerfield, IL) to be very effective (70–72).

Other complications include discitis after sacrocolpopexy, likely from suture placement into the vertebral disk at the time of surgery (73).

Following sacrocolpopexy, the graft material or its attaching sutures can expose through the vaginal muscularis and mucosa. This is a frequently cited complication of the procedure,

but fortunately is uncommon and only develops in 2–5 percent of cases (74,60). Symptoms of exposure can develop on an average of 14 months following surgery and classically consist of vaginal bleeding and discharge (75). During speculum examination, mesh or sutures can usually be directly visualized.

Failure of the procedure to cure prolapse is an additional concern. A meta-analysis of data from 21 studies noted that the overall recurrence rate of prolapse after sacrocolpopexy was 6.4 percent (3.4, 0.4, and 2.6 percent for anterior, apical, and posterior compartments, respectively) (76). The reoperation

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Figure 8.7 Closing the peritoneum. The peritoneum is closed from the vaginal apex to the sacral promontory with 2-0 delayed-absorbable suture in a running fashion.

rate was approximately 3 percent with 63.6 percent of those being posterior colporrhaphies (77). Overall, sacrocolpopexy is considered to be a durable and highly successful procedure.

In order to increase minimally invasive procedures for the repair of POP, the robotic-assisted and laparoscopic surgical approaches have been demonstrated to be feasible and are gaining popularity among pelvic floor reconstructive surgeons. Although outcome data for robotic-assisted sacrocolpopexy is only just emerging, several small series have demonstrated anatomic and functional outcomes, as well as complication rates, comparable to those reported for open surgery (78).

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Part 6 Research Design (Cont.)

Urologists have been at the forefront of the development and use of robotic technology. The first robot-assisted laparoscopic prostatectomy was performed in 2000. The FDA approved the da Vinci Robotic Surgical System in 2000. Its use has increased dramatically over the years, notably among urologists. Current residents and recently graduated urologists are almost universally exposed to robotic surgery. The field of robotics is ever changing. Advances are being made in the fields of telementoring and telerobotics as well as design changes making robotic surgery in combination with imaging such as MRI or CT more feasible. The field of urology has been quick to embrace technology and robotic surgical assistance, utilizing this technology for oncologic, urogynecologic, reconstructive, and pediatric urological cases.

Assistance during these operations is critical. Bedside assistants help with retraction, suction of the surgical field, placement of clips, passage of suture, use of a stapler, manipulation of the Foley catheter, removal of surgical specimen, etc. Clear communication between surgeon and assistant and surgeon and anesthesiologist is crucial for patient safety, operative technique, and patient outcomes.

Prostatectomy – Radical and Simple

In 2015, 220,800 men were diagnosed with prostate cancer, and 27,540 men died of the disease. Over

2.7 million men are living with prostate cancer in the United States currently (Howlader et al., n.d.). Overall, it is one of the most common conditions treated by urologists and is the most common urologic malignancy. In 2011, more than 80% of radical prostatectomies were performed with the assistance of a robot. While the cost of the robotic approach leads to criticisms, there are clear benefits (Skolarus et al., 2010). Further studies are ongoing, but with the widespread dissemination of robots into hospitals and

ever-increasing number of urologists trained on the robot, robotic-assisted laparoscopic prostatectomies will likely remain the surgery of choice for prostate cancer treatment.

Radical Prostatectomy

This operation involves removal of the entire prostate gland and seminal vesicles, with reconnection of the urethra directly to the bladder to restore continuity of the genitourinary tract. This is typically done for prostate cancer. It is one of the most common procedures utilizing robotic assistance, across all specialties. The original radical prostatectomy was performed in 1905 via a perineal approach, which was then modified to the lower abdominal extraperitoneal approach (McDougal et al., 2011).

Standard laparoscopy was tried for prostatectomy, but proved to be extremely difficult secondary to the lack of articulating instruments, which makes working in a deep, small space, such as the pelvis, difficult. While oncologic outcomes have not been proven to be superior to the standard open approach, blood loss, transfusion rates, and hospital length of stay have been improved with the robot. Incontinence and erectile dysfunction, two of the most common and significant complications of prostatectomy, are similar between open and robotic approaches (McDougal et al., 2011).

Most surgeons elect for a light bowel prep pre-operatively as the anatomy of the prostate is in very close proximity to the rectum, and rectal injury is possible. We routinely instruct our patients to drink clear liquids the day before surgery, along with a bottle of magnesium citrate. This allows for a cleaner field if rectal injury occurs. Anticoagulation is left to the discretion of the surgeon, but most elect to hold all anticoagulants preoperatively. Unlike open radical prostatectomy, the rates of transfusion are low and many surgeons do not routinely type and screen

patients. However, for simple prostatectomy, most surgeons will have blood readily available due to the risk of significant hemorrhage.

The operating suite is generally set up as shown in Figure 9.1. We do not administer pharmacologic DVT prophylaxis, but all patients have thromboembolic stockings and sequential compression devices for mechanical DVT prophylaxis. The patient is placed under general anesthesia with paralysis. It is our practice to have two large bore IVs with no need for arterial or central lines. An orogastric tube is placed for stomach decompression. The arms are tucked and the patient is placed in the low lithotomy position. Care is taken to ensure that the legs are well supported to avoid nerve injury, usually using Yellowfins[®] stirrups. A strap is placed across the chest to secure the patient to the table on nonskid padding, such as the Pink Pad[®], which limits patient shifting with bed movement. The patient is placed in maximal Trendelenburg position to allow the bowels to move cranially out of the pelvis (Figure 9.2). The abdomen, upper thighs, and genitalia are prepped using chlorhexidine. A Foley catheter

is placed after draping, which will be changed prior to the end of the procedure.

Entry into the abdomen is established just superior to the umbilicus, either using a Veress needle or the open Hasson technique. This location will be the camera port. As with any procedure involving the establishment of pneumoperitoneum, the anesthesiologist should watch for hypercarbia and oliguria. Communication between surgeon and anesthesiologist is key should pneumoperitoneum pressures need adjustment. If inguinal hernias are present, the scrotum may enlarge and fill with a significant amount of air, which should be manually decompressed at the conclusion of the procedure.

Once the 12-mm camera port is inserted just above the umbilicus, three 8-mm robotic trocars and a 12-mm assistant trocar are placed. The robot is docked between the patient's legs. Monopolar scissors are placed in the right hand, bipolar Maryland forceps in the left hand, and a ProGrasp[™] in the fourth arm (located on the left). The assistant sits on the patient's right.



Figure 9.1 This is the typical room setup for robotic cases. Note the position of the patient, anesthesia cart, console, and robot. This is an example of the non-skid pad which is useful to limit patient movement when placing in Trendelenburg.



Figure 9.1 (*continued*)

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Figure 9.2 This is typical positioning for a RALP. The patient is in Trendelenburg. All pressure points are padded including padding around any pressure points on the legs. The arms are tucked and a chest strap is in place. A non-skid pad limits the patient from sliding towards the head.

Upon entering the abdomen, adhesions are lysed. The sigmoid colon is freed and retracted out of the pelvis using the fourth arm. The procedure can then be accomplished working first anterior then posterior, or posterior then anterior. We typically perform a posterior approach and will describe this here. The peritoneum overlying the seminal vesicles and vasa deferentia is incised. The vas and seminal vesicles are dissected free bilaterally. The vasa are clipped and amputated. The posterior prostate is then dissected from the rectum moving caudally, along Denonvillier's fascia. Care is taken during this step to avoid rectal injury. This completes the posterior dissection.

We then move anteriorly and drop the bladder from the anterior abdominal wall between the medial umbilical ligaments. This opens the potential space of Retzius and is a filmy alveolar layer with minimal bleeding. This allows entry into the pelvis. Care is taken during these steps to ensure no injury to the inferior epigastric vessels. The lateral endopelvic fascia is then incised and the levator ani muscles are dissected laterally, exposing the lateral edges of the prostate. Anteriorly, care is taken to maintain the musculature as much as possible as these muscles control continence. If clinically indicated, the external, internal, and obturator lymph nodes are dissected and sent to pathology to complete staging. Care is taken during these steps to ensure no damage to the iliac vessels, which may result in significant hemorrhage. Additionally, avoiding electrocautery around the obturator nerves is crucial to avoid stimulating an obturator reflex (adduction of the ipsilateral leg). Some surgeons use clips to control lymphatics to minimize postoperative lymphocele formation.

The dorsal venous complex is controlled. We use suture ligation tacked up to the posterior pubic rami to ensure adequate tensioning. This step is crucial as the dorsal venous complex can be a significant source of bleeding, which makes visualization during the remainder of the operation difficult. The junction between the bladder and prostate is then identified and then opened horizontally until the catheter is identified. It is important to ensure the

bladder neck opening is small to improve continence rates and to avoid tailoring prior to anastomosis. It is also important to avoid ureteral injury. Once the bladder is opened, hematuria and/or decreased urine output is expected as urine drains into the abdominal cavity. The Foley catheter bag may fill with air as the pneumoperitoneum equalizes pressure via the exposed Foley catheter. The Foley catheter is then manipulated to alter exposure and the posterior bladder neck is transected. Dissection through the bladder neck has now reached our previous posterior dissection.

The prostatic pedicles are then controlled using clips or electrocautery. The dissection is then taken laterally and caudally releasing the prostate from its posterior and lateral attachments. This dissection is very important for the preservation of erectile function, and the nerve plexus responsible for erections lies in very close proximity. If possible, these nerves are spared, minimizing electrocautery in this plane. The apex of the prostate is then transected, the Foley removed, and the prostate is tucked into the lower abdomen near the assistant port. At this point, all major bleeding has ceased.

The pelvis is irrigated. Insufflation pressures are lowered to assess for hemostasis. The posterior urethrovesical anastomosis is then performed using an absorbable suture. Once

the posterior plate of the anastomosis is completed, the Foley is replaced with a larger one, typically 18 Fr, under direct vision to ensure proper position of the catheter in the bladder. The anastomosis is completed and tied. It is then leak- tested with retrograde filling of the bladder with water or saline via the Foley catheter. Surgeons may leave a drain in the pelvis if the anastomosis is not water- tight. The prostate is placed in a specimen bag and the robot is undocked. The specimen is extracted through the camera port site. Only the fascia at the extraction site is closed. The trocar sites are then closed using absorbable sutures.

The Foley catheter typically remains in place for one week postoperatively. If there is concern over healing of the anastomosis, the catheter may be left longer and a cystogram may be performed to evaluate for leakage.

Certain patient characteristics must be taken into consideration by both the surgeon and anesthesia team:

Obesity – Extra tissue and the steep Trendelenburg position may compromise the patient's

respirations and may allow for shifting with extreme positioning. Obese patients are at high risk for compression nerve injury. Standard open prostatectomy is technically more difficult in the obese patient due to difficulty reaching the deep pelvis, thus a robotic approach may be preferred for these patients. If necessary, bariatric instruments are available and trocars can be moved caudally to improve access to the pelvis with the robotic arms. In addition, obese patients are more likely to suffer from a deep venous thrombosis, and the decision to utilize both mechanical and chemical prophylaxis must be weighed preoperatively (Su, 2011).

Salvage procedures – These include patients who have undergone prior treatment of the pelvis, typically radiation and/or radioactive seed placement. This increases the level of difficulty of the operation and increases the chance of complications such as rectal injury and hemorrhage.

Prior abdominal surgery – This may increase operative times due to adhesions or difficulty entering the abdominal cavity if mesh was used for hernia repairs. Open Hasson technique should be utilized to gain access into the abdomen in patients at risk for adhesions. One can also perform a minilaparotomy with open adhesiolysis to safely place ports prior to RALP. The incision can then be closed around the camera port.

Hernia repair surgery can distort pelvic anatomy. Care must be taken to identify landmarks early on and throughout the case. The urachus and medial umbilical ligaments are common starting points to allow entry into the retropubic space. Care must be taken to dissect deep to any mesh that was previously placed during the hernia repair (Su, 2011).

Large prostate or median lobe – Large prostates may limit surgical advancement by limiting space in the pelvis for dissection and retraction. Early control of the dorsal venous complex is utilized to attempt to limit bleeding into the surgical field. Large prostates also often have increased vascularity, which can complicate dissection. Median lobes distort anatomy of the bladder neck dissection.

Care must be taken to ensure all prostate tissue is resected while preserving the ureteral orifices as they are closer to the prostatic base than in patients without a large median lobe (Su, 2011).

Simple Prostatectomy

This procedure treats benign urinary obstruction of the prostate, with glands that are too large to be efficiently treated by more traditional methods, i.e., transurethral resection. The posterior zone (where cancer typically develops) is left during subtotal resection; only the anterior and transition zones are removed. This procedure is very similar to the radical prostatectomy with respect to preparation and positioning. Only the obstructing glands of the prostate are removed; thus, the urethra and bladder are not cut and the urinary tract remains in continuity.

An important difference between the radical and simple robotic prostatectomy is an

increased risk of hemorrhage with simple prostatectomy. Measures are utilized to mitigate this risk such as arterial line use and readily available blood products. Additionally, the patient typically is placed on continuous bladder irrigation at the conclusion of the case due to significant hematuria.

Port placement and access to the abdomen are similar to the technique used for radical prostatectomy. The bladder is mobilized and the space of Retzius is entered. The anterior prostatic capsule is identified and the dorsal venous complex is ligated as for a radical prostatectomy. The bladder is opened transversely on the anterior surface of the junction of the bladder and prostate. Care should be taken to identify the ureteral orifices as they are often very close to the enlarged prostatic tissue. Ureteral stents can be placed to have continuous identification of the ureteral orifices if indicated. Next, the prostatic adenoma is identified and retracted, allowing the adenoma excision beginning posteriorly. The plane between capsule and adenoma is identified and the adenoma is dissected from the capsule circumferentially, from base to apex. Careful attention is paid near the apex to avoid inadvertent damage to the urethral sphincter. Hemostasis is achieved with suture ligation, which is typically needed at the 4 and 8 o'clock positions where the vasculature is located. A large three-way Foley catheter is placed into the urethra and bladder and filled with approximately 30 cc of fluid. The cystotomy is closed in a two-layer manner to ensure that it is watertight. This can be tested by instilling fluid into the bladder retrograde via the catheter and watching for leakage. Finally, the specimen is removed and the port sites are closed after extraction of the trocars.

Nephrectomy – Radical, Simple, and Partial

The use of robotic assistance for renal surgery has become common. Traditional open renal surgery typically involves a large flank incision, which is very painful. Urologists are increasingly using laparoscopic and robotic assistance during renal surgery. Studies comparing robotic renal surgery to open renal surgery commonly find decreased blood loss, pain, post-operative hospitalization, and use of narcotics for the robotic group (Emtage et al., 2015). Patients also tend to prefer the superior cosmesis of a minimally invasive approach.

Renal surgery has shifted from removal of the entire kidney to removal of only the diseased part of the kidney, depending on tumor size and location. A radical nephrectomy includes removal of everything within Gerota's fascia, i.e., the entire kidney and adrenal gland, while simple nephrectomy implies removal of the entire kidney, but not everything else contained within Gerota's. A partial nephrectomy removes only a part of the kidney, leaving some remaining kidney in situ. As a group, urologists are performing more partial nephrectomies to spare nephrons and preserve as much renal function as possible. This is becoming increasingly important in patients with comorbidities that can affect renal function.

A formal lymph node dissection is rarely performed unless clinically indicated. Renal cell carcinoma may involve a tumor thrombus extending into the renal vein, inferior vena cava, or heart. Tumor thrombus does not preclude use of robotic technology, but makes resection significantly more challenging. Robotic resection involving tumor thrombus is usually used only at high-volume centers with highly experienced surgeons.

Radical and Simple Nephrectomy

Bowel prep is not typically used preoperatively unless there is concern about potential colon injury during resection. Anticoagulation is left to the discretion of the surgeon, but most elect to hold all anticoagulants preoperatively. Preoperatively, renal function is assessed and patients are counseled on the risk of postoperative renal impairment. We do not administer pharmacologic DVT prophylaxis, but all patients have thromboembolic stockings and sequential compression devices for mechanical DVT prophylaxis.

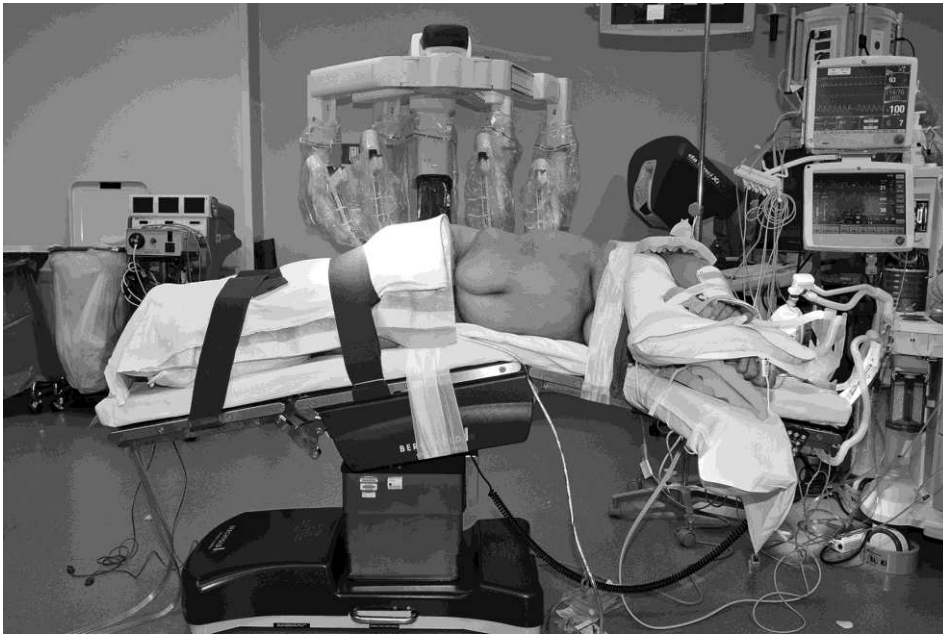


Figure 9.3 Flank positioning is frequently used for robotic surgery on the kidney. An axillary roll is placed and the lower leg is bent 90 degrees at the knee. Pillows are utilized to pad and position the arms. Silk tape secures the hips and chest to the table and the bed is then flexed to open the space below the ribs and above the iliac crest.

We advocate for preoperative imaging to be readily available in the operating suite, either on a large TV monitor or a nearby computer throughout the case, for reference if necessary.

The operating suite is generally set up as for prostatectomy, regardless of which side is being operated on. The patient is placed under general anesthesia with paralysis. It is our practice to have two large-bore IVs. Again, we do not routinely place arterial or central lines. An orogastric tube is placed for stomach decompression, and a Foley catheter is placed for bladder decompression. The patient is placed in the modified or full flank position with the affected kidney up toward the ceiling. This allows the bowels to fall away from the kidney. An axillary roll is placed along with a roll behind the patient's back for support. The lower leg is bent to 90 degrees. Numerous pillows are placed between the legs to support the top leg. The arms are carefully secured using pillows, ensuring no nerve injury and that the arms will not slip during the procedure. The hips and chest are secured to the table using silk tape. The bed is flexed to maximize working space between the costal margin and iliac crest (Figure 9.3). If necessary, the bed is then rotated, turning the patient's back toward the robot for docking. Communication between all members of the operating team is important during this step to ensure the endotracheal tube and lines remain in proper position. The patient is then prepped with chlorhexidine and draped.

Entry into the abdomen is established, either using a Veress needle or the open Hassan technique. The costal margin is palpated as the most cranial robotic port. The remaining ports are then chosen to allow adequate working space. Three or four arms may be used based on surgeon preference. The 12-mm camera port is placed first, and then 8-mm ports are placed under direct vision. Assistant port number and location is per surgeon preference, with many variations currently in use. The assistant sits on the patient's abdominal side. If working on the right side, a 5-mm trocar is placed just under the xyphoid process. A locking grasper is used to retract the liver cranially off the right kidney. The robot is docked from the patient's back. Monopolar scissors are placed in the right

hand and bipolar Maryland forceps in the left hand. If the fourth arm is used, it is the most caudal arm, and usually a fenestrated bipolar instrument is used.

The colon is reflected medially along the white line of Toldt, from the iliac vessels to the diaphragm, exposing the retroperitoneum. Care is taken to avoid injury to the colon during this step. On the left, the splenorenal ligament is divided allowing the spleen to fall medially. The tail of the pancreas is in close proximity, and care is taken to avoid injury during the resection. On the right, the hepatorenal ligament is divided releasing the liver cranially. Also on the right, a Kocher maneuver is performed to release the duodenum medially.

Moving toward the inferior pole of the kidney, the ureter is identified and elevated off the psoas muscle. This dissection is carried cranially toward the lower pole of the kidney and then the renal hilum. On the left, the gonadal vein courses with the ureter and can be traced directly up to its insertion into the renal vein. On the right, the gonadal vein enters the IVC directly, and thus care is taken not to tear the gonadal vein from the IVC, which would lead to significant bleeding.

The renal hilum is identified. A window above and below the hilum is created and a stapler is usually employed to control and divide the hilum – this is done by the assistant through the assistant port. All personnel scrubbed for the case need to be well versed in loading, operation, and troubleshooting of the stapler. Additional loads must be readily available in case of hemorrhage.

The upper pole of the kidney is freed. Care must be taken near the adrenal vein as it can cause significant bleeding. The decision to remove or spare the adrenal gland depends on certain tumor and patient characteristics. This should not affect the hypothalamic–pituitary–adrenal axis as the patient has a remaining contralateral adrenal gland. The posterior and lateral renal attachments are freed leaving the ureter as the only remaining attachments. This is then clipped and amputated. The kidney is placed in a specimen bag and extracted, with the site of extraction being left to surgeon preference. Only the fascia at the extraction site is closed. Trocar sites are then closed using absorbable sutures. A drain is not typically placed unless there

is concern for bleeding.

Partial Nephrectomy

Studies indicate that the adoption of robotic surgery by urologists has increased the rate of performing partial nephrectomies rather than a radical nephrectomy on small renal masses. The dexterity and visual detail provided by the robot have made this possible and more nephrons are spared as a result. Laparoscopic

surgery decreases blood loss and length of stay for partial and radical nephrectomies as compared to open surgery (Skolarus et al., 2010).

Partial nephrectomy may be performed by one of two approaches, transperitoneal or retroperitoneal. The decision on which to employ is based on numerous factors, including tumor location, body habitus, surgical history, and surgeon experience. Retroperitoneal surgery avoids entry into the peritoneal cavity and would be preferable to avoid anticipated intraabdominal adhesions and decrease bowel manipulation. This has been shown to reduce postoperative ileus (Emtage et al., 2015). Posterior renal masses can be difficult to safely access transperitoneally and are thus best suited for the retroperitoneal approach.

Preoperative preparation for partial nephrectomy is similar to radical nephrectomy. Most surgeons will type and cross a patient and have blood readily available due to the increased risk of bleeding during this procedure, and anesthesia will often place an arterial line due to this risk. Mannitol and Lasix, if used by the surgeon, should be available and drawn up prior to induction of anesthesia. Some surgeons believe these diuretics help protect renal function through an osmotic diuresis and free radical scavenging, thus theoretically protecting against ischemic damage (Mir et al., 2015). Operating suite setup and patient positioning are similar to radical nephrectomy.

For the transperitoneal approach, access into the abdomen and initial steps to the operation are also similar to radical nephrectomy. The colon is reflected and the ureter elevated to allow dissection cranially toward the renal hilum. Once the hilum is identified, the artery is carefully dissected circumferentially if selective artery only clamping will be employed. Gerota's fat overlying the kidney is opened and the kidney is mobilized adequately to identify the renal mass and allow adequate exposure for excision and repair. Again, imaging must be readily available intraoperatively for constant reference. Intraoperative ultrasound, controlled by either the assistant or surgeon, is used to delineate the renal mass from its surrounding

parenchyma. Mannitol and Lasix, if desired, are administered, ideally 10 minutes prior to vascular clamping. The renal capsule is scored around the tumor, leaving an adequate margin of normal renal tissue.

Prior to clamping, communication with all members of the operative team is imperative to ensure all supplies are readily available and that anesthesia is ready for potential blood loss. Personnel handoffs should be minimized during clamping. The hilum (or artery only) is clamped using a bulldog clamp introduced through the assistant port. A timer is started to monitor warm ischemia time. The tumor is then sharply excised. Some surgeons choose to control obvious vessels with clips during this dissection. The tumor is removed and tucked cranially under the diaphragm. The renal bed is then oversewn using an absorbable suture with a Lapra-ty® on the free end. Another Lapra-ty®, placed by the assistant, is used to tension this hemostatic stitch. The clamp is removed, the timer stopped, and hemostasis is assessed. Warm ischemia time less than 20 minutes is ideal to minimize ischemic damage to the remaining renal parenchyma. Another dose of Mannitol and Lasix is given, if desired. Additional vessels are oversewn as needed. The renorrhaphy – closure of the renal defect – is then performed using a larger absorbable suture with Hem-o-lock® and Lapra-ty® clips. These are cinched down and secured using more clips. The assistant passes all necessary sutures and clips.

Hemostatic agents may be placed over the renorrhaphy. Gerota's may be secured over the renal defect. A drain is left at the discretion of the surgeon, more often during partial nephrectomy than radical or simple nephrectomy. The kidney is placed in a specimen bag and extracted, with the site of extraction being left to surgeon preference, most commonly through the camera port site. Only the fascia at the extraction site is closed. All trocar sites are then closed using absorbable sutures.

For the retroperitoneal approach, positioning is the same as previously described. The camera port is placed above the iliac crest and lateral to the triangle of Petit. The lumbodorsal fascia is opened so that the finger can gently sweep away the peritoneum

and create a small space within the retroperitoneum. A balloon dissector is inserted and inflated under direct vision to create a working space. The balloon is removed and the camera is replaced in this area. The rest of the ports are placed. The robot is docked over the patient's head and parallel to the patient's spine. It is essential that anesthesia prepare for this setup. Drapes are not secured during this case at the patient's head due to need for robotic arm mobility. Fat surrounding the kidney is dissected away until Gerota's fascia is identified and then opened. The kidney and perinephric fat is elevated until the hilar vessels are identified. The renal artery and vein are identified and dissected free to allow

clamp placement. The remainder of the operation is similar to transperitoneal partial nephrectomy. Care must be taken during this operation to avoid entry into the peritoneum with port placement or during dissection (Ghani et al., 2014). Overall, the retroperitoneal approach is equivalent to the transperitoneal approach with respect to blood loss, alteration in renal function, and warm ischemia time. In one study, the retroperitoneal approach has been shown to decrease operative and hospital time compared to the transperitoneal approach (Stepanian et al., 2015).

The kidney is very vascular, receiving about 20 percent of total cardiac output. Bleeding is thus a challenge and concern for surgeons. This may be manifested as hemodynamic instability or hematuria intraoperatively, if the collecting system is entered. Immediately postoperatively, tight blood pressure control and bedrest can minimize the risk of bleeding. Blood counts are periodically checked. Should there be significant bleeding that does not respond to conservative measures such as transfusion or bedrest, embolization by interventional radiology is usually the next step. Entry into the collecting system may occur during tumor excision. The collecting system is usually repaired with a running absorbable suture to prevent urine leak. A drain should be placed if the collecting system is entered to monitor for urine leak. Placement of a JJ ureteral stent in an antegrade fashion may also be employed.

Nephroureterectomy

Nephroureterectomy is utilized in the treatment of carcinoma of the ureter or renal pelvis, termed upper tract urothelial cell carcinoma (UTUC). Due to the rarity of UTUC, this procedure is not commonly performed and will not be described in great detail here. However, it is worth mentioning because of the recent Xi robotic system that has been developed.

This procedure involves removal of the entire kidney, entire ureter, and a cuff of bladder around the ipsilateral ureteral orifice. Thus, access to both the upper abdomen

and lower pelvis is necessary to complete the operation. The kidney work can be done as described for a nephrectomy, but the bladder work cannot be done with ports in the described locations. With the previous S and Si models of the robot, the robot needed to be undocked, additional ports placed to work in the pelvis, and then redocked. One of the main advantages of the newest Xi system is the ability to manipulate the arms of the robot to perform multiquadrant surgery, such as that needed for nephroureterectomy.

Cystoprostatectomy with Reconstruction

The cystoprostatectomy for the treatment of bladder cancer involves removal of all organs of the anterior pelvis – bladder, prostate, seminal vesicles in men and bladder, vagina, uterus, fallopian tubes, ovaries in women. The procedure also calls for an aggressive lymph node dissection, removing the common, external, and internal iliac and obturator lymph nodes. Negative lymphadenectomy of at least 12 nodes is a positive prognostic indicator (McDougal et al., 2011). The rate of robotic cystectomies is increasing. Between 2004 and 2010, robotic cystectomy increased from

0.6 percent to 12.8 percent (Lau et al., 2015). This new approach has been proven to decrease transfusion rates and blood loss. Operative time may be longer than the traditional open approach, but hospital course tends to be shorter for surgeries undergoing robotic assistance (Skolarus et al., 2010; Lau et al., 2015).

Bladder cancer generally affects older men with significant comorbidities. Some surgeons elect for neoadjuvant chemotherapy for muscle-invasive bladder cancer, often consisting of regimens of methotrexate, vinblastine, doxorubicin, and cisplatin, or gemcitabine and cisplatin. There is clear data that neoadjuvant chemotherapy can achieve a complete pathologic node response in select patients (Zargar-Shoshtari et al., 2016). Chemotherapy has many obvious side effects, with two important ones being weight loss and malnutrition. These need to be minimized to allow patients to maintain adequate nutritional status. Once the bladder and associated structures are removed, the ureters need to

somehow be diverted so all urine can drain externally. This involves use of bowel to create either continent or incontinent diversions. Details of these different diversions are beyond the scope of this chapter, but suffice it to say that the creation of an ileal conduit is the most common diversion. It is an incontinent diversion and has the lowest complication rate of all diversion options but does require an external urostomy appliance for urine collection. Continent diversions have higher complication rates such as stones, incontinence, or inability to catheterize and are more complex to perform. Also, continent diversions require the patient to perform some type of catheterization program with irrigations (Farnham & Cookson, 2004).

Cystectomy surgery carries the highest rate of morbidity and mortality of all major urologic oncologic operations. The overall complication rate is 48 percent, with a 20 percent rehospitalization rate and 4.2 percent mortality rate (Lau et al., 2015). The need for mobilization and resection of bowel to create a urinary diversion makes patients at high risk for postoperative ileus and bowel obstruction. Prolonged hospital stays put patients at risk for urinary tract infections, venous thrombosis, pulmonary embolism, and pneumonia. Many studies look at the care of these patients intraoperatively and postoperatively to attempt to define pathways and decrease complications in this population.

Preoperatively, the patient meets with the ostomy nurse, who educates the patient on what to expect and marks the patient's future stoma site. This mark must persist until the operation is performed to allow for correct stoma localization when created. A formal bowel preparation is ordered preoperatively due to the harvesting of bowel to create the diversion as well as the risk of rectal injury. Some surgeons elect to check nutrition labs preoperatively to optimize wound healing after major surgery, as malnourishment increases perioperative morbidity and mortality (Cerantola et al., 2013). Anticoagulation is left to the discretion of the surgeon. Due to the high risk of thromboembolic events and the length of time of the procedure, most surgeons will administer some type of

pharmacologic prophylaxis in addition to mechanical measures, prior to the induction of anesthesia. Like the radical prostatectomy, robotic cystectomy has decreased blood loss compared to the open version of the procedure, so patients are usually typed and screened preoperatively, but blood does not need to be readily available.

The operating suite is generally set up just as for a robotic prostatectomy. The patient is placed under general anesthesia with paralysis. It is our practice to have two large-bore IVs and an arterial line. An orogastric tube is placed for stomach decompression. The arms are tucked and the patient is placed in the low lithotomy position similar to a radical prostatectomy. The patient is again placed in maximal Trendelenburg position on nonskid padding, such as the Pink Pad®, and prepped and draped just as for prostatectomy. A Foley catheter is placed after draping, which will be removed prior to the end of the procedure.

Entry into the abdomen and port placement are performed the same as for a radical prostatectomy. We

attempt to place the right hand port where the stoma is marked, if possible. The assistant sits on the patient's left. The robot is docked between the patient's legs. Monopolar scissors are placed in the right hand, bipolar Maryland forceps in the left hand, and a ProGrasp™ in the fourth arm located on the right. An additional suprapubic 12-mm port will be placed when the diversion portion of the procedure occurs.

We begin by reflecting the descending and sigmoid colon medially along the white line of Toldt. We then identify the ureter on the left, dissecting this free distally and proximally to allow significant mobility. The distal ureter is clipped and amputated. A margin is sent for frozen section to confirm no malignancy. On the left, it is imperative that the ureter is adequately freed as the ureter will pass under the sigmoid mesentery to the right side to be plugged into the ileal conduit. If the margin is positive, a more proximal margin is sent until a negative margin is achieved. We then proceed with the lymph node dissection, which removes the common, internal, and external iliac nodes along with the obturator nodes. Dissection around these large vessels has potential for significant bleeding should vascular injury occur.

The posterior dissection is done as with a radical prostatectomy, clearing the prostate from the rectum posteriorly. The anterior dissection is also performed like a radical prostatectomy. This allows us to identify the lateral pedicle of the bladder and prostate, the only remaining attachments laterally, which is controlled with a stapler through the assistant port. These steps are repeated on the right side. The apex of the prostate is then transected and the specimen is freed. The specimen is placed in a bag and tucked deep into the pelvis. The urethra remains in place in a man. In a woman, the specimen contains the uterus, fallopian tubes, and ovaries, and the surgeon then performs a urethrectomy, due to the short length of the urethra, from a perineal approach. The vagina is then oversewn from this same approach to close the dependent portion of the pelvis.

A window is created bluntly behind the sigmoid mesentery and the left ureter is passed under the sigmoid, through this window, to the right side. Next the diversion is created. An ileal conduit will be described here, as it is the most common diversion and what we routinely perform. This may be done completely intracorporally or alternatively using a small lower midline laparotomy incision, per surgeon's preference. A 15–20-cm portion of ileum is isolated about

20 cm from the ileocecal valve using a stapler through an additional suprapubic 12-mm port. This allows the terminal ileum to remain in place, as this has important absorptive function of vitamin B12. The length of the conduit depends on the patient's body habitus and has important metabolic consequences as patients develop a hypokalemic, hyperchloremic metabolic acidosis with longer segments producing more profound derangements. The conduit, however, needs to reach from the peritoneal cavity to the patient's skin, which can be a great distance in the obese patient.

Bowel continuity is restored creating a side-to-side anastomosis, again with a stapler through the suprapubic port. The conduit segment is placed under the bowel anastomosis. The ureters are then connected to the conduit using an absorbable suture. Prior to finishing each anastomosis, the assistant introduces ureteral stents through the left lateral assistant port. These are placed up into the kidneys and into the conduit. These will be expelled on their own in the coming weeks, but may require cystoscopic removal if they remain in place. These stents protect the anastomosis while healing and ensuring adequate draining of the kidneys. We typically use a few additional sutures to reinforce our anastomosis as the majority of our patients are at risk for poor wound healing due to our aggressive use of neoadjuvant chemotherapy.

At this point, the robotic portion of the procedure is complete. The robot is undocked and the specimen is extracted through the midline camera port incision, which is extended as needed. The stoma end of the conduit is pulled to the skin at the marked location. The stoma is performed in the standard fashion using absorbable sutures. A drain is left to monitor for leaks. A Foley catheter may be left as a pelvic drain per surgeon's preference.

In conclusion, the robot has revolutionized surgery for many specialties, including urology. Initially embraced for robotic surgery, the uses and types of surgeries performed robotically have exploded over the past few years. Robots are utilized vastly for oncologic surgery but have also been

embraced for reconstructive, pediatric, urogynecologic, and even stone surgery. The anesthesiologist must be well versed in laparoscopic and robotic surgery and familiarity with the basic surgical steps, and possible complications can only enhance the surgeon-anesthesiologist relationship and ultimately lead to improved patient outcomes.

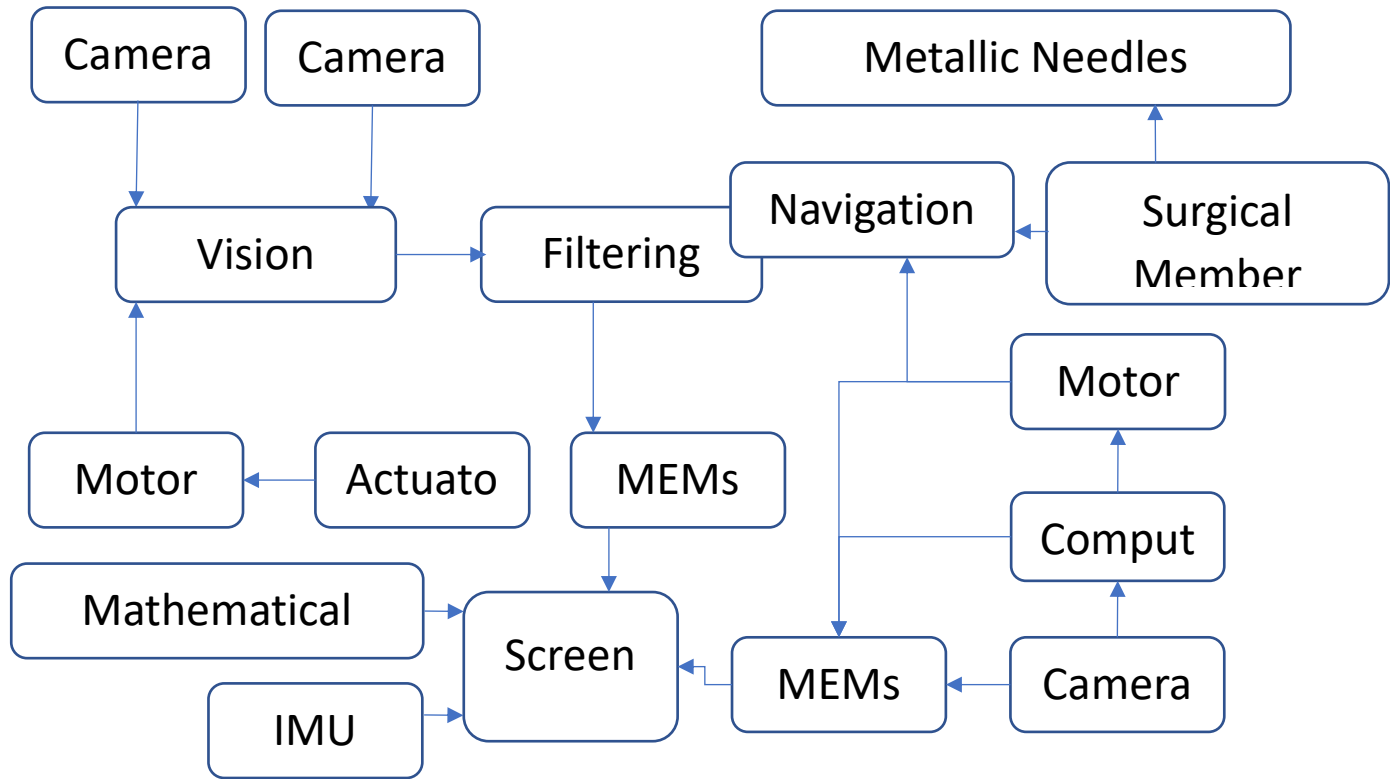
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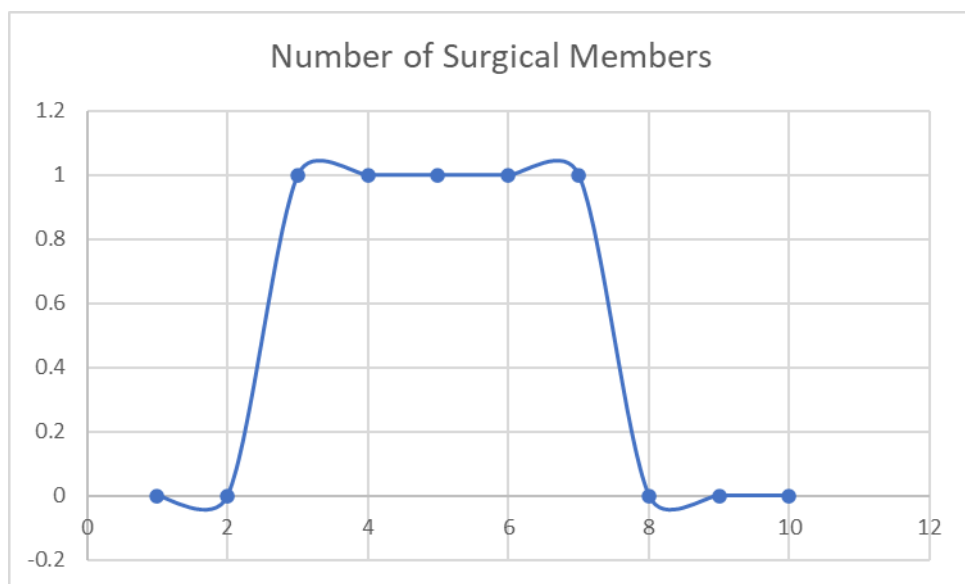
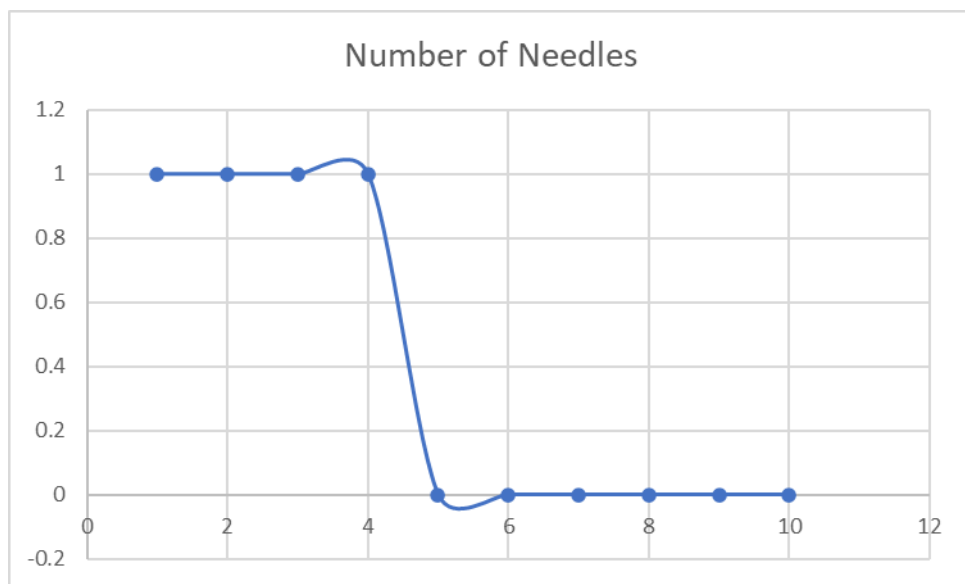
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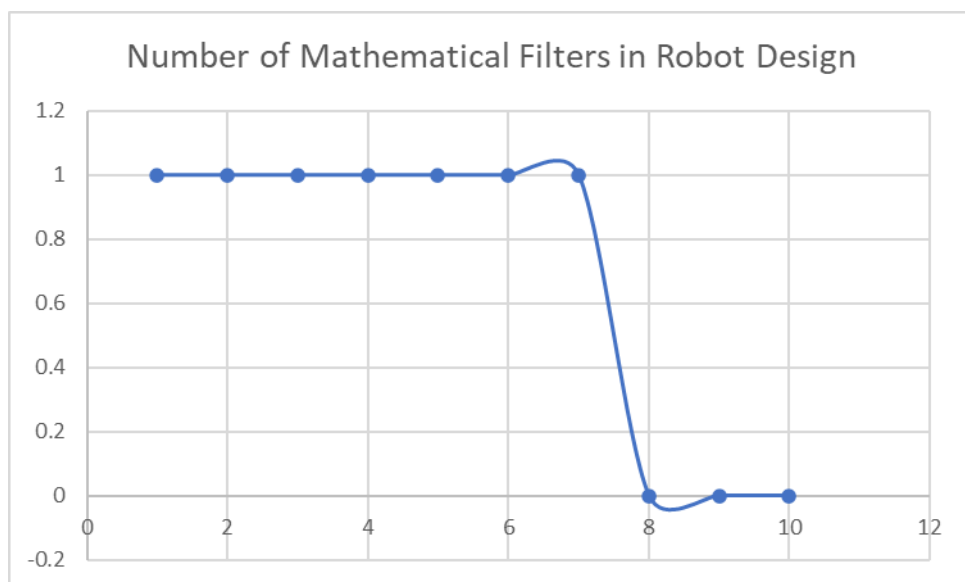
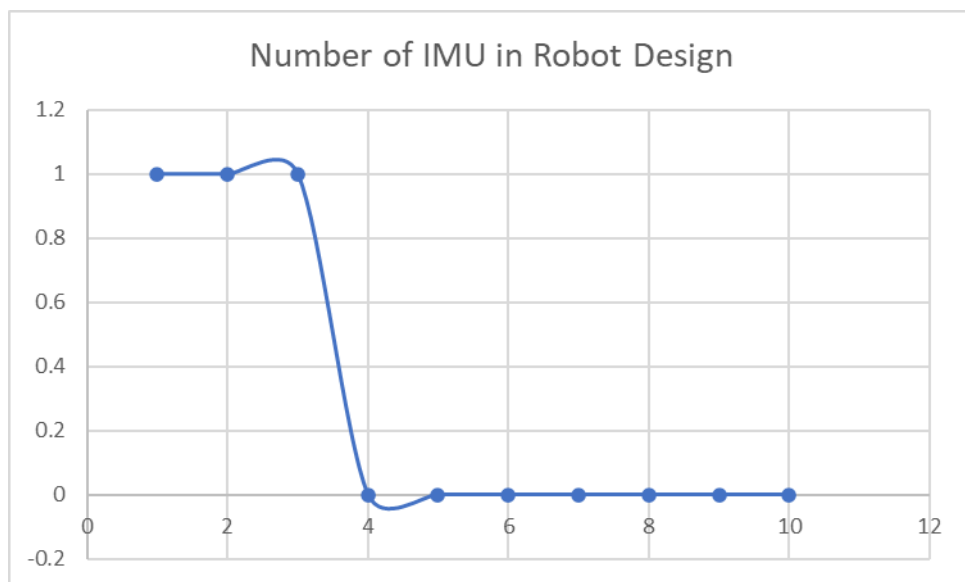
Part 7 Research Results and Analysis

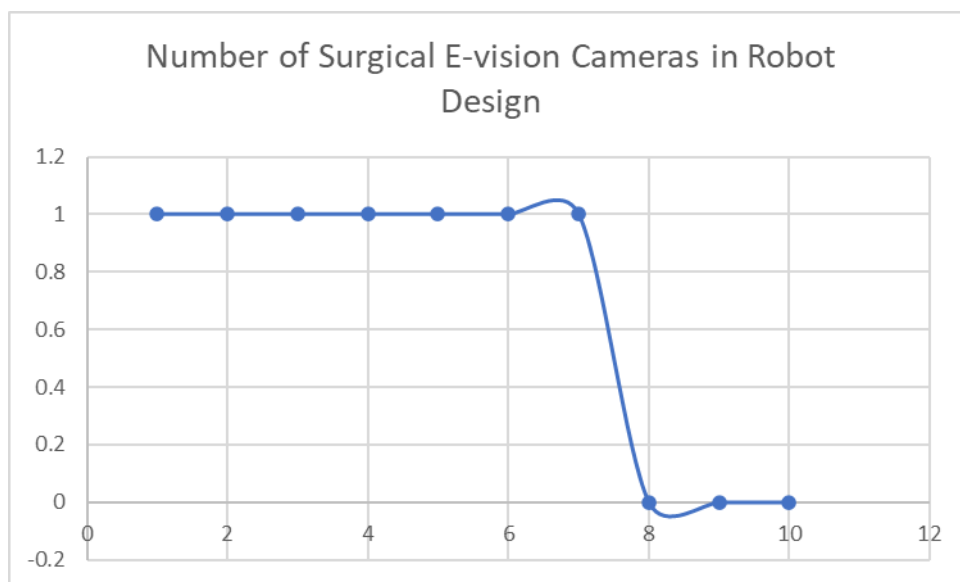
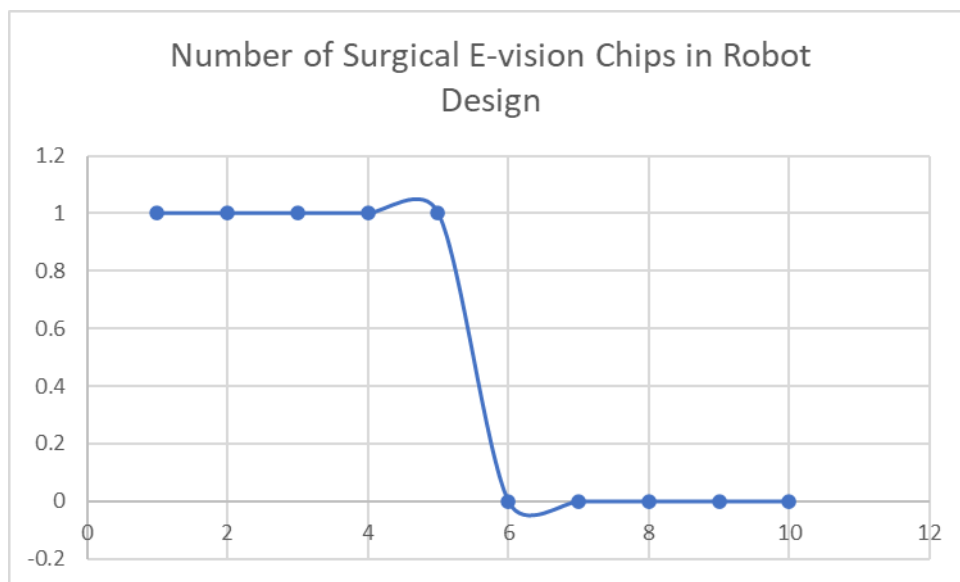
Throughout our research journey, the researcher had introduced a complete diagram for a surgical Multi-Robotic System. The aim of this robot is to perform the hardest kinds of Human bod surgery. The surgery can be through endoscopy or special needles as we knew in previous chapters. The system contains main electrical and electronic functions. In order to assemble such a system, we need Sensor's functionality and Robotic functionality. The sensor part contains multi camera, vision CPU, Motor and Actuator. The robot part contains Camera and Computer Vision CPUs. Motor and Motor Control Unit. Surgery navigation Unit and Metallic Needles Unit. There is extra Unit controlled by Surgical Members. The Surgical Robot also contains additional Units such as filtering, IMU, MEMS and Screens. The functionality between the Robot System parts appears in the below diagram.

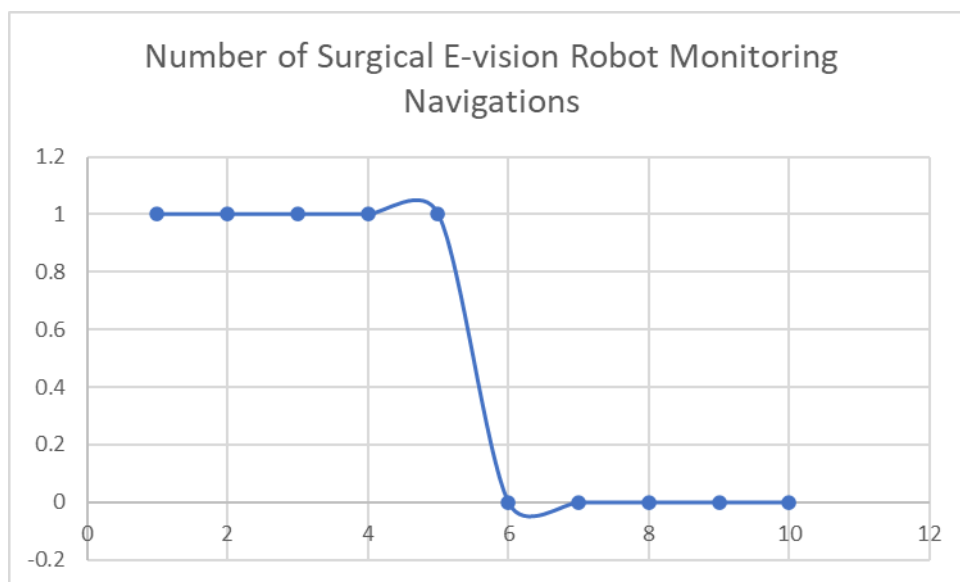
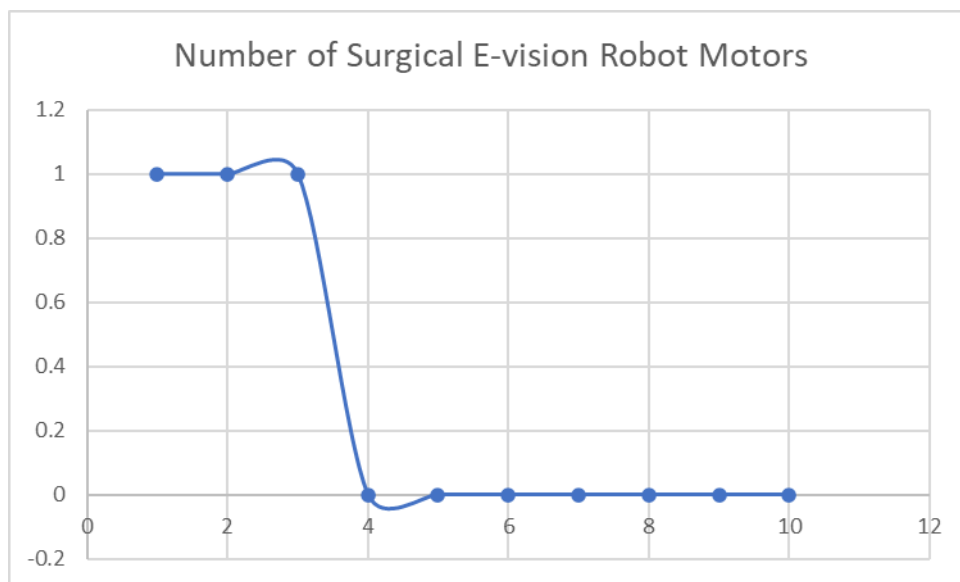


Research Results Diagrams

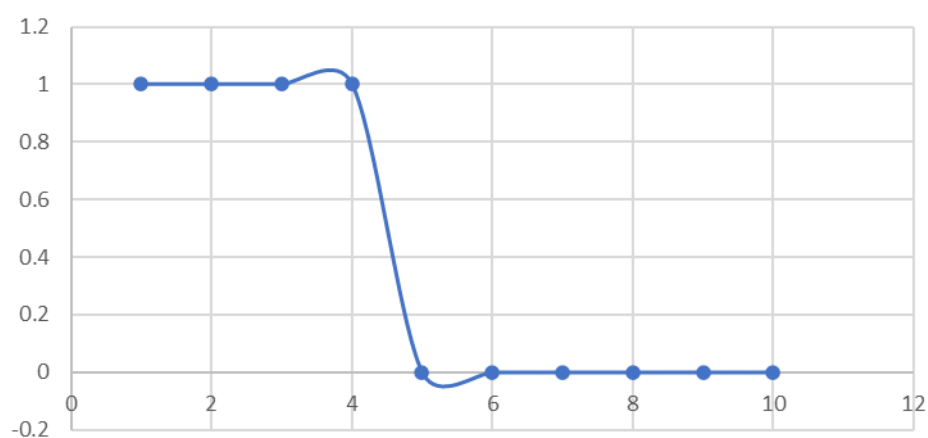




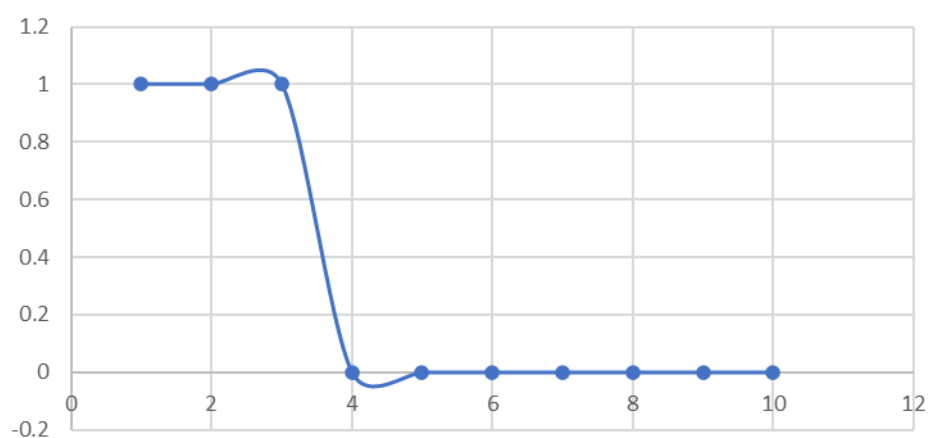


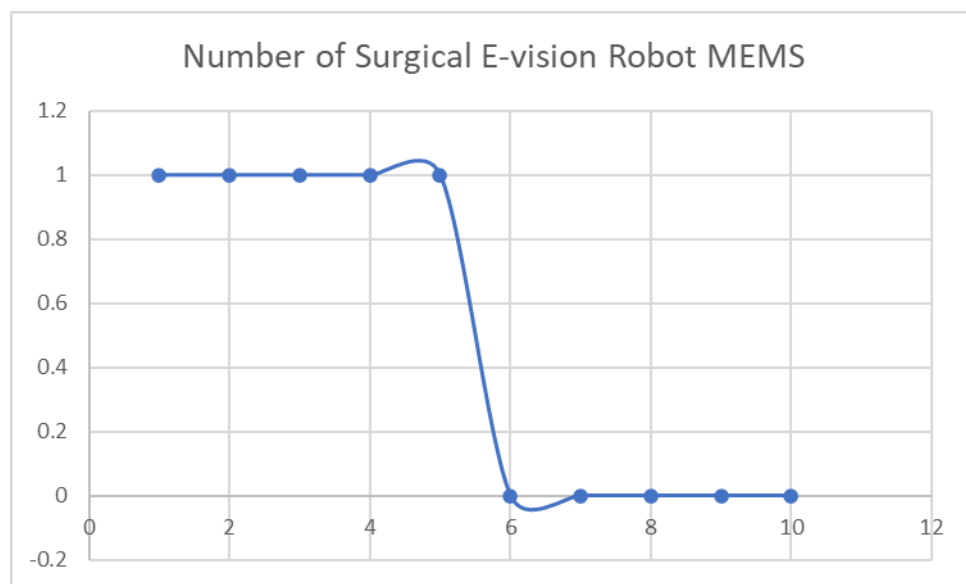


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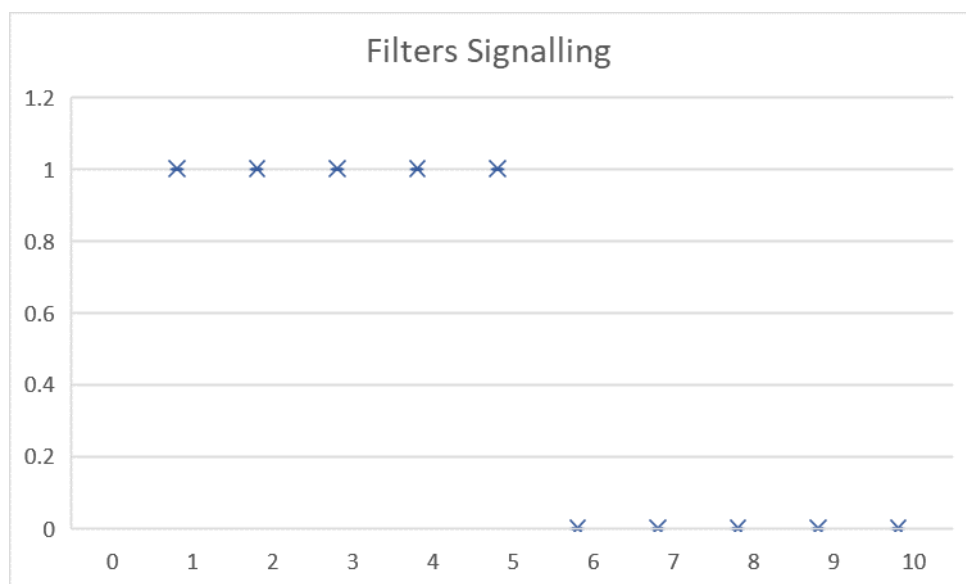


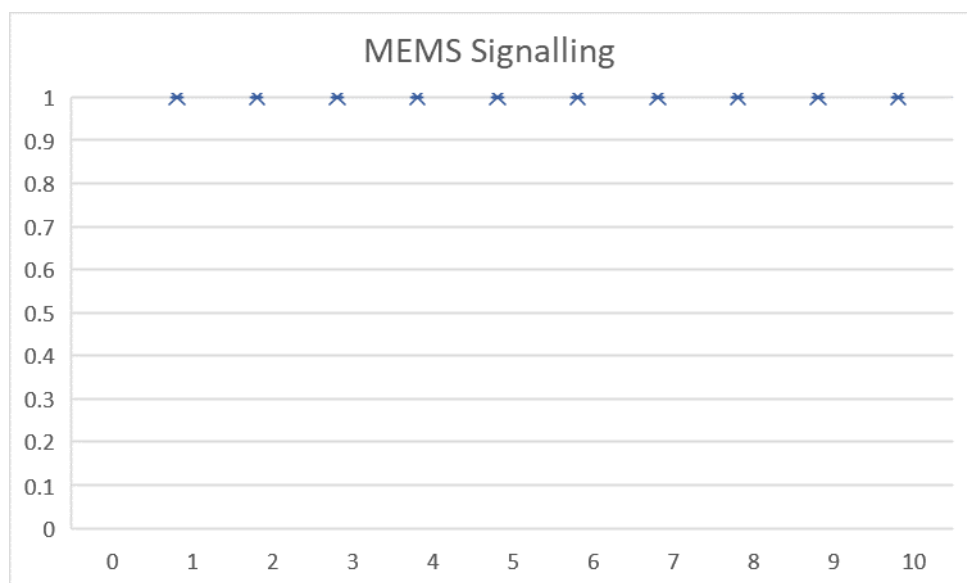
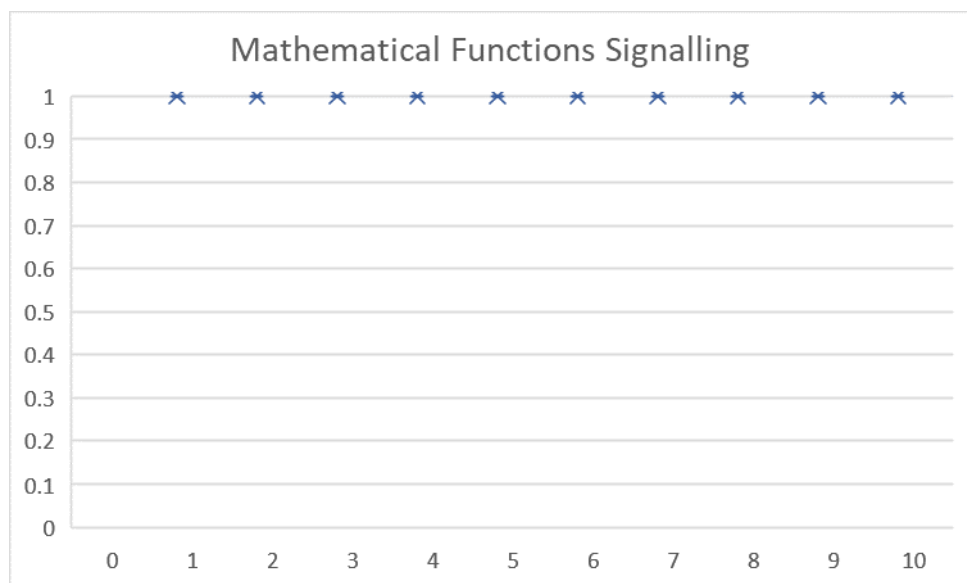
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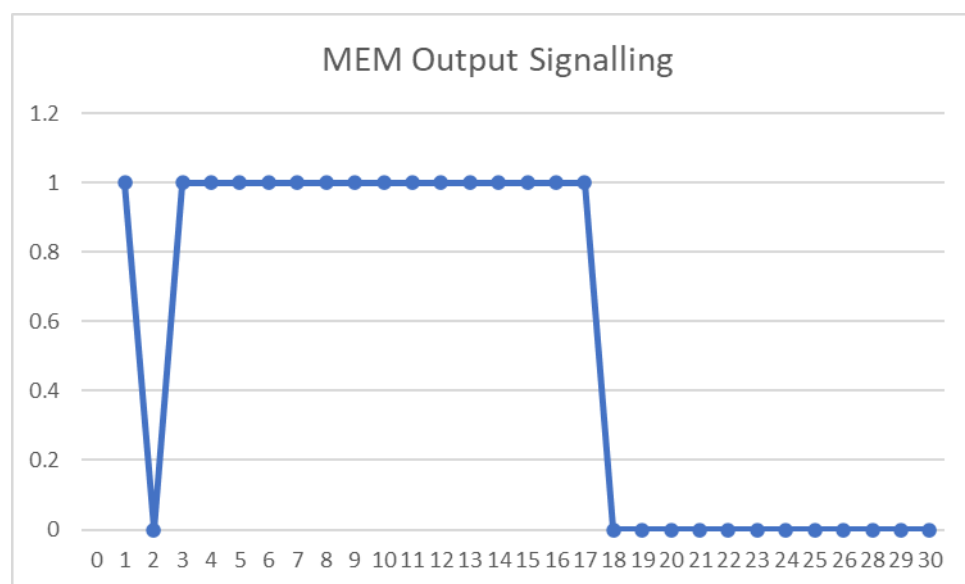
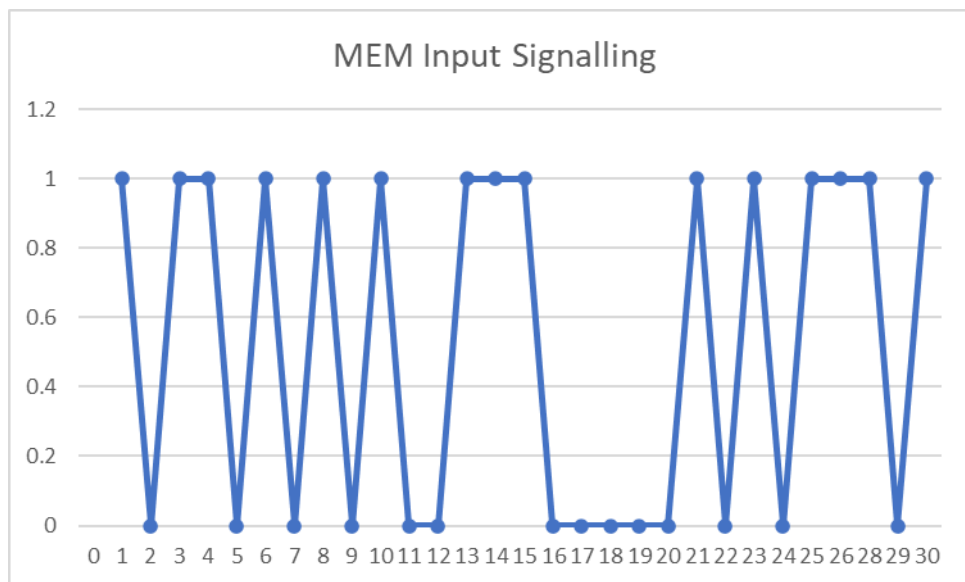


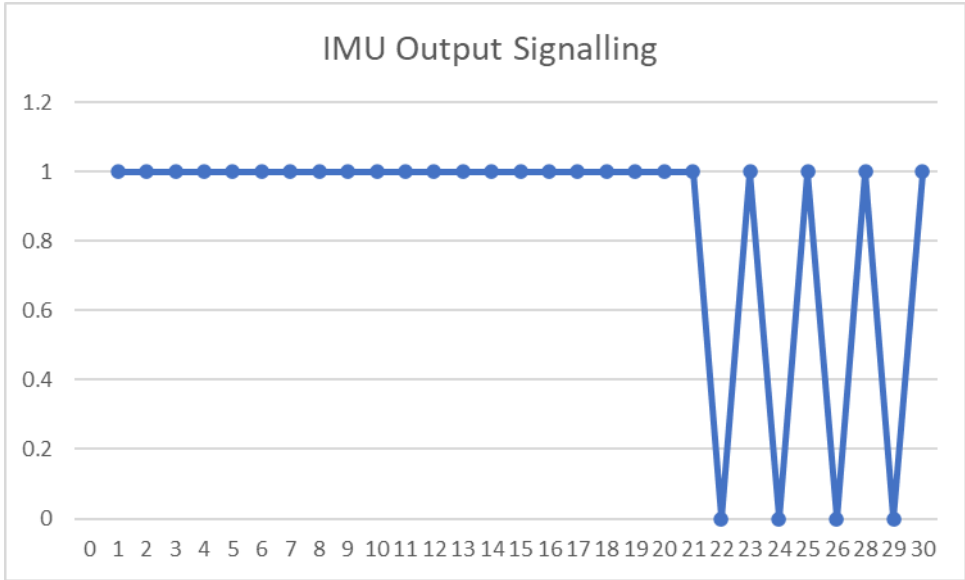
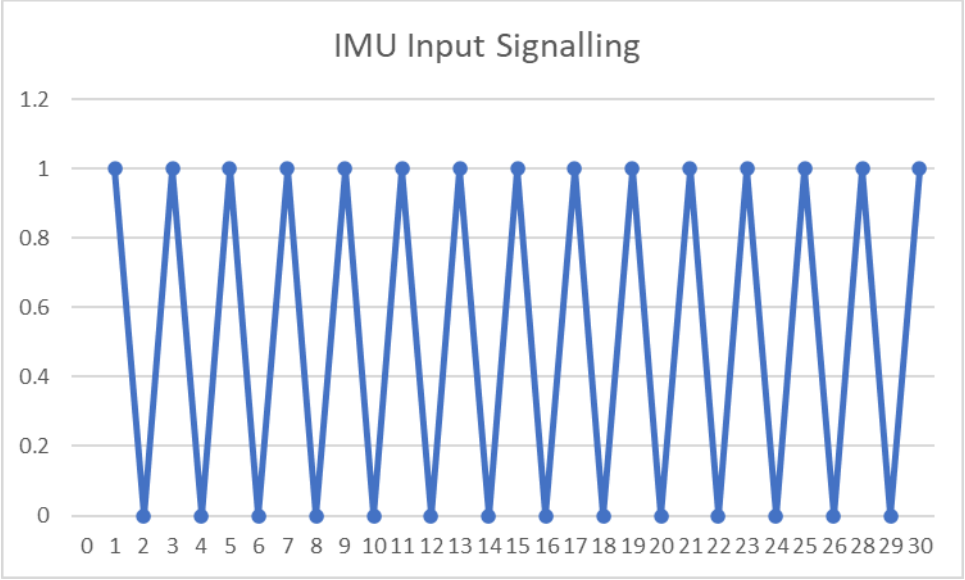


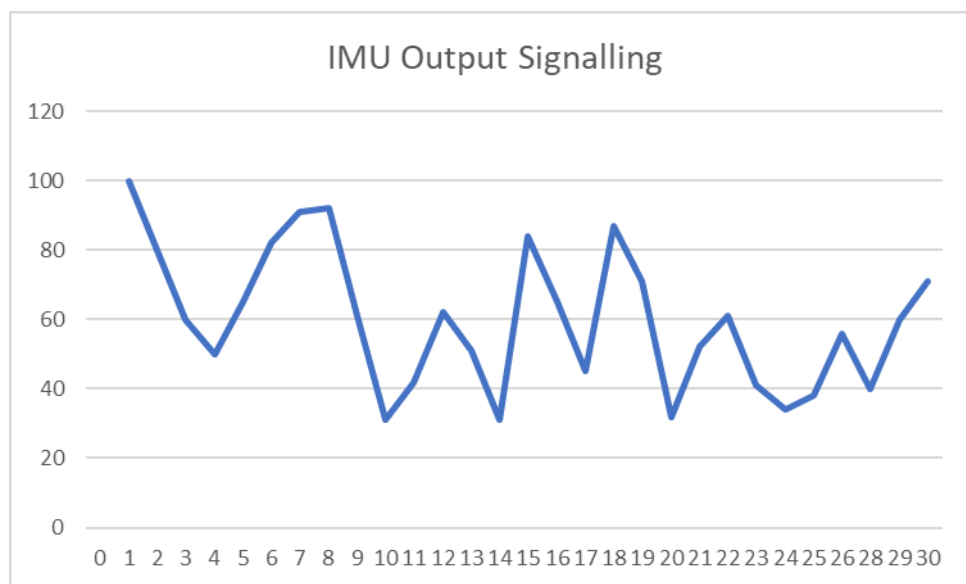
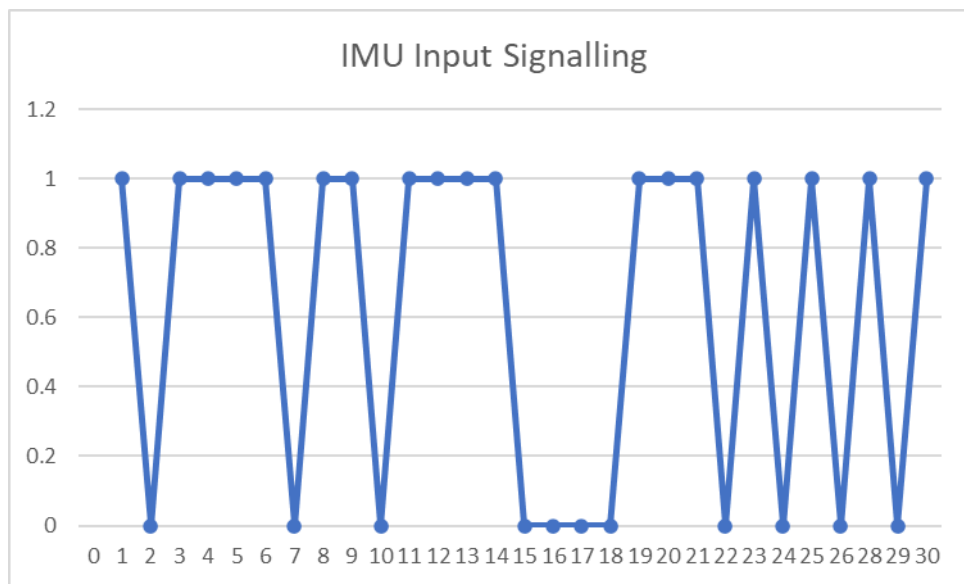
Readings from Laboratory

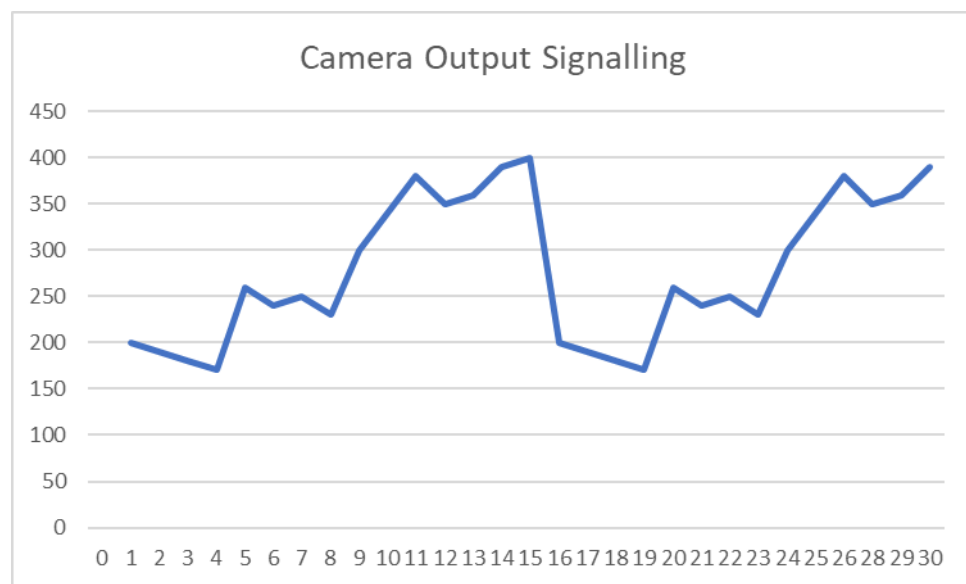
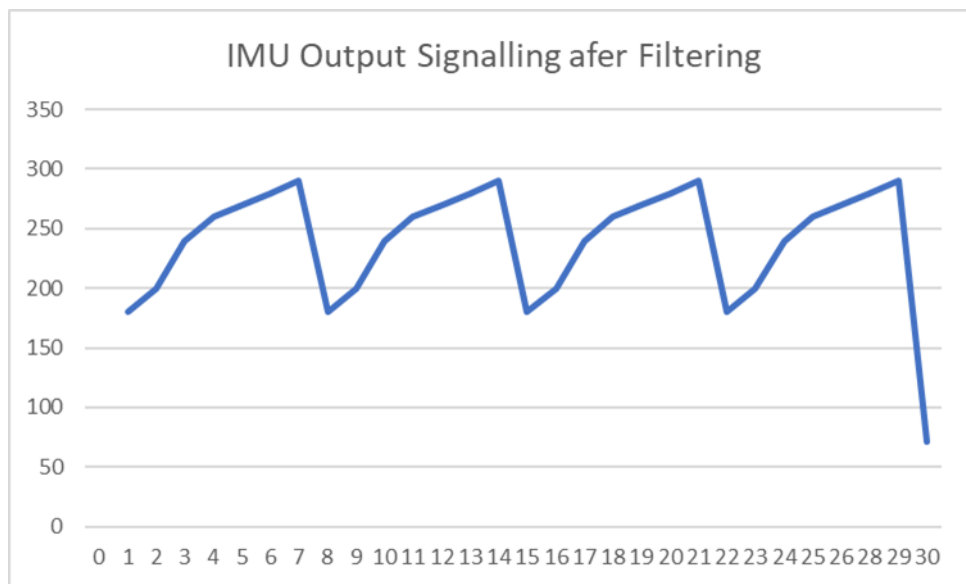












Research Analysis

Deployable Laparoscopic Robotic Surgical System

4.1 Introduction to Laparoscopic and Robotic Laparoscopic Surgery

Minimally invasive surgical techniques have emerged as a trend in medicine with more advantages over conventional methods, such as short recovery time for the patient, reduced pain due to smaller incisions, and less hemorrhaging. Laparoscopy is an endoscopic surgical operation in the abdomen or pelvis through small incisions with the use of a camera (Fig. 4.1¹). Typically, a number of small openings (three to six) with a size of 0.5–1.5 cm are made on the body of a patient through which surgical instruments are inserted. These instruments include a laparoscope, which is a long, thin instrument with a light source at the tip of it to illuminate the inside of the abdomen or pelvis. The laparoscope is also equipped with a lens at its tip that takes images and sends them to a video monitor through optical fibers for the surgeon and other staff to view in real time. The abdomen is filled with carbon dioxide (CO₂) through a special needle, which is inserted just below the navel. This gas is very helpful in separating the organs inside the abdominal cavity and making it easier for the surgeon to see the organs during

¹<http://www.cincinnatifertility.com/infertility-treatment/laparoscopy>

laparoscopy. The gas is removed at the end of the procedure. Figure

4.2 compares conventional and laparoscopic cholecystectomy.

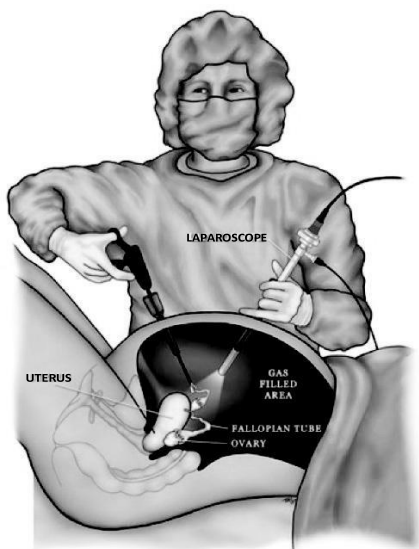


Figure 4.1 Laparoscopic surgical procedure.

Robot-assisted surgery has introduced a new era of minimally invasive surgical procedures and is going to revolutionize the entire field of conventional open surgery by introducing methods that are far less invasive and by offering many fundamental clinical improvements that are outstanding for both patients and surgeons. Robots are also being used more to help with laparoscopic surgeries. Significant research has been conducted on the utilization of robots in surgical procedures, the outcome of which has been verified by testing commercial and noncommercial robotic surgical systems. Horgan and Vanuno (2001) published a technical report on the use of robotic systems in laparoscopy in which they concluded that robot-assisted operations are safer and more effective

as compared to conventional laparoscopic procedures. Russell H. Taylor and Dan Stoianovici (2003) provide a comprehensive review of robotic surgical systems developed. Sabharwal, Pradhan, and Kumar (2006) evaluated the da Vinci[®] surgical robot for use in urology, more specifically radical prostatectomy, renal surgery, and adrenalectomy. Their study shows that the da Vinci[®] system could successfully be

utilized in urological surgeries and has led to a set of standards for robot-assisted operations. Indeed, the use of the da Vinci[®] robot in a number of other surgeries, such as general surgery and cardiac surgery, has been successful as well (Hemal and Menon, 2004). Recent technological advents in video imaging, endoscopic techniques, and instrumentation have converted a number of manual operations into robotic ones.

Robotic telescopic assistance with systems such as AESOP[®] or robotic procedural laparoscopy with systems such as da Vinci[®] or ZEUS[®] are two frequent approaches to perform minimally invasive surgeries (Shew, Ostlie, and Holcomb, 2003). The former is a rather semiautomated method due to manual adjustments of optical fiber endoscopic cameras. The latter, on the other hand, involves the use of teleoperative methods, where the robotic system is of a master– slave type and the surgeon performs surgery from a distance. These systems have been widely used in cardiology, gynecology (Yildirim, 2010), urology (Ashish Sabharwal, Pradhan, and Kumar, 2006; Casale and Kojima, 2009), general surgery, laparoscopy, etc.

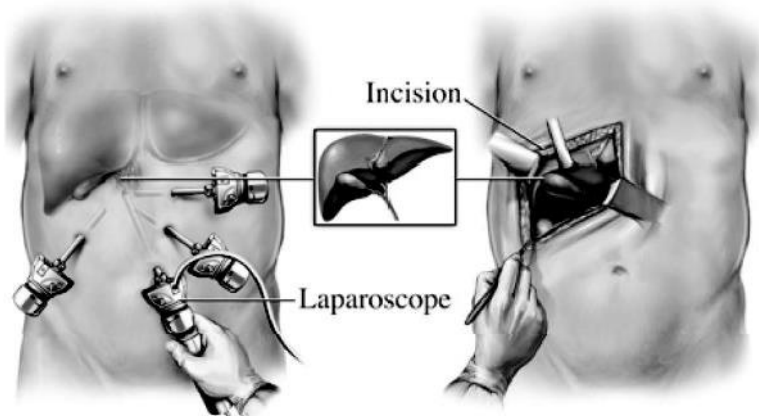


Figure 4.2 Laparoscopic and conventional cholecystectomy.²

A teleoperative robotic system comprises two fundamental units. One is an ergonomically designed surgical master station housing the surgeon as the

master of surgical robotic operation. He/she sits on a chair and uses a pair of multi-degree-of-freedom controllers

²<http://etsyitemoftheday.com/gallbladders/>

for manipulation of a number of distant robotic end effectors and an endoscopic camera. The video monitor enables the surgeon to observe and control the surgical operation on the body of the patient. The other major unit is a robotic slave system that actually performs the surgery on the patient's body by delivering different surgical end effectors into his or her body to do surgical tasks such as gripping, cutting, and suturing. The end effectors are equipped with different sensors to receive continuous information on force and displacements.

Many patents and patent applications have been reported in connection with robotic surgery. Van Der Brug, Blik, and Gerritsen (1999) developed an image-guided surgical system to show a surgeon the position of a surgical instrument in an operating area in the body of a patient during a surgical procedure. Diolaiti (2010) describes a control system for a minimally invasive surgical system that could be used as both a centralized and a distributed system. As a centralized system, a motion controller receives master inputs, sensor inputs from the slave arms, and optimization inputs and uses them to send out control signals to an instrument, an imaging system, and a guide tube controller. As a distributed system, a control and transform processor receives data from a master arm controller, an instrument controller, an imaging system controller, and a guide tube controller and distributes data received from one controller to the other controllers. The other controllers use the received data, along with the optimization goals, to control associated slave arms in a distributed but coordinated way. Nowlin et al. (2011) introduce surgical robotic devices, systems, and methods that use surgical robotic linkages that may have more degrees of freedom than an associated surgical end effector in space. Pivoting of a tool about an aperture site is achieved through a software-based tool motion

control. Linkages can take multiple configurations to deliver the end effector to a given position, which helps with collision prevention. Larkin and Shafer (2011) introduce a surgical instrument, which includes articulated arms having a distal end, a proximal end, and one joint region disposed between the distal and proximal ends; an optical fiber bend sensor and a detection system coupled to it; and a control system comprising a servo controller for effectuating

movement of the arm. The compact, flexible, snake-like structure of the instrument gives additional dexterity to the manipulator.

4.2 AESOP[®], ZEUS[®], and da Vinci[®]: First Methods and Systems in Robotic Laparoscopy

4.2.1 AESOP[®]

AESOP[®] (Fig. 4.3) was developed by Computer Motion, Goleta, CA. With a Food and Drug Administration (FDA) clearance in 1994, it became the first robot to assist in a surgery. AESOP[®] was released in several generations, such as 1000, 2000, and 3000, with the latest models having more features, such as a voice recognition system to receive voice commands from a surgeon. Hermes[®], a platform designed with the purpose of networking the operating room (OR) through voice controls, enables a surgeon to fully and directly control the surgical equipment (Horgan and Vanuno, 2001). A normal surgical procedure with AESOP[®] would include making three to five small incisions in a patient's body through which an endoscopic camera and robotic instruments are inserted.



(a)



(b)



(c)

Figure 4.3 AESOP® 3000 robotic surgical system; different views.

4.2.2 Zeus[®]

Zeus[®] (Fig. 4.4) is a robotic system developed by the same company, Computer Motion. It includes three interactive arms: the first arm is voice activated and controls the laparoscope; the other two arms are controlled via joysticks at the surgeon's workstation and manipulate surgical instruments (Horgan and Vanuno, 2001).

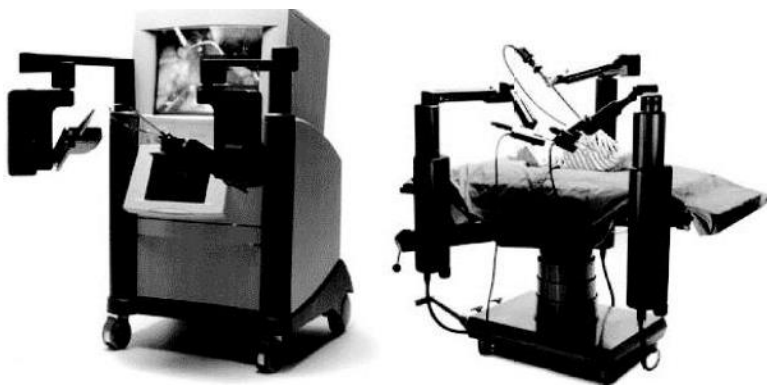


Figure 4.4 Zeus[®] robotic surgical system.

4.2.3 Da Vinci[®]

Da Vinci[®] (Fig. 4.5) is a robotic system developed by Intuitive Surgical, Sunnydale, CA. It consists of two main entities, a surgeon's console housing the surgeon as the master of the surgical operation and a slave robot composed of four robotic arms. The robot is under full control of the surgeon and is never autonomous. The surgeon is provided with a stereoscopic and panoramic view of the surgical scene and controls the movements of the robotic arms via joysticks in the surgeon's console. In the slave robot, which actually performs the surgery on the patient's body, one of the arms positions an endoscopic camera with two lenses inside the body, while the other three

manipulate surgical instruments and act as a gripper, a scalpel, scissors, a bovie, and unipolar or bipolar electrocautery instruments. The da Vinci® system also includes multiple, redundant safety features to reduce human error possibilities.

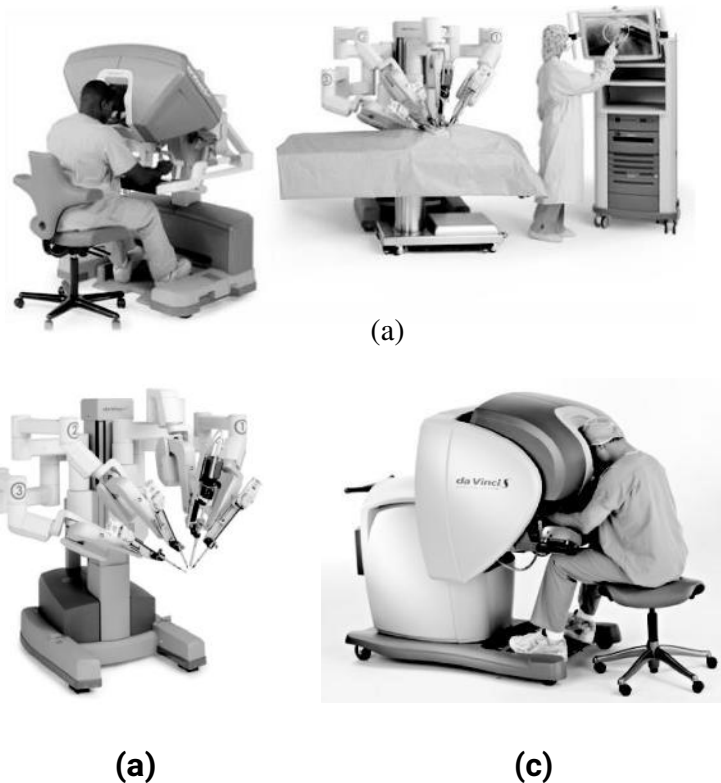


Figure 4.5 Da Vinci[®] robotic surgical system. (a) The whole system, (b) the surgical arm cart, and (c) the surgeon's console.

In conventional laparoscopy, the surgeon operates while standing, using handheld, long-shafted instruments, and to see an image of the target anatomy, he/she has to look up and away from the instruments to a close-by 2D monitor. The surgeon also depends on his/her assistant to position the camera correctly. In contrast, the da Vinci[®] system is developed to enhance conventional laparoscopy. Using the ergonomically designed da Vinci[®] system, a physician can operate from a seated position at the surgeon's console, with eyes and hands positioned in line with the instruments. The surgeon's hand

movements, to manipulate the instruments or to reposition the camera, are scaled, filtered, and translated into more precise micromovements of the instruments, which operate through small

incisions in the body. Figure 4.6 illustrates a typical scene of a surgical procedure with the help of the da Vinci[®] robotic system. In the following section, we will describe different sections and parts of a robotic surgical system with the help of da Vinci[®] as the only widely used commercial robotic system for use in surgeries.

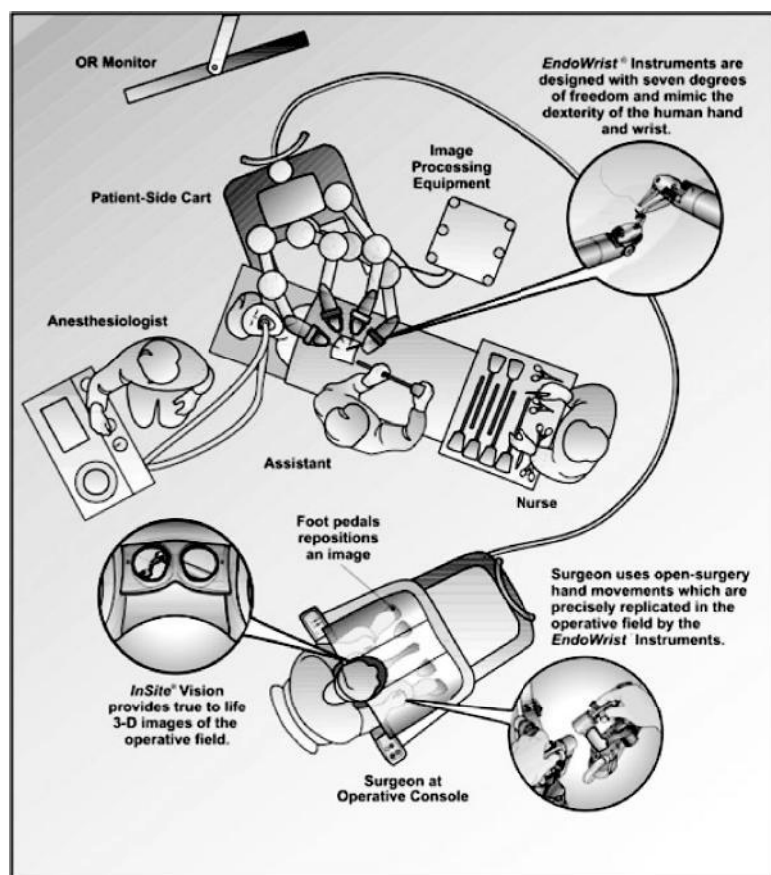


Figure 4.6 The da Vinci[®] robotic surgical system in an OR.

Any robot-assisted surgical system should comprise five main units: a surgeon console, image-processing equipment, surgical instruments, a slave

robot, and an endoscopic camera (Fig. 4.7). In the following section, we will elaborate on each of these units, exploiting the da Vinci[®] robotic surgical system-associated items, which are:

- Surgeon console
- Image-processing equipment
- EndoWrist® instruments
- Surgical arm cart
- High-resolution 3D endoscope



Figure 4.7 The da Vinci® robotic surgical system main units. (1) A surgeon console, (2) image-processing equipment, (3) EndoWrist® instruments, (4) a surgical arm cart, and (5) a high-resolution 3D endoscope.

4.2.3.1 Surgeon console

The surgeon sits comfortably at the da Vinci® console (Fig. 4.8) and looks at a generated panoramic image of the surgical operation through two eyeholes. To operate, the surgeon uses the two foot pedals and two hand controllers to manipulate the slave robot arms. As the surgeon moves the controllers, the slave robot responds accordingly in real time, scaling, filtering, and translating his/her hand, wrist, and finger movements into micromovements of surgical instruments at the patient-side cart.

The master controls are located below the display,

and the hand and eye are aligned naturally for optimal performance. The foot switch panel gives the surgeon the flexibility to perform a multitude of tasks such as exchanging different types of surgical instruments. The surgeon is provided with an immersive stereo viewer for more precision.

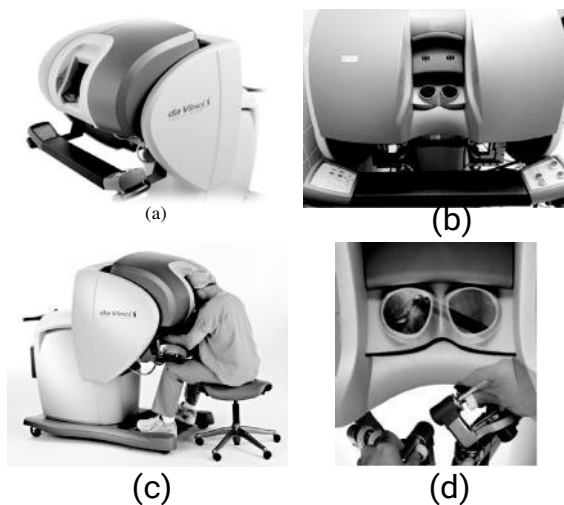


Figure 4.8 The da Vinci[®] surgeon console; different views.

An integrated surgeon touchpad is used to perform comprehensive control of video, audio, and system settings. Moreover, audio/ visual feedback constantly notifies the surgeon and the OR team of system status and functions (Fig. 4.9).

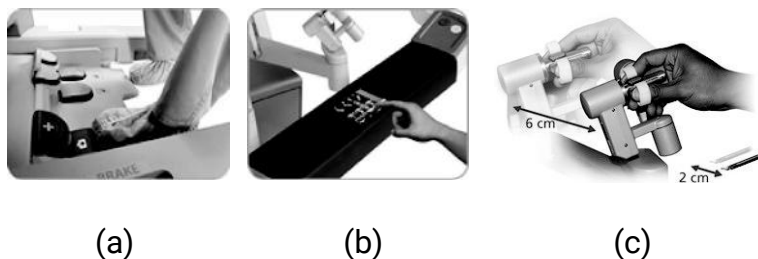


Figure 4.9 The da Vinci[®] surgeon console; different sections. (a) A surgeon touchpad, (b) a fingertip controller and scaling feature, and (c) foot pedals.

Dual console capability (Fig. 4.10) offers training and collaboration during a minimally invasive surgical

intervention. In collaboration mode, each surgeon sits at his/her own console and views the same image of the operation. Two surgeons of the same or different specialties can collaborate on a single case, exchanging control of the instrument arms and the endoscope at any time. In training mode, the teaching surgeon can give control of the instruments to the resident/fellow at appropriate times. This see-and-repeat model of instruction catalyzes the learning procedures.



Figure 4.10 The da Vinci® surgeon dual console.

4.2.2.2 Image-processing equipment

The slave robot on a patient's side inserts a high-definition (HD) 3D endoscope into the body of the patient to capture images of his/ her anatomy and send them to image-processing equipment, which provides a true-to-life image of the patient's anatomy. A large view of the operating field with natural depth perception is shown on a monitor available on the vision cart. A magnification feature allows surgeons to handle surgeries more easily and efficiently, especially in operations with limited space, such as the chest and abdomen (Figs. 4.11 and 4.12).



Figure 4.11 The da Vinci[®] surgeon console vision system.

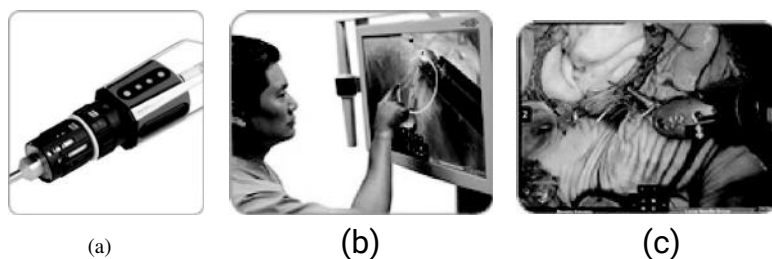


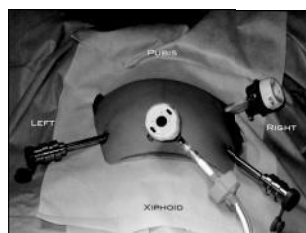
Figure 4.12 The da Vinci® image-processing equipment. (a) A wide-screen touch screen, (b) visual resolution (1080i HD), (c) a 3D HD camera head.

4.2.3.3 EndoWrist® instruments

Da Vinci® EndoWrist® surgical instruments are the ones in contact with target organs and perform different surgical tasks. These instruments include needle drivers, graspers, scalpels, scissors, monopolar and bipolar cautery instruments, ultrasonic energy instruments, clip appliers, etc. Cannulas (Fig. 4.13) guide surgical instruments into the body to the target organ. They provide easy insertion of surgical instruments into the body without damaging the surrounding tissue and organs due to frequent instrument exchange. A complete list of EndoWrist® surgical instruments, cannulas, etc., is available in *EndoWrist Instrument & Accessory Catalog* released by Intuitive Surgical.



(a)



(b)

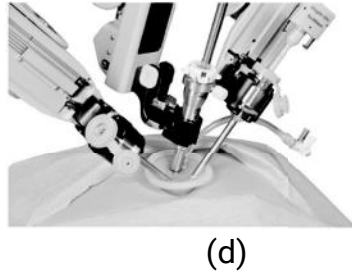


Figure 4.13 Da Vinci[®] cannulas; different representations.

EndoWrist[®] surgical instruments (Figs. 4.14 and 4.15) have 7 degrees of freedom with 90 degrees of articulation, which are inserted into the body through 1–2 cm incisions. These instruments provide the surgeon with more dexterity and precision, which make the operation easier with greater outcomes. The surgeon's hand movements are scaled and transferred to these instruments. They come in two different general sizes, 5 mm and 8 mm.

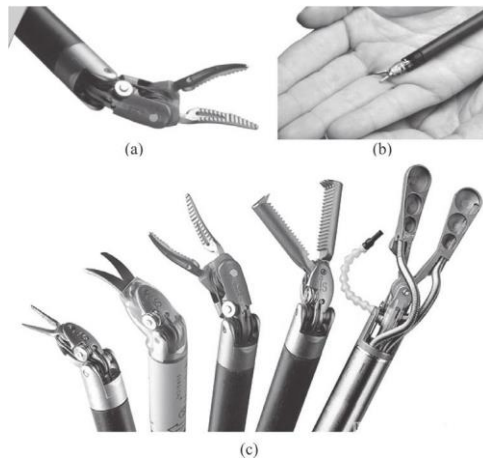


Figure 4.14 Da Vinci[®] EndoWrist[®] surgical instruments; different representations.

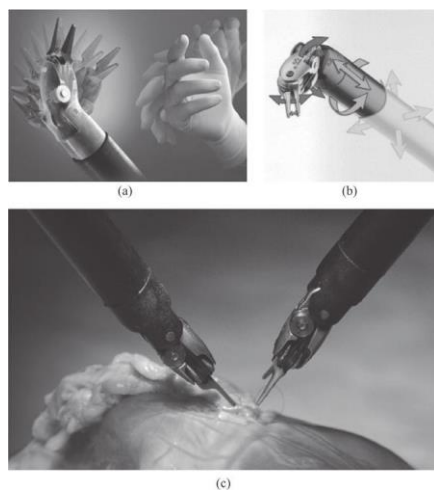


Figure 4.15 Da Vinci® EndoWrist® surgical instruments. (a) Degrees of freedom, (b) dexterity, and (c) instruments in use.

4.2.3.4Surgical arm cart

The da Vinci[®] slave robot has four multiquadrant access arms, three of which hold EndoWrist[®] surgical instruments (Fig. 4.16). The other arm positions the endoscopic camera. These arms deliver the surgical instruments into the patient's body under full control of the surgeon and move around a fixed pivot point to reduce trauma to the patient.

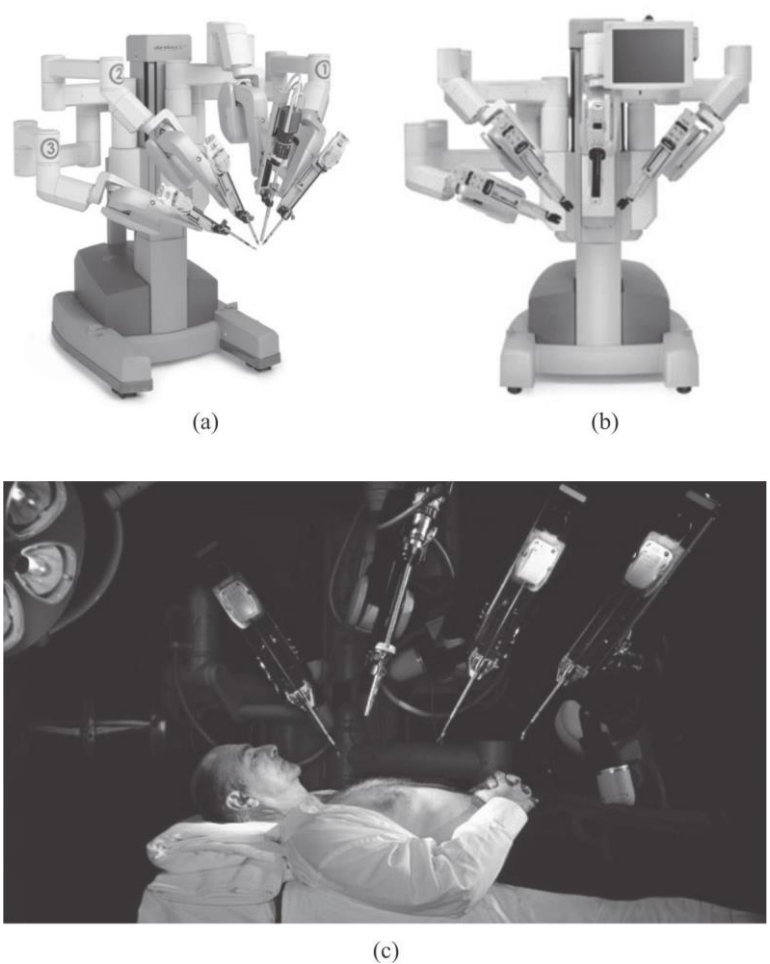


Figure 4.16 The da Vinci[®] surgical arm cart.

4.2.3.5 High-resolution 3D endoscope

The endoscopic camera that is inserted into the patient's body to capture image of the surgery is shown in Fig. 4.17. There are two types of endoscopes released by Intuitive Surgical, 0° and 30° stereo endoscopes.

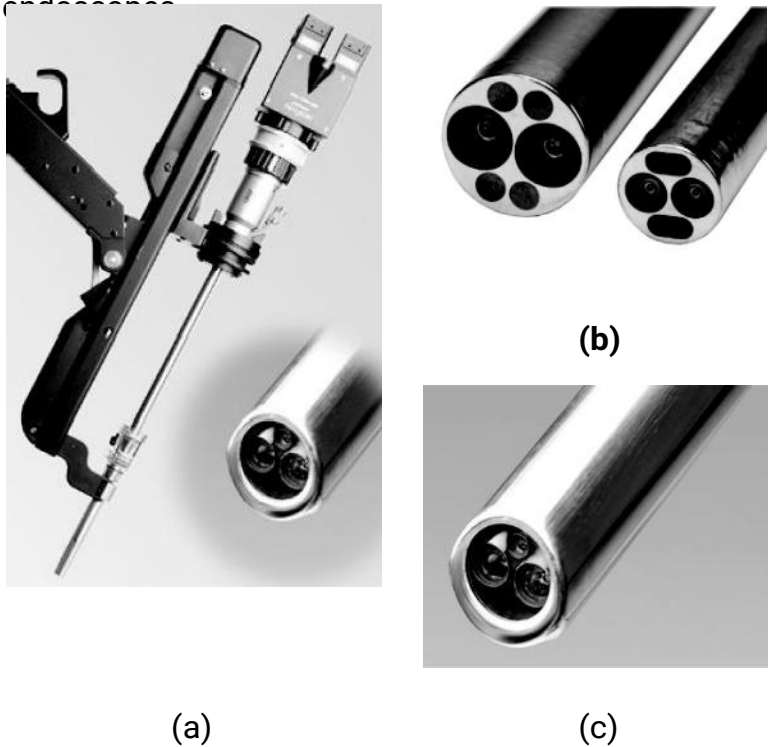


Figure 4.17 Da Vinci® high-resolution 3D endoscopes.

Figure 4.18 is a pictorial presentation of the benefits of robot- assisted minimally invasive surgeries to conventional ones and is as follows: (a) multi-incision laparoscopy versus single-site da Vinci® surgery, (b) open hysterectomy incision versus da Vinci® hysterectomy incision, (c) da Vinci® thyroidectomy versus open thyroidectomy, (d) open kidney surgery incision versus da Vinci® surgery incision, (e) open surgical incision versus da Vinci® mitral valve repair

incision, and (f) open prostatectomy incision versus da Vinci[®] prostatectomy incision.

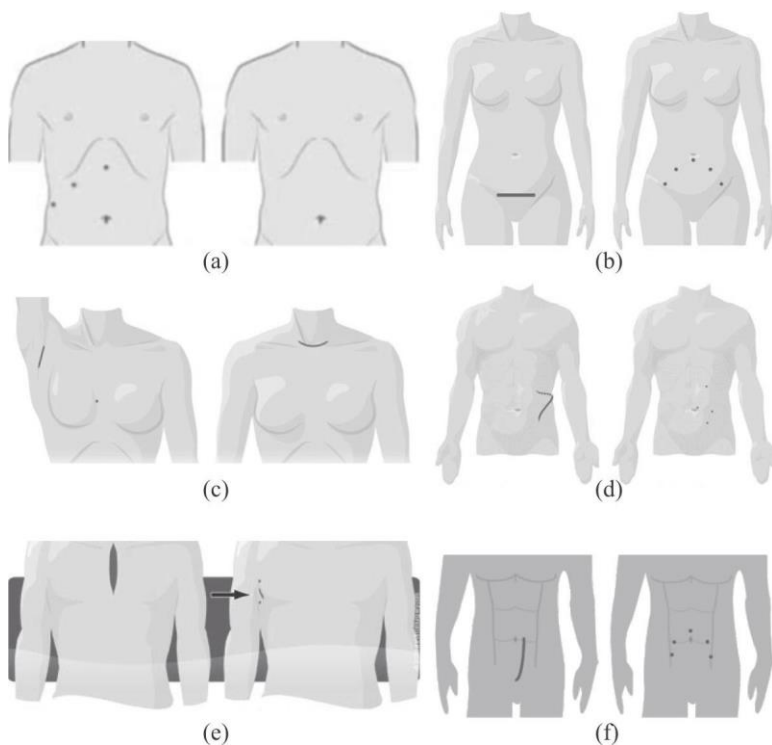


Figure 4.18 Difference between conventional surgical procedures and robot-assisted ones with the help of the da Vinci® robot.

The following picture (Fig. 4.19) shows the outcome of a robot-assisted surgery with the help of the da Vinci® Surgical System.

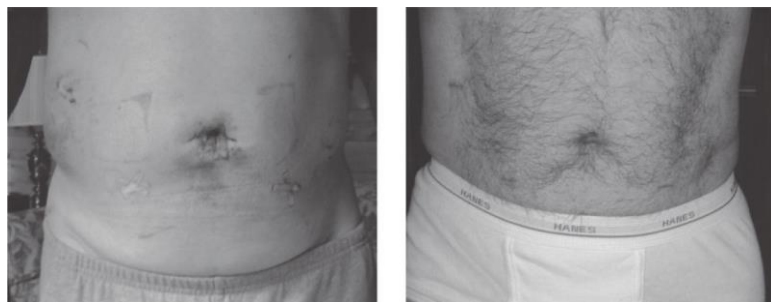


Figure 4.19 Result of a robot-assisted surgery with the help of the da Vinci[®] robot.

Robotic surgical systems are still under continuous improvements. One major issue yet to be solved is the big size of the surgeon's console and surgical slave robot. The da Vinci[®] Surgical System occupies a considerable amount of working space in the OR and makes it inconvenient for surgeons and nurses to be around the surgical bed, when necessary. It also takes up a lot of useful space in the OR when not working. Thus, the introduction of a new system that takes less space of the OR in both working and nonworking modes is essential. We developed a new type of robotic surgical system at the University of Maine, which is currently under provisional patent status (#61718822). Our focus is on the introduction of compact alternatives for sections 1 and 4 of the da Vinci[®] system, which are the surgeon's console and the surgical arm cart, respectively.

In the following section, we give an introduction to deployable structures as the base of our proposed robotic surgical system.

4.3 Deployable Structures

4.3.1 Introduction to Deployable Structures

Deployable structures that can adjust their configuration to a predetermined size or shape under specific operating conditions have found a great deal of interest in various fields of industry (Gantes and Konitopoulou, 2004). The term "smart deployable structure" refers to the capability of such structures to switch from one configuration to another to meet any engineering requirements. Most deployable structures that have been developed are open- closed structures that fulfill their functionality after full deployment. They are specifically used for efficient packing during storage and transportation. Well-known examples of these bi-state structures range from small structures,

such as deployable tents, to large civil structures, such as retractable roofs of sports stadiums (Pellegrino and Calladine, 1986), (Kassabian, You, and Pellegrino, 1999). Highly engineered examples include space structures such as solar arrays and antennas on spacecraft in which compactness, light weight, and easy deployment are necessary for such structures to be compactly stowed for launch and then autonomously deployed to their final configuration. Currently, the final deployed shape of such

structures is limited to simple linear or circular geometry. However, development of structures that are capable of deploying to different desired curves may have a large number of applications ranging from biomedical applications such as gastrointestinal robotic surgery to complex curvilinear deployable space structures.

Several mechanisms have been proposed to obtain shape- morphing structures (Del Grosso and Basso, 2010). One example is truss structures in which some of the truss links are replaced with linear displacement actuators and can be deployed from a tightly packed form to the functional state (Onoda, Fu, and Minesugi, 1996; Sofla, Elzey, and Wadley, 2009). Another example is tensegrity mechanisms, which are lightweight space structures consisting of compression members surrounded by a network of tension members (Fest et al., 2003). These mechanisms change their shape on the basis of the static or dynamic equilibrium state.

Scissor-like element (SLE) structures are an important class of smart structures that are unique in terms of simplicity, deploying mechanism, and application (Fig. 4.20).

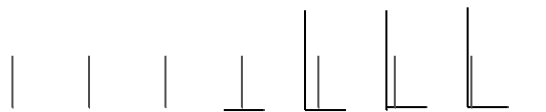


Figure 4.20 Linear deployment of the SLE mechanism.

SLE structures are mechanical configurations consisting of a set of rigid elements connected to each other at an intermediate point by revolute joints. Normally, SLE structures are one-degree-of-freedom mechanisms that deploy to the final shape with high

accuracy using an actuator that controls the entire shape. Ease of transportation, light weight, space-saving quality, high strength, and stability against external loadings are important advantages of these smart structures that have made their application promising in grabbers, robotic end effectors, structural roofs, and space structures. An outstanding application of SLE-based mechanisms has been introduced by Pinero (1961), who developed a full-size foldable theater, which arrived at the site on a single wheelbarrow and was then unfolded

on the basis of an SLE mechanism. Hoberman (1990, 1991, 2007) made considerable advance in the design of retractable structures based on SLE mechanisms when he discovered the simple angulated element.

Interestingly, SLE structures can also be found in biological structures at the cellular level. For instance, the DNA structure exhibits self-assembling into an expanded pattern, which is similar to that of an SLE (Fig. 4.21) (Strong, 2004).

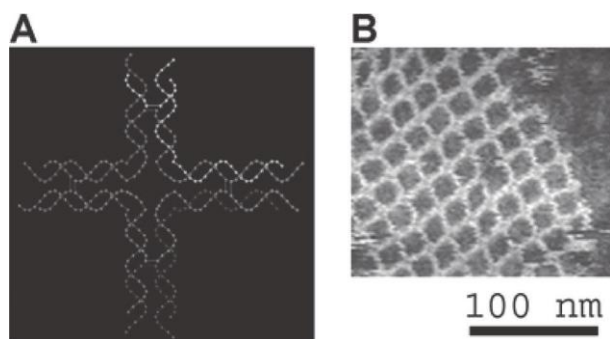


Figure 4.21 The DNA structure on the left (schematically shown) will self-assemble into the structure visualized by atomic force microscopy on the right (Strong, 2004).

Chen et al. (2002) suggested a new design based on diagonals (web struts) and lower chords to enhance the structural stiffness of deployable structures. Tsutomu and Tokai (1997) presented a cable scissors arch (CSA) based on a scissor mechanism in which three- hinged arch scissors and flexible cables were used to control the shape. Shahinpoor (1996) introduced a novel design of multifingered robotic grabbers capable of rapidly deploying their robotic fingers for grabbing tasks. An interesting case is presented in a paper submitted by Maden, Korkmaza, and Akgünb (2011) in which the authors discuss basic typologies, geometric principles, design rules, and

constraints of planar scissor structural mechanisms (SSMs). In this paper they further develop trigonometric calculation methods for different types of SSMs, using a deductive approach, and relate these concepts to architectural applications, where traditional inductive methods are inappropriate (Maden, Korkmaza, and Akgünb, 2011).

4.3.2 Geometrical Characteristics of Circular Deployable Structures

Assuming all the links have the same length, the final deployed shape of an SLE structure depends on the location of its revolute joints. If all of the links are pivoted to each other at the center of each link (zero off-center) the structure deploys linearly; otherwise the shape of the structure will turn into a curvilinear pattern. In case of a constant off-center value of all hinge points, the final deployed shape will be circular after deployment. Figures 4.22a and 4.22b show an example of a constant off-center structure before and after deployment, respectively. Basically, one end of the first link set is pivoted to the ground, while the other end is actuated using a linear pneumatic, hydraulic, or electric actuator acting on a straight horizontal line. It can be seen that the trajectory of points on different links does not follow a circular pattern, showing that the radius of curvature of the mechanism varies as it expands. For a circular expansion, all the pivot points are located off-center, which causes the structure to move while following a curve.

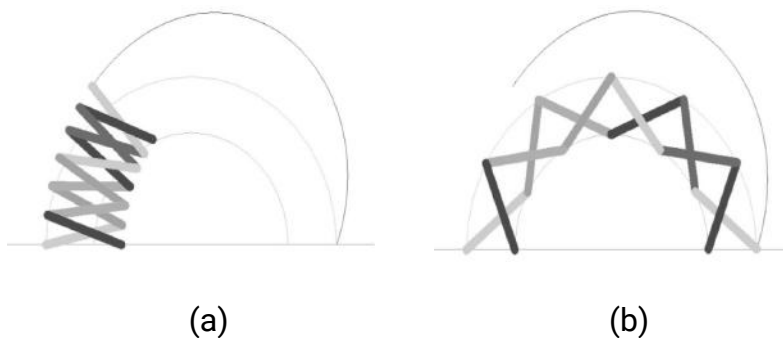


Figure 4.22 Circular deployable structure (a) in closed mode and (b) in deployed mode.

Referring to Fig. 4.23, the dependency of overall

radius on amount of deployment can be calculated by the following equation:

$$R = \frac{a \cdot \sin q}{\sin q - \sin^{-1} \frac{a}{R}} \quad (4.1)$$

$$\frac{1}{\sin \hat{1}} = \frac{\hat{1} \cdot b}{2} \cdot \hat{1}^\circ$$

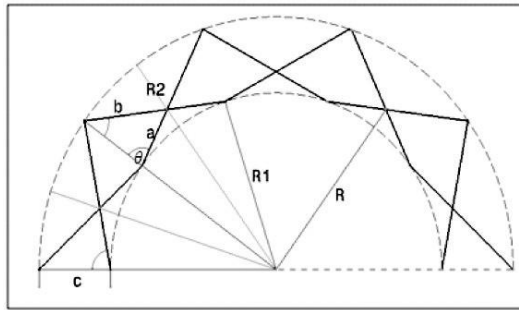


Figure 4.23 Dependency of the deployed radius on the offset and the amount of deployment.

As it is shown, the final radius of the deployed circle depends on the amount of offset, a/b . In the special case of $a = b$, the deployed radius R goes to infinity, which shows the structure deploys linearly. On the basis of this analysis, it can be concluded that by adjusting the offset value of the pivot points, we can control the final deployed shape of these types of structures. Depicted in the next section is a geometrical method to adjust the location of the pivot points in order for the mechanism to be deployed to a predesigned shape.

It should be mentioned that a range of dexterous grabbers can be designed on the basis of these deployable mechanisms. An important application of this concept can be found in the field of robotics where improving the dexterity of end effectors during the grabbing is of high importance. In Figs. 4.24 and 4.25 the 3D models of designed multifingered grabbers in the role of robotic grabbers are demonstrated.

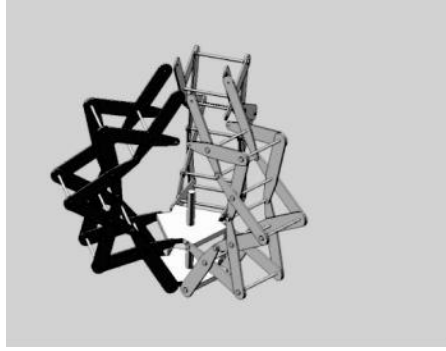


Figure 4.24 Three-finger robotic grabber based on an SLE in deployed mode.

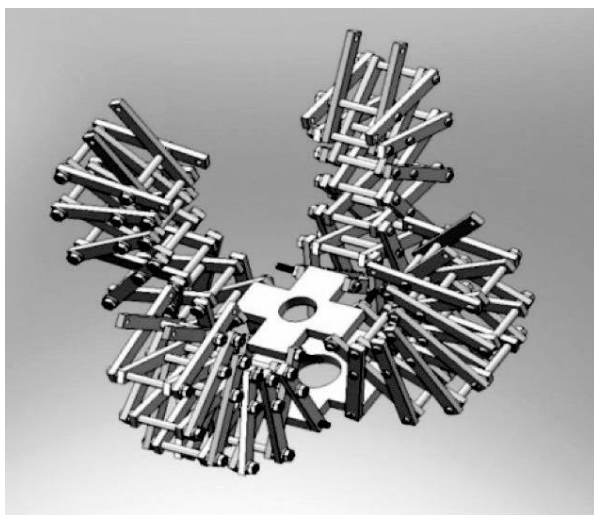


Figure 4.25 Four-finger robotic grabber based on an SLE in deployed mode.

An important advantage of these types of deployable grabbers over other types of grabbers is that these mechanisms can be deployed using only one actuator. Two experimental models were fabricated on the basis of these designs, and successful deployment is demonstrated in Figs. 4.26 and 4.27.



Figure 4.26 An experimental model for a three-finger robotic grabber

based on an SLE in deployed mode.

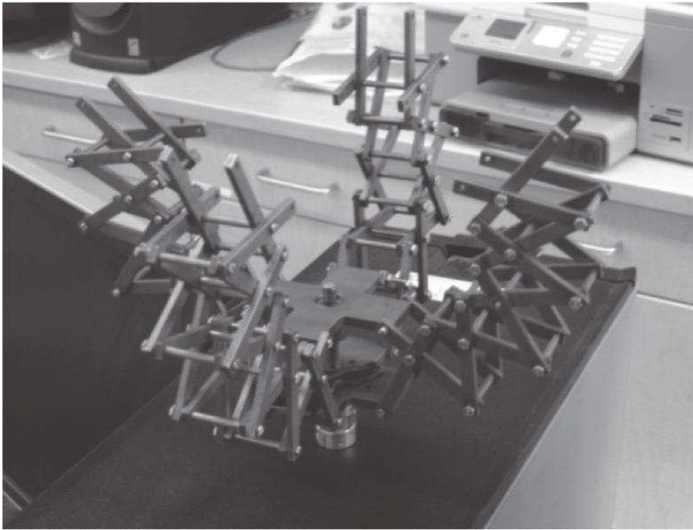


Figure 4.27 An experimental model for a four-finger robotic grabber based on an SLE in deployed mode.

4.3.3 Geometrical Characteristics of Curvilinear Deployable Structures

In Fig. 4.28, a design process to achieve a desired final deployed shape is shown. Two circular curves are attached to each other, and an offset of each curve is created. By equally partitioning each of the curves and constructing the links lines, it can be seen that the pivot joints offset from one of the strips varies in the transition point of the two circular curves, which allows the deployed shape to be a combination of the two curves.

Figure 4.29a,b demonstrates a virtual simulation of the proposed mechanism using ADAMS software. 26 rigid links have been pivoted by 35 revolute joints, and a point-curve constraint is applied at the end link where the actuation is applied on the constrained point. Basically, a point-curve constraint allows the link to have rotation but constrains a point of the link to move

on a selected straight line. In practice, the amount of contraction depends on the width of links; to have a more contracted shape, thinner links are required. In Fig. 4.29a, the total displacement of end effectors is plotted with

respect to the actuation displacement. As can be seen, the maximum reaching point of the end link does not necessarily happen at the states of fully closed, fully deployed, or predesigned configuration.

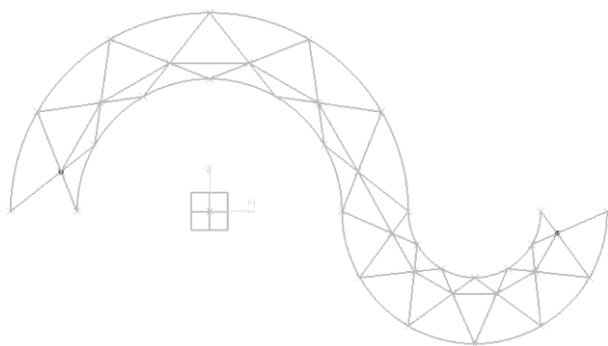
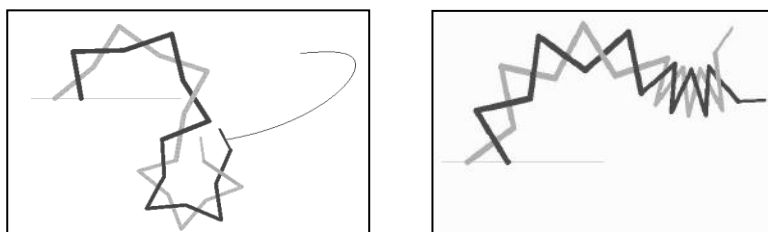


Figure 4.28 Initial curve, joint location, and path design.



(a)

(b)

Figure 4.29 Virtual modeling of the mechanism. (a) Deployed and (b) closed.

Figure 4.30 demonstrates the trajectory of the end effectors with respect to the actuation length variation. Figure 4.31 shows the trajectory of the end effectors during the deployment, which is a complex curvilinear path. As can be observed, during the deployment the radius of curvature at each instant is not constant and depends on the amount of deployment (the angle between two links) for a designed offset value. In the

next section, a mathematical model is presented to describe the exact geometry of trajectory and its relation with the actuation length.

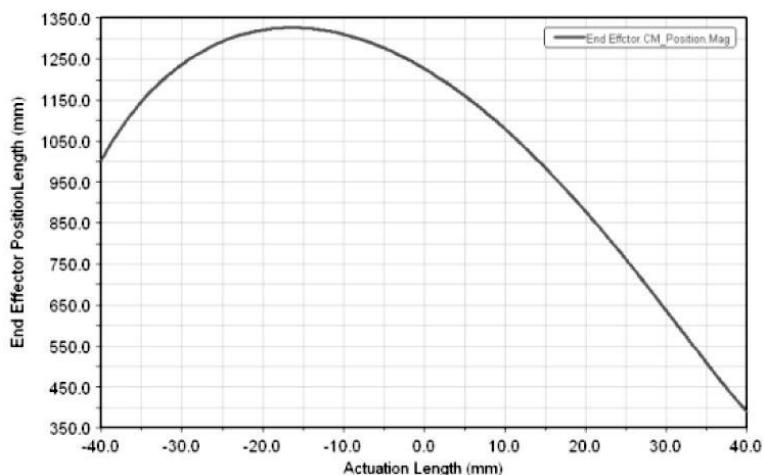


Figure 4.30 Trajectory of the end effectors vs. the actuation length.

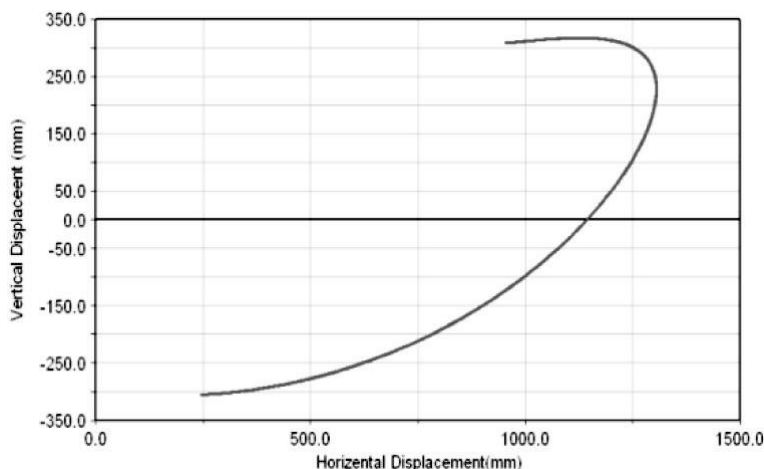


Figure 4.31 Trajectory of the end effectors during deployment.

Figures 4.32 and 4.33 show the displacement of the last three middle joints in x and y directions, respectively, with respect to time. The actuation length of zero refers to the design configuration of two combined circles, and two other extreme actuation

lengths refer to fully closed and fully deployed shapes.

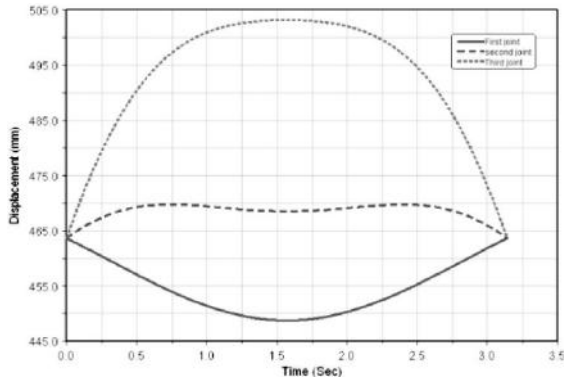


Figure 4.32 Horizontal displacement of the first three middle joints.

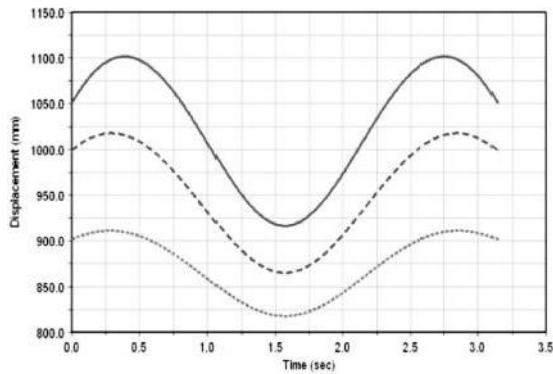


Figure 4.33 Vertical displacement of the last three middle joints.

4.3.4 Mathematical Model of Curvilinear Deployable Structures

This novel curvilinear structure could have many different applications in fields like biomedical engineering and civil engineering. To accomplish a specific task in any of the aforementioned engineering fields, it needs to be guided and deployed into a predetermined curve within a specific period of time. Any curve can be expressed by some mathematical models, and to curvilinearly expand the deployable

structure through the curve, some mathematical models for the entire structure are needed so that joints and links are properly actuated to accomplish the specific mission. Geometrical relations between the joints and links of the structure are used to obtain the following mathematical models (Fig. 4.34).

Using simple geometrical relationships between linkages, the position of the n^{th} pin in the structure can be easily calculated:

$$\vec{X}^{\sim} = \sum_{i=1}^n \frac{D_i \cos q_i}{\sin q_i} \vec{X}_n^{\sim}$$

$$\vec{Y}^{\sim} = \sum_{i=1}^n \frac{D_i \sin q_i}{\sin q_i} \vec{Y}_n^{\sim} \quad (4.2)$$

$$\vec{X}_n^{\sim} = \sum_{i=1}^n D_i \vec{X}_i^{\sim}$$

$$\vec{Y}_n^{\sim} = \sum_{i=1}^n D_i \vec{Y}_i^{\sim}$$

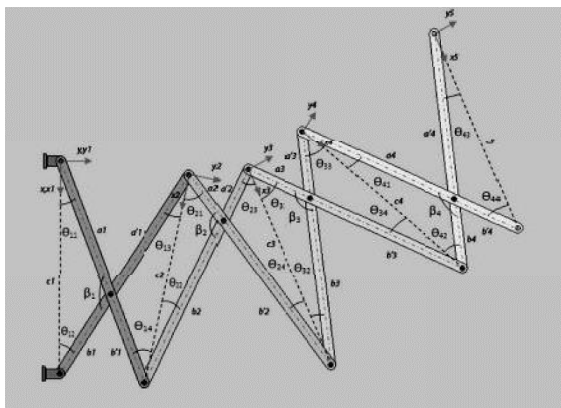


Figure 4.34 Geometrical properties of a curvilinear deployable structure.

Here all the parameters are illustrated in Fig. 4.34 and are calculated as follows:

$$\cos q_1 = \frac{\hat{a}_j^2 + c_j^2 - b_j^2}{2 a_j c_j} = F_j^* \quad (4.3)$$

Thus

$$\hat{a}_j = \frac{\sqrt{1 - F_j^{*2}}}{\sin q_1}$$

$$q_1 = \tan^{-1} \left(\frac{F_j^*}{\hat{a}_j} \right) \quad (4.4)$$

Similarly, for all angles we have

$$\hat{b}_j = \frac{b_j^2 + c_j^2 - a_j^2}{2 b_j c_j} = Y_j$$

$$\cos q_2 = \frac{2 \hat{b}_j c_j}{b_j^2 + c_j^2 - a_j^2} = Y_j \quad (4.5)$$

$$q_2 = \tan^{-1} \left(\frac{\sqrt{1 - Y_j^{*2}}}{Y_j^*} \right) = \hat{b}_j \quad (4.6)$$

$$b_i = p - q_{i1} - q_{i2} \quad (4.7)$$

$$q = \frac{\sqrt{a_i^2 + c_i^2 - b_i^2}}{a_i^*} = *$$

$$\cos \beta_i = \frac{c_{i+1} - c_i}{2 a_i c_{i+1}} \quad (4.8)$$

$$q\beta = \tan^{-1} \frac{\sqrt{1 - \epsilon_i^{*2}}}{\epsilon_i^*} \quad (4.9)$$

$$q = \frac{\sqrt{b_i^2 + c_i^2 - a_i^2}}{a_i^*} = \quad (4.10)$$

$$\cos \beta_i = \frac{c_{i+1} - c_i}{2 b_i c_{i+1}} \quad (4.11)$$

The length of the connecting line of any two opposing joints can be expressed as

$$= \frac{c_{i+1}}{\sqrt{a_i^2 + b_i^2 - 2 a_i b_i \cos \beta_i}} \quad (4.12)$$

The position of the midpin in the n^{th} local coordinate frame is

$$X_n = a_n \cdot \cos q_{n1} \quad (4.13)$$

$$Y_n = a_n \cdot \sin q_{n1} \quad (4.14)$$

For more simplification, the following substitutions are used in deriving the previously mentioned general equation for the position of the n^{th} pin in the structure:

$$p_{i+1} = c_i - (a_i + b_i) \cdot \cos q_{i2} \quad (4.15)$$

$$q_{i+1} = (a_i + b_i) \cdot \sin q_{i2} \quad (4.16)$$

$$q_{D,i+1} = q_{i1} - q_{i4} \quad (4.17)$$

$$p_1 = q_1 = q_{D1} = 0 \quad (4.18)$$

The orientation of the dotted line in the n^{th} pair of link is

$$m_{xn} = \tan q_{inc} \quad (4.19)$$

And the orientation of the line perpendicular to the dotted line in the n^{th} pair of link, which is usually the orientation of the end effectors, is

$$m_{yn} = \frac{1}{\tan q} \quad (4.20)$$

where c

$n-1$

$$q_{inc} = \text{Total incline} = \sum_{i=1}^{n-1} \Delta q_i \quad (4.21)$$

$i=1$

The structural characteristics of the mechanism are as follows: The number of links is 8, and the number of hinge joints is 12.

The length of the links is 20 cm. Other parameters are as follows:

Vector of a_i parameters: [153510] Vector of $a\dot{\phi}_i$ parameters: [153510] Vector of b_i parameters: [5171510] Vector of $b\dot{\phi}_i$ parameters: [5171510]

Using these equations, a kinematic simulation of the deploying process is shown in Figs. 4.35 and 4.36. Figure 4.35 demonstrates the change in the orientation of the end effectors of the last link set, which is the same as the orientation of the line perpendicular to the dotted line of the last link set with respect to the change in the length of linear actuator. Figure 4.36 demonstrates the trajectory of the end joint for a 5.5 cm actuation.

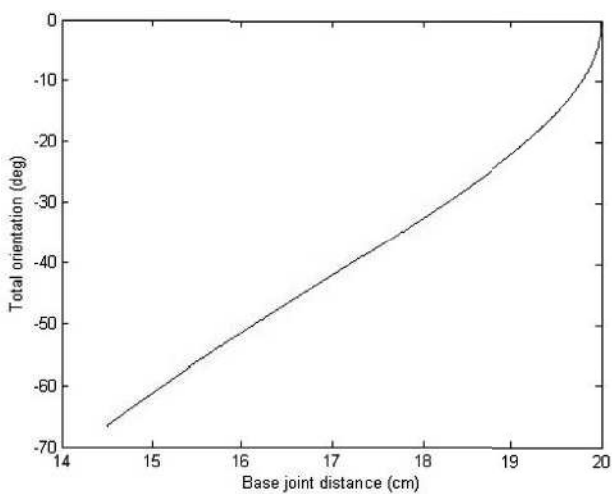


Figure 4.35 Change in the orientation of the last link vs. change in the displacement of the linear actuator.

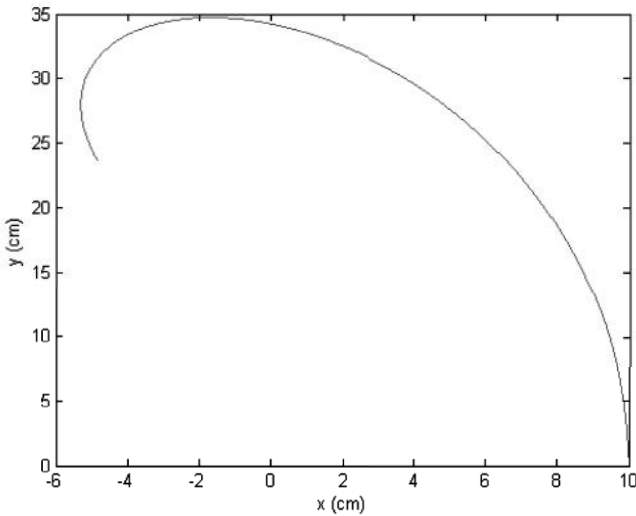


Figure 4.36 Trajectory of the end joint for a 5.5 cm actuation.

4.3.5 Servo-Motorized Intermediate Pins: A Novel Approach

In the previous sections it was shown that by adjusting the offset distance of pivots and lengths of intermediate linkages, the structure can be deployed to any complex shape. This point was proven through a multibody dynamic analysis, and eventually a mathematical model was developed. Similar findings were concluded by Maden, Korkmaza, and Akgünb (2011) in their study, where the authors more specifically discuss the implementation of this method in intricate architectural shapes. Despite the advantages of this model, it lacks flexibility in that pivot points limit the final deployed shape to only one. However, there is a way to overcome this drawback of the simple structure discussed above. This can be achieved through the introduction of a movable pin at the midspan between two ends of each linkage member, said pin being free to move on a screw that connects the two ends of the linkage, while being driven by servo motors installed inside the linkage structure. Two linkage members of a single scissor unit

are interconnected at the pins via a connection that permits said movable pins to rotate relative to each other. With the proposed mechanism a highly reconfigurable 2D robot is achieved to cover a sufficient amount of workspace with high dexterity (Fig. 4.37).

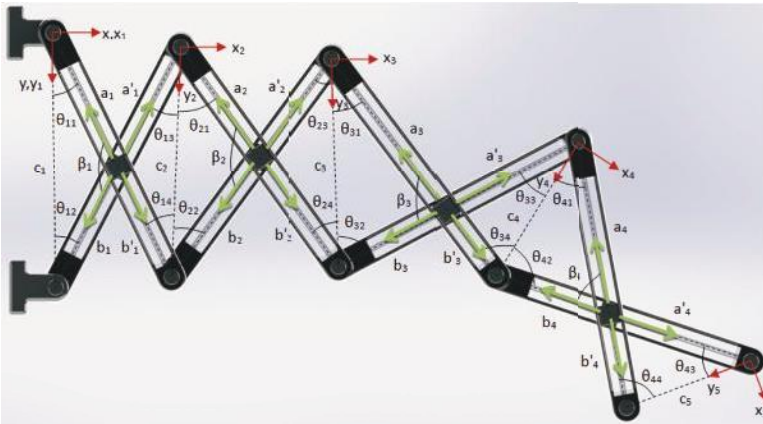


Figure 4.37 Novel deployable structure with motorized intermediate pins.

4.4 Laparoscopic Robotic System with Flexible Deployable Structures

4.4.1 Introduction to Our System

In the last section, we proved that an SLE structure with servo- motorized intermediate pins can take any configuration in its deployment plane. As the mathematical models and graphs show, this novel approach toward SLE structures makes it highly dexterous. This highly dexterous 2D robotic system can reach any point in its deploying plane at any orientation through redundant configurations. The system's configuration is obtained through proper control of servo motors to move intermediate pins and open/ close the span of the first link set. Different end effectors can be attached on the last link set of this robot. The robot can deliver the end effectors to any point at any orientation.

Mounting this 2D robot on a spherical joint yields a highly dexterous 3D robot capable of reaching any point in 3D space at any orientation. This is achieved through controlling the deployment plane via the spherical joint at the base by tilting and rolling. In 3D

space a plane can be defined by a point and a line, the line representing the orientation of the surgical instrument in the space and the point would be the base or the spherical joint by which the deployment plane of the 2D mechanism can be controlled. Therefore, if the deploying plane of the 2D structure coincides with the plane passing

through the mentioned point and line, the structure can now be deployed in the aforementioned plane in order to reach the desired position at the desired orientation in 3D space. The core idea of our proposed system is using the novel, highly dexterous 2D structure on a spherical base to make a robotic arm capable of dexterously manipulating surgical instruments and endoscopic cameras in 3D space (Shahinpoor and Gheshmi, 2012).

Our proposed robotic surgical system, which can also be used for training of medical students/residents, consists of two major units, a master surgeon console/station and a robotic surgical slave. We discuss each next.

- *Master surgeon console.* The surgeon's station consists of an ergonomically designed chair, a pair of vision goggles, and a pair of joysticks. The joysticks can be installed on the chair with the help of two platforms. The imaging goggles generate a panoramic view of the surgical scene and assist the surgeon to maintain a natural posture and handle surgeries more easily and comfortably. Imaging features such as magnification further help the surgeon operate more precisely. The surgeon sits on the chair as the master of the robotic surgical procedure and controls the surgical operation via the joysticks. His/ her hand movements are scaled, filtered, and translated into movements of surgical instruments snapped onto the robotic slave arms. Using a pair of joysticks and a pair of vision goggles is a space-efficient alternative for current bulky surgeon stations.
- *Robotic surgical slave.* The robotic slave arm is an SLE structure with movable midspan pins mounted on a spherical actuator to change its deployment plane. The relative locations of intermediate pins are altered by servo motors

located inside linkages. Figure 4.38 shows a linkage used in the proposed surgical slave robot. As shown in Fig. 4.39, several of these robotic arms can be attached to the sides of the surgical bed in order to manipulate surgical instruments and endoscopic cameras. At the end of the surgery the manipulator arms are contracted and can be placed underneath the surgical bed. Movements of these manipulator arms are under direct control of the surgeon as the master of the surgical intervention. With the proposed robotic surgical slave arms, minimal space is taken up in the surgical room during and after operations.



Figure 4.38 A typical linkage in an SLE structure with movable midspan pins.

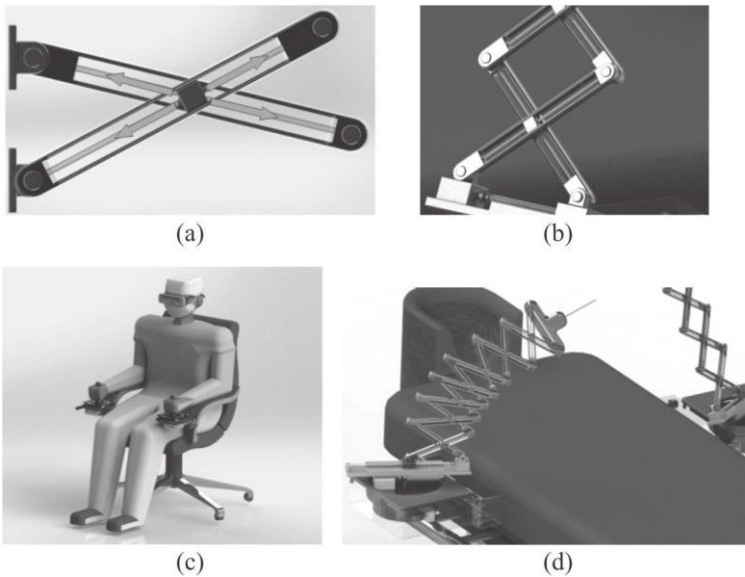


Figure 4.39 The proposed space-efficient robotic surgical system; different views.

Typically four arms are employed to perform robotic surgeries, but depending upon the complexity and need of a surgery, more arms can be utilized. The robotic arms can be either fixed to the sides of a surgical bed or put on a rail in order to be able to slide along the bed to perform surgeries on different parts of the body. As depicted in accompanying diagrams, the body of the structure can be covered with a flexible latex-like tube, preventing contact of human hands with the structure of the robotic system.

Figure 4.40 and 4.41 are views from the surgical scene, with flexible plastic sleeves installed around the deployable structure and covers on double-structure arms, respectively.

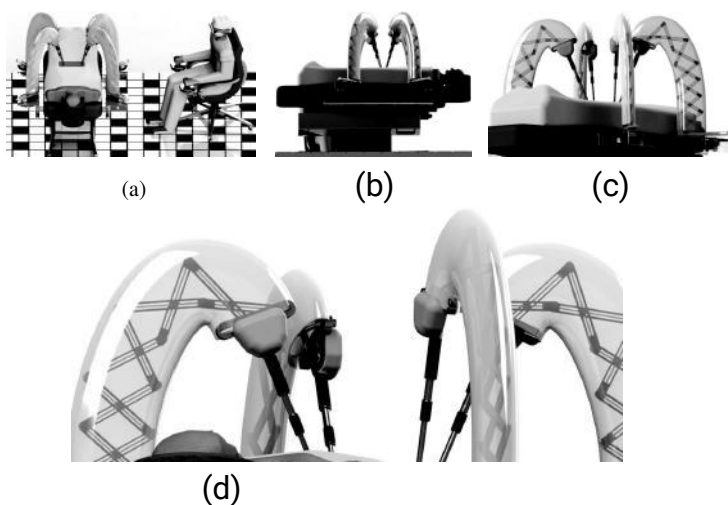


Figure 4.40 Different views from the surgical scene; flexible tubes installed around the deployable structure.

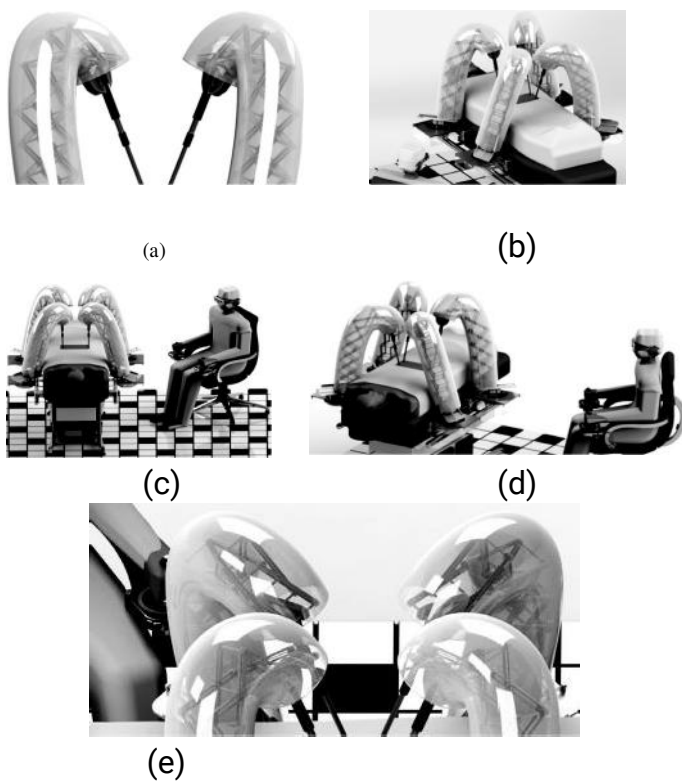


Figure 4.41 Application of covers on double-structure arms for enhanced safety.

In the proposed surgical system, at least one degree of rotational freedom is considered for surgical instruments. This rotation is about the axis of the surgical instrument, and its associated actuator is installed on the instrument itself.

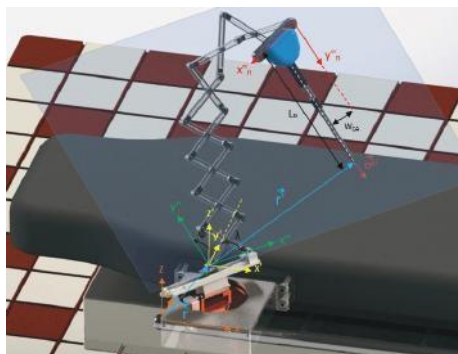
Redundant safety features can be considered for the robotic surgical system in order to prevent any possible damage to target organs. These features include position limit, speed limit, force limit, etc.

Different actuation methods and mechanisms can be utilized for altering the position of the intermediate pins, that of the first linkage set, and the rotation and tilting of the base. These methods include mechanical, hydraulic, pneumatic, piezoelectric, and electromechanical actuation and the use of parallel mechanisms.

The proposed robotic system is ideal for shipping to places with people in need of medical operations, such as battlefields, as that is one of the major goals of robotic surgery.

4.4.2 Forward and Inverse Kinematic Analysis

In the following section we derive forward kinematic equations for the proposed 3D deployable robotic surgical manipulator. Parameters of the robotic surgical arm are shown in Fig. 4.42.



(a)

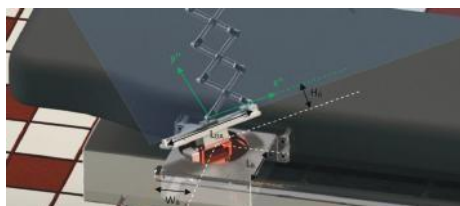


Figure 4.42 Parameters of the proposed deployable robotic surgical arm.

For the $x_{CC}y_{CC}$ deployment plane shown in Fig. 4.42, Eq. 4.2 becomes

$$\begin{aligned} \begin{pmatrix} X_{CC} \\ Y_{CC} \end{pmatrix} &= \begin{pmatrix} \cos q & -\sin q \\ \sin q & \cos q \end{pmatrix} \begin{pmatrix} X_{AC} \\ Y_{AC} \end{pmatrix} \\ &= \begin{pmatrix} \cos q & -\sin q \\ \sin q & \cos q \end{pmatrix} \begin{pmatrix} X_{AC} \\ Y_{AC} \end{pmatrix} \end{aligned} \quad (4.22)$$

$$\begin{pmatrix} X_{CC} \\ Y_{CC} \end{pmatrix} = \begin{pmatrix} \cos q & -\sin q \\ \sin q & \cos q \end{pmatrix} \begin{pmatrix} X_{AC} \\ Y_{AC} \end{pmatrix}$$

$$\begin{pmatrix} X_{CC} \\ Y_{CC} \end{pmatrix} = \begin{pmatrix} \cos q & -\sin q \\ \sin q & \cos q \end{pmatrix} \begin{pmatrix} X_{AC} \\ Y_{AC} \end{pmatrix}$$

X_{AC} and Y_{AC} are the position components of the tip of the surgical instrument in the $x_{AC}y_{AC}$ plane:

$$\begin{aligned} X_{AC} &= \\ W_{CA} &= Y \\ L_{SI} &= L_{SI} \end{aligned}$$

Other parameters in Eq. 4.2 remain the same, as defined in Fig.

4.34.

Thus, the position of the tip of the surgical instrument in the $x_{CC}y_{CC}$ coordinate frame is

$$\mathbf{r}_{CC} = X_{CC} \mathbf{i}_{CC} + Y_{CC} \mathbf{j}_{CC}$$

Components of $\mathbf{r}_{CC}$ in the $x_{CC}y_{CC}z_{CC}$ coordinate system are

$$r_{CC} = X_{CC} \sin \theta - Y_{CC} \sin q$$

$$\cos \theta / r_{CC} = X_{CC} \cos \theta +$$

Y
 CC
 CC
 CC
 s
 i
 n
 q

$$\sin \theta \mathbf{r}_{\theta Z} = Y_{\theta\theta} \cos q \quad (4.23)$$

Thus, $\mathbf{r}_{\theta}$ in the $x_{\theta}y_{\theta}z_{\theta}$ coordinate system is

$$\mathbf{r}_{\theta x_{\theta} y_{\theta} z_{\theta}} = (X_{\theta\theta} \sin \theta - Y_{\theta\theta} \sin q \cos \theta) \mathbf{i}_{x_{\theta} y_{\theta} z_{\theta}}$$

$$+ (X_{\theta\theta} \cos \theta + Y_{\theta\theta} \sin q \sin \theta) \mathbf{j}_{x_{\theta} y_{\theta} z_{\theta}} + (Y_{\theta\theta} \cos q) \mathbf{k}_{x_{\theta} y_{\theta} z_{\theta}}$$

(4.24)

or

$$\mathbf{r}_{\theta x_{\theta} y_{\theta} z_{\theta}} = \begin{bmatrix} X_{\theta\theta} \sin \theta - Y_{\theta\theta} \sin q \cos \theta \\ X_{\theta\theta} \cos \theta + Y_{\theta\theta} \sin q \sin \theta \\ Y_{\theta\theta} \cos q \end{bmatrix}$$

$$\mathbf{r}_{\theta} = \begin{bmatrix} X_{\theta\theta} \sin \theta - Y_{\theta\theta} \sin q \cos \theta \\ X_{\theta\theta} \cos \theta + Y_{\theta\theta} \sin q \sin \theta \\ Y_{\theta\theta} \cos q \end{bmatrix} \quad (4.25)$$

$$\mathbf{r}_{\theta} = \begin{bmatrix} X_{\theta\theta} \sin \theta - Y_{\theta\theta} \sin q \cos \theta \\ X_{\theta\theta} \cos \theta + Y_{\theta\theta} \sin q \sin \theta \\ Y_{\theta\theta} \cos q \end{bmatrix}$$

$$\mathbf{r}_{\theta Z} = \begin{bmatrix} 0 \\ 0 \\ Y_{\theta\theta} \cos q \end{bmatrix}$$

$$\mathbf{r}_{\theta} = \begin{bmatrix} X_{\theta\theta} \sin \theta - Y_{\theta\theta} \sin q \cos \theta \\ X_{\theta\theta} \cos \theta + Y_{\theta\theta} \sin q \sin \theta \\ Y_{\theta\theta} \cos q \end{bmatrix}$$

The position of the tip of the surgical instrument in the xyz coordinate frame is

$$\mathbf{r}_{\text{Sl tip}} + \mathbf{r}_{\text{c}} = \mathbf{r} \quad (4.26)$$

$$xyz = xyz = x' y' z'$$

where we have $\mathbf{r}_{xyz}$ and $\mathbf{r}_{xyz}$ calculated as the following:

$$\mathbf{r} = W - \sin q \cos \theta + \hat{L}_{DA} - c \sin \theta$$

$$x = \frac{B}{B} \hat{e}_A^2 \sim$$

$$r = L + H \sin q \sin \theta + \hat{L}_{DA} - c \cos \theta$$

$$y = \frac{B}{B} \hat{e}_A^2 \sim$$

$$r_z = H_B \cos q$$

or

$$\mathbf{r} = \hat{e}_W - H \sin q \cos \theta + \hat{L}_{DA} - c \sin \theta \mathbf{i}$$

$$\begin{matrix} x & \hat{e}_A^2 & B \\ y & \hat{e}_A^2 & 2^1 \\ z & B \end{matrix} \quad \hat{e}_A^2 \sim \theta - \diamond_{xyz}$$

$$+ \hat{e}_L + H$$

$$\begin{aligned}
 \hat{E} &= \frac{\hat{E}_{DA}}{L} \\
 \hat{E}_{CA} &= \left[W_B - H_B \sin q \cos \theta + \frac{H_B \sin q \sin \theta}{L} - c_1 \sim \sin \theta \right] \\
 &+ \left[L \sim + L + H \sin q \sin \theta + L - c \right] \cos \theta \\
 &+ \left[S_1 \sim + \frac{H}{L} \sin q \sin \theta - 1 \sim \right] \\
 &+ \left[1 \sim + \frac{H}{L} \cos q \right] \quad (4.29)
 \end{aligned}$$

$$r_{SI \text{ tip } i} = r_{SI} + r_{SI} + r_{SI} \quad (4.30)$$

$$xyz \ x \ xyz \ y \ xyz \ z \ xyz$$

According to Eq. 4.21, the orientation of the surgical instrument in the $x_{CC}y_{CC}$ plane is

$$\begin{aligned}
 \text{inc } q &= \text{Total incline in } x_{CC}y_{CC} \text{ plane} \\
 &= \sum_{j=1}^{n-1} \hat{A}_{CDj+1} \\
 &= 1
 \end{aligned}$$

Referring to Fig. 4.42, the components of the unit vector of the direction of the surgical instrument in xyz are

$$o = \cos q \quad SI \quad \text{inc}$$

$$\begin{matrix} x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix} \begin{matrix} \sin I \\ -\sin q \end{matrix} \begin{matrix} \sin q \end{matrix} \begin{matrix} \cos I \\ \end{matrix}$$

$$\begin{matrix} o \\ inc \end{matrix}^{SI} = \begin{matrix} \cos q \\ \sin q \end{matrix} \begin{matrix} \cos I \\ \end{matrix} + \begin{matrix} x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix} \begin{matrix} \sin q \end{matrix} \begin{matrix} \sin I \\ \end{matrix}$$

$$y \begin{matrix} x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix}$$

$$\begin{matrix} o \\ c \end{matrix}^{SI} = \begin{matrix} \sin q \\ \end{matrix} \begin{matrix} \cos q \\ \end{matrix}$$

$$z \begin{matrix} x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix}$$

$$\begin{matrix} Thu \\ s \end{matrix} \begin{matrix} o \\ sin q \end{matrix}^{SI} = \begin{matrix} \cos q \\ \sin q \end{matrix} \begin{matrix} inc \\ \end{matrix} \begin{matrix} \sin I \\ - \end{matrix} \begin{matrix} \sin q \end{matrix} \begin{matrix} \cos I \\ \end{matrix} \begin{matrix} i \end{matrix}$$

$$\begin{matrix} xyz \\ inc \\ x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix} \begin{matrix} x \\ y \end{matrix} \begin{matrix} xyz \\ \end{matrix} \begin{matrix} (4.31) \\ \end{matrix}$$

$$\begin{matrix} + \\ inc \end{matrix} \begin{matrix} \sin q \\ \cos q \end{matrix} \begin{matrix} \sin q \\ \cos q \end{matrix} \begin{matrix} k \\ \end{matrix} \begin{matrix} xyz \\ \end{matrix}$$

The unit vector of the direction of the surgical instrument in xyz

is

$$\begin{matrix} o \\ SI \end{matrix} \begin{matrix} e \\ \end{matrix} = \begin{matrix} xyz \\ \end{matrix} \begin{matrix} SI \\ \end{matrix} \begin{matrix} xyz \\ \end{matrix}$$

SI | |
 (
 xyz 4
 .
 3
 2
)

The proposed robotic arm can take multiple configurations to deliver a surgical instrument at a specific point at a specific orientation. To find the best configuration, which is inverse

kinematics, we need to define an optimization objective. For instance, to move from one configuration to another, we can minimize the sweep area, the electrical energy used by the system, etc. Once the objective is known, we can determine the system parameters with the use of numerical methods since there is no interest in pursuing an analytical solution for such complex forward kinematics equations.

Part 8 Conclusion

The Past, Present, and Future of Robotics

A Surgical and Anesthetic Perspective

Maunak V. Rana and Aladino De Ranieri

Origins

There has been a significant increase in the volume of robotic surgical procedures in the last decade. Robotic surgery was born in 1985 with the Programmable Universal Machine for Assembly (PUMA 560) robot arm, which was used in a CT-guided neurosurgical biopsy procedure. Since that fateful use of adjunctive technology, robotic surgery has increasingly been utilized for surgery. The first laparoscopic surgery, a cholecystectomy, was performed in 1987. The PUMA system was subsequently used to perform a robotic transurethral resection. In 1990, the AESOP system, developed by Computer Motion, became the first system approved for endoscopic robotic surgery. The new millennium saw the da Vinci system approved by the FDA as the first robotic system for laparoscopic surgery.¹ This development was a particularly momentous event in the history of robotic surgery because this was the first time the regulatory agency approved an entire system, including instruments and cameras, for robotic surgery. In essence, this heralded the transition from robotic tools to an entire robotic platform. The three-dimensional screen and image allowed for better visualization, coupled with the introduction of miniaturized arms that decreased tissue trespass and ergonomic wrist movement led to a virtual representation of surgery, controlled by a surgeon at a remote controller system.

Innovation in surgical technology coupled with exposure of anesthesiologists to keep abreast of these changes will allow for surgical teams to progress toward newer vistas, allowing for as real as experience as possible, regardless of the virtual approach to surgery.

Financial Considerations

As surgical advancement is considered, direct and hidden costs are to be considered, when evaluating the benefits of innovation. Currently, the da Vinci system has initial equipment costs in the arena of \$2 million. Coupled with this is a service contract of at least \$100,000 per year, and \$200 per-case single-use equipment. An estimate is that a typical robotic procedure costs \$1,000–2,000 more than a corresponding laparoscopic procedure.²

Additionally, surgical and operating room time factors into cost considerations for future development. The innovation in robotic equipment has led to improved visualization and technique with improvements in equipment. Operating room costs are variable, which range from \$15–20 per operating room minute for a basic surgery versus \$30–80 per

operating room minute for more complex cases.³ When analyzing the cost–benefit ratio, centers should ask whether advancement in the robotic platform leads to faster operating times and, therefore, less costs.

Surgical and Anesthetic Considerations

Robotic surgery has advanced the progress of virtually every surgical subspecialty. There has been a rapid development and incorporation of robotics in surgery over the past three decades, resulting in numerous benefits and, at the same time, several challenges. The laparoscopic approach rapidly became a preferred technique to many open procedures due to decreased perioperative comorbidities, decreased length of stay, decreased trespass on tissues with smaller physical footprint of equipment, and increased patient satisfaction.^{4,5} The trend and demand for minimally invasive surgery fueled a subsequent generation of robotics

In order to keep up with the addition of robotic surgery into the realm of training programs, consensus statements have been developed by a multidisciplinary group of experts. A gradual-stepped approach is advocated to guide a new robotic surgeon to proficient and expert levels.⁶ Innovation in medicine leads to improvements in patient safety. With advancement in robotic surgery, enhancement of the surgical platform would lead to improvement in visualization and

a decrease in iatrogenic injury that can result from the surgical technique. Vascular and visceral injury can be decreased, as manipulation of tissues and surgical dissection can be improved. Surgeon experience will also improve as newer technologies are embraced and utilized. Currently, the risk of iatrogenic injury has been reported to be 0.4–5 per 10,000 cases. This spread of injury would potentially trend downward with greater experience and improved technology.⁷

Alongside the surgical enhancements to the robotic world, vigilance and considerations from anesthesiologists involved in these operations can lead to safer operations.^{8,9} Anesthesia providers have a limited patient access due to the physical layout of the robotic platform and equipment.¹⁰ Currently, for robotic abdominopelvic surgery, a steep degree of Trendelenburg position is required to optimally visualize the pelvis and lower abdomen. This has obvious ramifications on patient position as a patient improperly secured may be in danger of falls and potential damage from surgical instruments and access devices. Additionally, neuropathic injuries may occur with inadequate and improperly positioned shoulder braces. This effect leads to a decrease in the FRC, leading to an altered V/Q mismatch, further challenging the anesthetic management of patients who may be obese and at risk for respiratory compromise. From a strictly mechanical perspective, migration of the endotracheal tube may occur, leading to a mainstem translocation of the tube, compounding atelectasis and pulmonary compromise. Furthermore, vital organ edema may develop, particularly in the brain, upper airways, and lungs. The result of this increased fluid aberration is an increase in intracerebral and ophthalmic pressures.

The physical presence of the pneumoperitoneum applied for visualization during robotic

surgery can lead to deleterious effects that anesthesiologists need to be cognizant about. The development of increased peak airway pressure, hypercarbia, atelectasis, with potentiality for gas embolism and pneumothorax are additive with the positioning concerns highlighted above.

Anesthesiologists also need to be vigilant for the risk of occult blood loss, as visualization is not as global as with open procedures. Hemodynamic along with cardiac changes in physiologic parameters can clue in the perioperative physician on alterations.

Due to the fact that robotic surgeries can be longer procedures than similar open approaches, the concern

of hypothermia may develop as patients are exposed to more gas via peritoneal insufflation along with anesthetic gas. As surgical technology improves, these risks would be decreased, leading to fewer theoretical iatrogenic concerns.

A significant enhancement that can lead to improvement in visualization is the use of augmented reality surgery. Augmented reality serves to enhance the visualization of a surgical target with a superimposed image, leading to an improvement in complex surgical dissections.^{11,12} The concept of adding and improving on spatially visualized objects, once the brainchild of science fiction, has a role in the advancement of robotic surgery. The improvement involves the concept of registration, which is the process of placing two images in the same coordinate system, effectively aligning corresponding points.¹² A clear example of this enhancement is having a preprocedure ultrasound or CT scan superimposed on a visualized surgical space.¹³ The benefit of this added reality is the overlaying of ultrasound anatomy over the visualized image. This addition assists the surgeon in appreciating the nuances of surface anatomy, an ability particularly suited for surgical encounters requiring fine dexterity, such as tumor resection surgery.¹⁴ Augmented reality will have a role not only in the education of established surgeons but also those physicians in graduate medical training programs.¹⁵

Anesthetic Considerations

Robotics has also been utilized in anesthesia, which includes manual and pharmacologic robots. Manual robots assist anesthesiologists in performing an increasing number of procedures to a differing degree.¹⁶ Patient intubation is being evaluated in a robotic platform as is the placement of nerve blocks for regional anesthesia.¹⁶⁻¹⁸ The Kepler robotic system has been utilized for intubation in humans.^{17,18} This system was tested in ASA I patients with a platform made up of a joystick, the JACO robotic arm, a video laryngoscope, and a software control system (Figure 22.1). A webcam was used to provide live video feed of the entire process. The median intubation time was 21 s. There were no reported dental injuries, esophageal intubation, mucosal/lip bleeding or damage. One intubation was abandoned due to laryngoscope fogging.

Pharmacological robots are those technologies that are involved in the

administration of anes- thetic agents to surgical patients. An early robotic

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Figure 22.1 The Kepler intubating system (edited image from McGill University Medical Center. Accessed November 28, 2015 from https://muhc.ca/sites/default/files/news/DrHemmerling_KIS_closeup_20avril2011.jpg). Courtesy of Montreal General Hospital MUHC.

anesthesia provider, McSleepy, was developed at McGill University. The device is a closed-loop system that has been used to deliver IV sedation, narcotic, and muscle relaxant.¹⁹ Closed-loop systems integrate patient data and calculate and administer anesthetic agents for surgical patients. The McSleepy system monitors patient consciousness and movement and then delivers agents based on patient characteristics and algorithmic programming. Additionally, surgeon and anesthesiologist preference can be incorporated into the platform's delivery of medication via artificial intelligence technology. Further robotic technology has been developed to assist in procedural sedation. A robotic "team" was tested in 2010 with McSleepy and da Vinci surgical robotics in a patient undergoing prostatectomy.²⁰ The SEDASYS system (Ethicon) has recently been approved by the FDA as a computer-assisted sedation delivery system to administer Propofol during gastrointestinal procedures, including

esophagoduodenoscopy and colonoscopy.²¹ The device utilizes standard ASA monitors and delivers Propofol and oxygen based upon patient responsiveness measured as grip strength to an audible cue. This technique is known as an automated responsiveness monitor (ARM). SEDASYS was presented to reduce

the risks of oversedation as patients had less oxygen desaturation than control patients. These target-controlled infusion devices have raised controversy as to their imprecision in achieving and maintaining the desired drug concentration.²²

Pain Management Robotics

Robotic platforms are also being tested for use in pain management procedures. In one study, a robotic needle arm driver was used to place twelve 22-gauge needles in a cadaveric lumbar paraspinal target.²³ The robotic arm was from URobotics Laboratory at Johns Hopkins based on a platform for accessing kidney targets via a fluoroscopic percutaneous approach. The system consisted of a robotic arm/needle driver, a mounting base, a touch screen, and a joystick controller. The motion of the robotic arm included multiple degrees of freedom with the ability to rotate for theoretical accuracy with needle placement. The physician operator controlled the robotic arm via a joystick and was able to retain manual control as required. Target points were a nerve root and the parafacet region. Biplanar fluoroscopic guidance was used after needle placement to gauge accuracy. The results were fairly precise as the needles were within 3 mm of

predetermined targets, with the average at 1.44 mm. Time for needle placement and fluoroscopic exposure was not reported in this feasibility study.

Another feasibility study was performed on patients comparing operator-controlled robotic blocks and manual blocks, each in 10 patients in the L3–S1 levels. One patient in the robotic group required to be converted to the manual approach due to malfunction as the needle was slipping from the driver during placement. In this study, robotic-assisted interventions were deemed feasible.²⁴

Moreover, robotic platforms utilizing flexible needles and trajectories to target tissues, thereby avoiding iatrogenic injury of neurovascular structures, have been tested and are under development.

Robotic-assisted procedures are also being tested for regional anesthesia and peripheral nerve blockade.²⁵ In this study, the da Vinci system was used to perform an ultrasound-guided nerve block with a Tuohy needle and perineural catheter with an ultrasound phantom. This feasibility study demonstrated that the da Vinci system, already utilized for surgical indications and handling surgical instruments, was able to grasp and manipulate a 21-gauge 90-mm needle; additionally, the platform allowed for sufficient dexterity to attach a syringe (luer-lock) to the injection portion of the needle. Furthermore, the stimulating portion of the needle was attached to the peripheral nerve stimulator without difficulty. While the ultrasound probe required manual placement on the target, the high-frequency probe was stabilized by the robotic platform.

The Magellan system is a robotic platform uniquely devised and utilized for peripheral nerve blockade, which may be a less expensive option than other systems as this is a dedicated nerve block platform. The cost of a robotic arm is approximately \$50,000.²⁶ This Canadian system is a multicomponent platform: a robotic arm, joystick controller, nerve block, and needle with an ultrasound device. Dedicated control software is used to guide the system that allows for remote performance of nerve blocks.

The robotic arm is the JACO (Kinova Robotics), which is an assistive robotic device that has been utilized for performing activities of daily living. The weight of the carbon fiber device is 5 kg. The arm can be configured to right or left side, which can be customized to physician comfort and preference. The arm has six degrees of motion with a reach of 35.4 inches with two fingers and an opposing “thumb.”

Additionally, the operator can control the speed of the arm via three settings: low (0.15 m/s), medium (0.075 m/s), and high (0.0425 m/s). Safety mechanisms are built into the system to prevent insertion of the needle beyond a preset depth.

A benefit of this platform is that the arm is mounted via a console at the bedside that allows close proximity of the interventionalist.²⁶ The sciatic nerve at the popliteal fossa was the target of researchers in this evaluation of patients undergoing surgery with sciatic nerve block. This study evaluated 13 patients receiving a total of 16 blocks who underwent testing with identification of the sciatic nerve by a manual approach.

From an ergonomic and logistical standpoint, the Magellan system was placed at the head. The robot was then used to place a tuohy needle and inject 35 ml of 0.25 percent

bupivacaine via an out-of-plane ultrasound technique targeting the nerve sheath, but avoiding intraneural injection. The administration of medication was performed manually, with aspiration intermittently after every 5 ml of administration. In this study, all 16 blocks were found to be successful with a mean time of just over 3 min for the block; no complications were noted. Ultrasound guidance alone was used to facilitate the nerve block without nerve stimulation.

Future Directions

Surgical robotics have advanced every surgical sub- specialty. Technical enhancements improve opera- tive access, suturing, and range of motion of tissue manipulation. An improvement that has noticeably enhanced surgical approaches to robot-assisted pro- cedures is via the addition of laparoscopic single-site surgery (LESS) to the surgical armamentarium. The development of LESS has allowed for a single port to access surgical targets, thereby decreasing surgi- cal scar, improving tissue healing, and lesser tissue pain. This platform would also be of benefit to anes- thesiologists as accessing surgical targets via a single port would have a smaller “footprint” and allow for triangulation of tissues. These benefits are coupled with improved surgical access and dexterity that the robotic platform provides.^{4,5}

Another future arena for robotic surgery is in the resection of head and neck malignancies.²⁷ Due to the increase in cases of oropharyngeal cancers, linked to the predilection of human papillomavirus to the

Table 22.1 Surgical operating platforms

Platform	Comment
da Vinci (Intuitive Surgical)	Most commonly used platform; patent to expire in 2016
RAVEN (University of Washington/University of California)	Remote platform with Linux operating system
SPIDER (Transenterix)	Single-port laparoscopy with flexible instruments
SURGIBOT (Transenterix)	Portable robotic system; allows for

oropharynx, there is an incidence in the number of patients presenting for surgical resection. Robotic surgery has been advocated for resection of these tumors via a transoral approach. Innovations in urologic surgery include increased use of robotics via the LESS platform. Hepatobiliary surgery has advanced with the integration of the robotic approach.²⁸ This study evaluated patients who underwent robot-assisted liver surgery (ROBR) and compared surgical outcomes with laparoscopic liver resection (LAPR). The rate of major hepatectomy was higher in the LAPR approach, while a parenchyma-sparing approach was used in the ROBR. The rate of conversion to open was higher in the ROBR group versus the LAPR approach. In addition, the ROBR group had a higher mean blood loss. The authors opined, however, that despite the higher blood loss and conversion to open surgery rates, the robotic approach allows for increased dexterity and access to poorly accessible targets, particularly superiorly and posteriorly located liver tumors. More authors have corroborated this benefit.²⁹ A significant benefit with the introduction and refinement of the robotic approach is the ability to provide resection with parenchymal preservation.

Robotics and image-guided percutaneous endovascular repair are increasingly utilized in vascular surgery. These minimally invasive techniques increase the surgeon's precision and dexterity and consequently are replacing the traditional open techniques and greatly reducing the associated comorbidities. Endovascular repair is the first-line treatment for an abdominal aortic aneurysm.³⁰ The Sensei robotic system has been utilized for catheter guidance for cardiac applications. The Niobe system is a stereotactic magnetic navigation system used for catheter guidance and cardiac ablation.³¹

Numerous robotic systems are being developed, which could compete with the near-universally

utilized da Vinci platform with the patent expiring in 2016 (Table 22.1). The Raven I and Raven II robots are prototype systems that incorporate the advantages of the da Vinci system – remotely controlled platform with enhanced dexterity, which can facilitate minimally invasive surgery. The Raven and evolving Raven II systems are Linux-based operating platforms and have a network-integrated researcher who can interact with the robot in real time. This is an advancement from current systems in that updates and support can occur during surgery, rather than before and after the surgical procedure.³² TransEnterix developed the SPIDER surgical system, which uses flexible instruments to facilitate single-port laparoscopic surgery.³³ Presumably with the flexible instrument system, more inaccessible targets may be reached with more pliable instruments. The SurgiBot, also produced by TransEnterix, is a portable robotic laparoscopic system in the evolution of the SPIDER technology and is currently being FDA-tested. The portable SurgiBot has a smaller footprint, thus allowing the surgeon to operate at the bedside within the sterile

field. It requires less ancillary staff support and utilizes novel flexible instrumentation, which may reduce the number of incisions and improve structural access.³⁴

Summary

Robotic surgery has advanced from being an adjunctive device to an integrated and fundamental technology for operative patient care. Costs of devices are

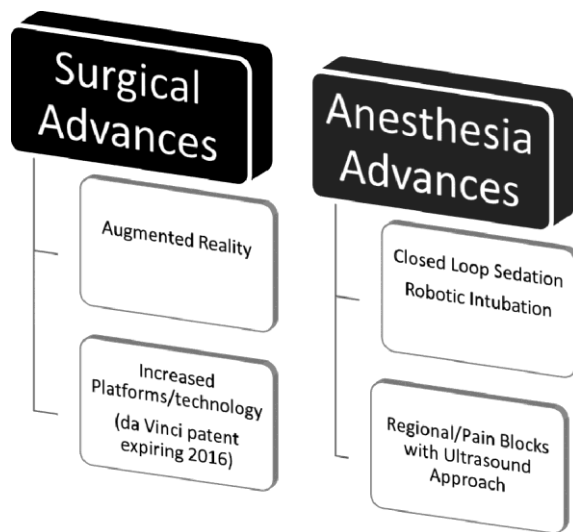


Figure 22.2 Future directions in surgery and anesthesia

decreasing along with smaller platforms for bedside procedures. Along with advancements in the surgical area came developments in the anesthesia world (see Figure 22.2). From closed-loop systems designed to allow drug delivery in a precise, algorithmic fashion to the use of robotics for interventional procedures, the robot serves to advance patient care. The October 2010 robotic surgery in Canada involving a robotic anesthesiology device may be a foreshadowing of the future of the operative environment.

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