Matthew Kroh
Sricharan Chalikonda
Editors

Essentials of Robotic Surgery

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To my wife, Jean, for her love and support,
and to our wonderful children, Sophia, Eva, and Carter,
who fill me with joy.

M.K.

To my wonderful wife, Stephanie, and to our boys,
Shreyas and Symon. You are the best. Thank you.

S.C.

Preface

Disruptive technologies have resulted in quantum advances in surgical procedures. The efforts of such innovation yield better outcomes for our patients and, fundamentally, are at the core of surgical innovation. The introduction of laparoscopy to general surgery in the 1990s and the ensuing "minimally invasive" revolution have ushered in a new era of faster recovery, less pain, and fewer peri-operative complications. Initially with cholecystectomy, and eventually throughout the diverse procedures that comprise general surgery, minimally invasive techniques continue to be taught, remodeled, and refined.

The introduction of robotic assisted surgery has continued this progress. Robotics in the realm of general surgery is a relatively new application, but it is rapidly expanding. Advanced robotic technologies allow surgeons and their patients access to procedures performed with high definition, 3-dimensional visualization of structures, precise and ergonomic movements with increased degrees of freedom, and the possibility to re-create open surgery in a less invasive way.

This text is unique in that it represents the application of this advanced technology to the major disease processes of general surgery. Written by recognized leaders in their fields, each chapter examines specific applications of robotic surgery in a sub-specialty of general surgery. Each author examines the technical aspects of the respective robotic procedures and also reviews the current applications and outcomes for these techniques. The editors are grateful for the participation of these expert surgeons in this effort, and we understand that through luminaries such as these the advancement of the practice of surgery continues.

We hope that you enjoy this comprehensive resource for some of the most cutting-edge procedures in general surgery.

Cleveland, OH, USA

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History of and Current Systems in Robotic Surgery

1

Heidi Ryan and Shawn Tsuda

Introduction

By strict definition, a robot is a mechanical or virtual agent, controlled by a computer program or other electronic circuitry. Autonomy, either fully or partly, is a prerequisite to the definition of a robot. This can range from a machine that simply mimics humanoid or lifelike movements to the concept of fully realized robots that have intelligence or self-awareness.

The branch of science and technology dealing with the concept, design, construction, and implementation of robots is robotics. The word "robot" itself originates from the Czech language, meaning "forced labor." It was first coined by Czech playwright Karel Capek in 1921 [1]. If applying the requisite definition of autonomy, and therefore the implication of electronic or computerized components, the first robots were developed by William Grey Walter in England in the late 1940s. But societal impact can first be recognized by the use of robots by General Motors first in 1961 to lift pieces of heavy metal in the factory to avoid risk to human workers and improve efficiency (Fig. 1.1). Robots have since been applied to major facets of modern society, most notably in manufacturing and most impressively in tasks and environments hostile to humans, such as space, deep sea, or in combat.

Robots in Medicine

Robots in surgery have been used in a spectrum of capacities. One way to classify how robots are used to assist surgeons was described by Nathoo and colleagues and was comprised of three systems. First, a system can be supervisory controlled, where the surgical intervention is preprogrammed into a computer, and the system then carries out the steps autonomously, albeit under the supervision of a surgeon. This can be combined with patient-specific imaging, which navigates the robotic system specifically to the patient's anatomy. Secondly, a robot can function through telesurgery. Here, the surgeon manipulates the robot remotely, from any given distance, in real time. The third way robots can provide surgical assistance is through a shared-control system. A shared system implies that while the surgeon controls the movements of the robot, the robot in turn also provides input or feedback to the actions. This can be through enhancement of movements such as reducing tremor or limiting movements which would result in error (Table 1.1) [2].

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Fig. 1.1 Robots in the vehicle manufacturing industry (Courtesy of Universal Robots and Foto Design Gasparini)

Table 1.1 Classification system of "robots" by Nathoo et al.[a]

Categories	Definition	Examples
Supervisory	The surgeon preprograms the robot off-line first and the robot follows the specified motions autonomously, albeit under the supervision of the surgeon	Probot ROBODOC®
Telesurgical	The robot is directly controlled by the surgeon via an online input device or surgical manipulator. The robot faithfully follows the motions of the input device simultaneously in a master-and-slave-like manner	Da Vinci™ ZEUS PARAMIS SPORT™
Shared-control	The surgeon remains in control of the procedure and the robot offers some feedback or provides stability for the instrument being manipulated by the surgeon. The control is somewhat shared by both the surgeon and the robot	da Vinci™ Eye robot

[a]Data from Ref. [2]

Initial Robots

Dr. James McEwen, Dr. Brian Day, Geof Auchinleck, and a team of engineering students developed the first surgical robot in Vancouver, BC, in 1983. Dubbed the "Arthrobot," it was used in total hip arthroplasty to prepare the femur for implantation after femoral head resection [3].

In 1985, a robot called PUMA 560 was used to place a needle for a brain biopsy using CT guidance. PUMA 560 had six degrees of freedom and was able to reach any point within its axis of movement. This robot was able to determine its own position via a potentiometer which controlled six servomotors—a mechanical concept known as a servomechanism or the ability of a device to accept negative feedback and correct its function accordingly (Fig. 1.2) [4].

In 1988, the Probot was developed at the Imperial College of London and was used to perform prostatic surgery. It is designed to allow a surgeon to specify a volume within the prostate to be cut and then automatically cut this without further intervention from the surgeon. In 1992, the ROBODOC® from Integrated Surgical Systems was developed to reduce human error in milling cementless implants for hip replacement. Radiographic evaluations showed statistically

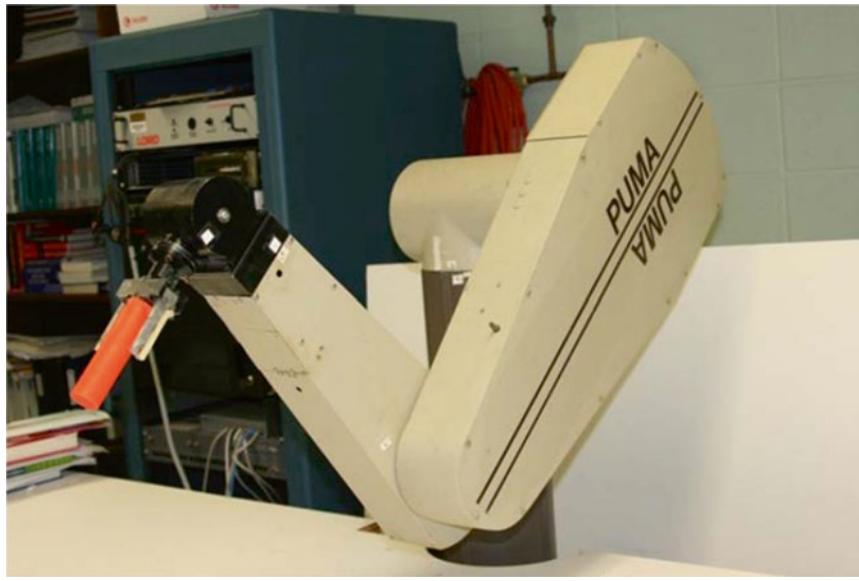

Fig. 1.2 PUMA 560 in experiment (Used with permission from Lin H-I and Lee C.S.G. Measurement of the Robot Motor Capability of a Robot Motor System: A Fitts's-Law-Inspired Approach. Sensors 2013; 13:8412–8430)

superior fit and positioning for the femoral component of hip replacements in a large series [5].

The late 1990s saw the first iterations of robotic-assisted surgery as is most common today. The first of these were laparoscopic camera-holding robotic devices. Dr. Yulun Wang and colleagues, through a National Aeronautics and Space Administration (NASA) grant, created the Automated Endoscopic System for Optimal Positioning or AESOP® (Computer Motion). The idea with AESOP® 1000 was to replace the human camera holder, allowing the primary surgeon to control the camera with a hand or foot switch. A more advanced AESOP® 2000 was developed in 1996 and included voice control. Later, in 1998, a more advanced model with an additional elbow joint was coined AESOP® 3000. AESOP® was initially used to perform laparoscopic cholecystectomies, but was eventually applied to more advanced laparoscopic procedures such as adrenalectomy and thoracoscopic operations (Fig. 1.3) [6–8].

A similar camera manipulator is the EndoAssist, which is programmed to follow intuitive head movements of the surgeon. This free-standing device uses an infrared headband worn by the surgeon and a receiver that translates the transmitted signals into motion. The receiver unit determines the surgeon's field of view by detecting his or her head position and moves the camera accordingly. Thus, the camera angle can easily be controlled by simple glances in the desired direction, instead of relying on and communicating with an assistant for camera placement. Movement of EndoAssist only occurs when activated by the foot switch, which otherwise frees the surgeon's head movements when camera adjustment is not needed. The EndoAssist robot has been used to aid in cholecystectomies and various colorectal surgeries [9–11].

PMAT is another camera-holder system designed by Professor Mishra of India, with the assistance of engineers from Mexico. The PMAT system offers three degrees of freedom and consists of a lightweight aluminum harness attached to a laparoscopic camera worn over the surgeon's shoulders. Active movement of the laparoscope is controlled by a switch on the harness and passive motion can be conducted by simply turning the operator's body. This mechatronic assistant acts as an extra hand, eliminating the need for a secondary human camera operator, and provides

autonomy for the surgeon to maneuver the laparoscope by himself or herself. This device has been used successfully in laparoscopic appendectomy and ovarian cystectomy and has helped in the evolution of ideal laparoscope-holding devices [12].

In Romania, a robot called PARAMIS (Parallel Robot for Minimally Invasive Surgery) was experimentally developed and invented for laparoscope camera positioning. This system was produced at a relatively low cost considering the extensive benefits offered including the possibility to transform PARAMIS into a rigid and stable multi-armed robot controlled from a console, as well as allowing a surgeon the ability to command a large area of positioning of the laparoscope and other surgical instruments, from many different interfaces: joystick, microphone, mouse, keyboard, and haptic device. Error and damage to the surgical patient is minimized due to the various advantages offered by PARAMIS, which assist the surgeon to prevent fatigue and maximize capabilities. Advantages include: tremor reduction, enhanced precision of movements, utilization of both hands during procedure, reduced eyestrain, and enhanced visibility or control of surgical field, and the need for a second surgeon present during the entire procedure is eliminated [13].

Development of Current Systems

The first da Vinci® (Intuitive Surgical, Inc.) prototype called ZEUS emerged in the late 1990s. Introduced by Computer Motion, the three-armed robot is equipped with a voice-activated AESOP®-based endoscope and two arms that act as extensions to the surgeon's arms that are equipped to hold 28 surgical instruments. The second set of arms can be remotely controlled by a surgeon on a computer, allowing precise and microscopic movement. In 1997, ZEUS was first applied in a laparoscopic cholecystectomy. In 1999, ZEUS

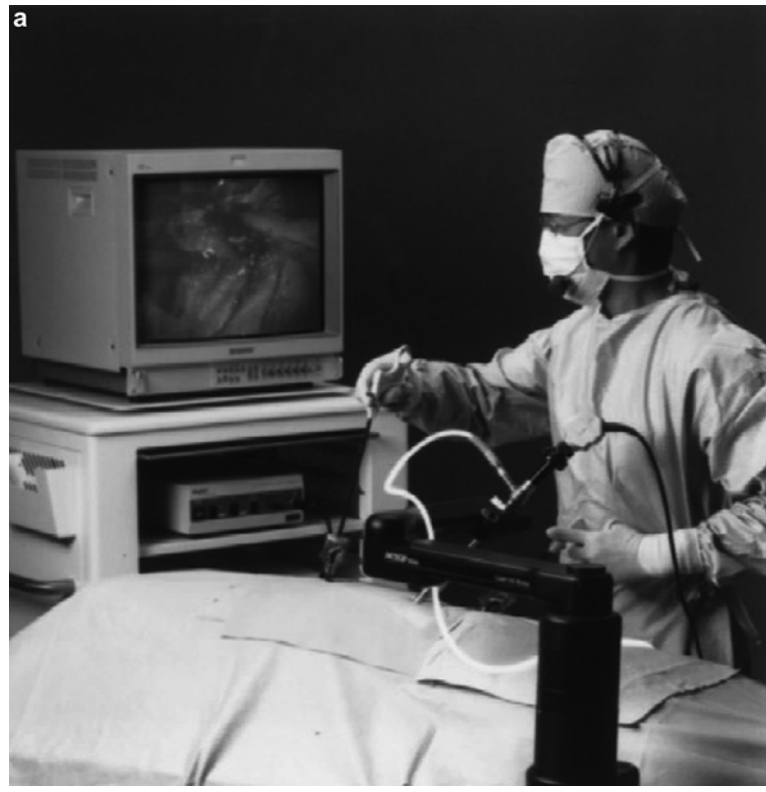

Fig. 1.3 AESOP®. ((**a**): Used with permission from Intuitive Surgical, Inc., and from Allaf ME, Jackman SV, Schulam PG et al. Laparoscopic Visual Field: Voice vs foot pedal interfaces for control of the AESOP robot. Surgical Endoscopy 1998;12:1415–1418. (**b**): Used with permission from Mettler L, Ibrahim M. Jonat W. One year of experience working with the aid of a robotic assistant (the voice-controlled optic holder AESOP) in gynecological endoscopic surgery. Human Reproduction 1998; 13(10): 2748–2750)

Fig. 1.3 (continued)

was successfully used to perform a fallopian tube anastomosis in Cleveland and robotically assisted heart bypass by Dr. Wolf and Dr. Michler at Ohio State University. Other monumental cases using ZEUS include the first beating heart coronary artery bypass graft (CABG) in 1999 by Dr. Douglas Boyd and Dr. Reiza Rayman in Canada, as well as a remote gall bladder surgery in Strasbourg, France, performed by Dr. Marescaux in New York. In 2003, Computer Motion merged with Intuitive Surgical to increase efforts in advancing medical robotic technology; however, ZEUS was shortly discontinued in favor of the newer and more sophisticated da Vinci® Surgical System (Fig. 1.4) (Table 1.2) [14].

da Vinci® Surgical System

In 2000, Intuitive Surgical released the da Vinci® Surgical System to the public after its FDA approval. The da Vinci® Surgical System is also a multi-armed interactive robot comprised of a control console, a vision system cart, and a patient-side cart (Fig. 1.5). The control console seats the surgeon and is usually located remotely from the

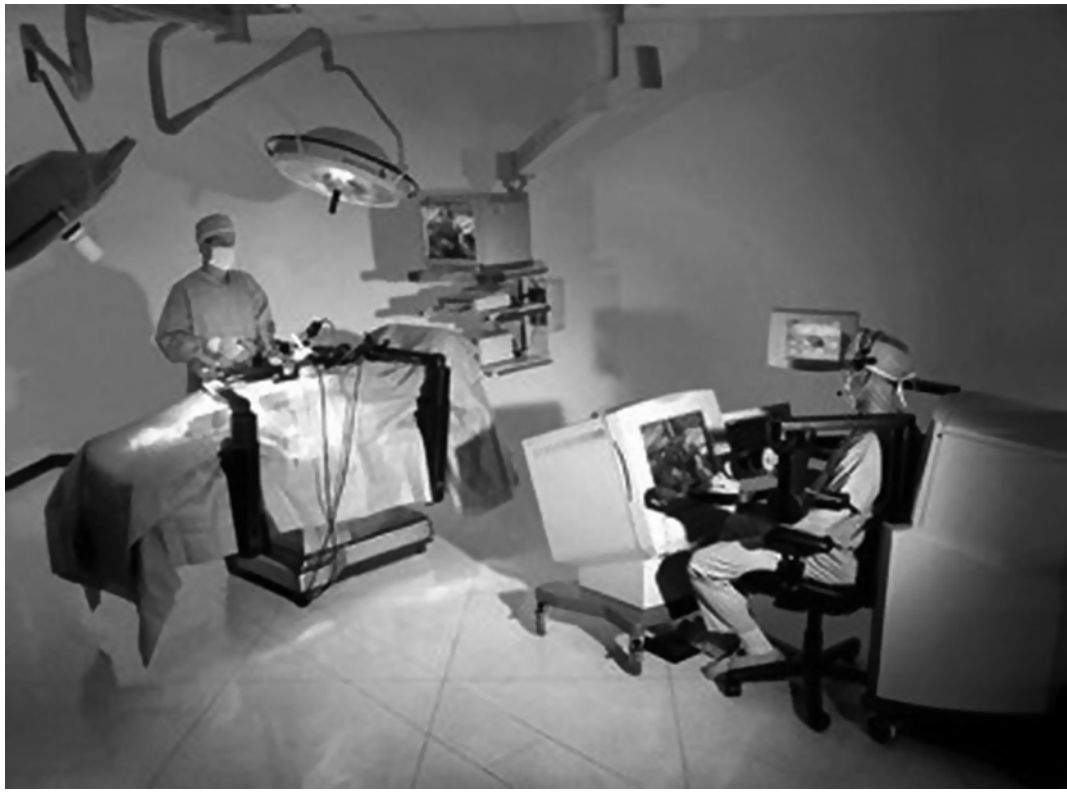

Fig. 1.4 ZEUS Robotic Surgical System (Used with permission from Faust RA, Kant AJ, Lorincz A et al. Robotic endoscopic surgery in a porcine model of the infant neck. J Robotic Surg 2007;1:75–83)

Table 1.2 Landmark surgeries using early robots

Year	Event
1983	Arthrobot was developed for preparing the femur during a total hip arthroplasty
1985	PUMA 560 was used to place a needle for a brain biopsy
1988	Probot was developed at the Imperial College of London and was used to perform prostatic surgery
1992	ROBODOC® was introduced by Integrated Surgical Systems to assist with femur hip replacements
1997	ZEUS, made by Computer Motion, was first used to perform laparoscopic cholecystectomy
1999	ZEUS was used to perform fallopian tube anastomosis
1999	ZEUS was used to perform the first robotically assisted heart bypass at the Ohio State University in the United States World's first robotic-assisted CABG surgery using ZEUS was also performed in Canada
2001	Professor Marescaux, while in New York, used ZEUS to remotely perform gall bladder surgery in Strasbourg, France
2003	Intuitive Surgical merged with Computer Motion and ZEUS was discontinued

operative table. The console is ergonomically supportive, designed to provide a position in which the surgeon manipulates the master controls while viewing live high-definition 3D video input from the vision system. Movement of the surgeon's hand and instrument tips are synchronous and intuitive, unlike with conventional laparoscopy, during which the surgeon must move the hand in the opposite direction of the instrument tip motion due to the fulcrum effect [15]. The da Vinci®

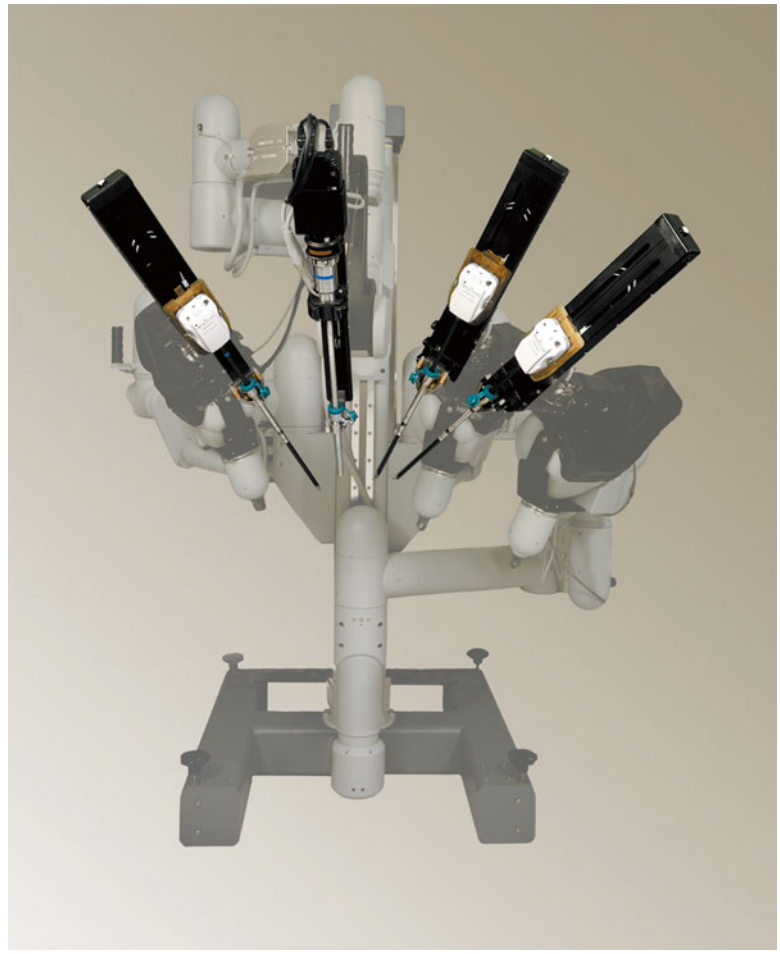

Fig. 1.5 Patient cart with 4th arm: da Vinci® Surgical System (Copyright © 2014 Intuitive Surgical, Inc. Used with permission)

restores proper hand-eye coordination, and the robot follows surgeon input synergistically as the movements are made at the fingertip controls [1].

In addition, the computer system is equipped with software and hardware filters that scale large movements to micromovements, thereby compensating for hand tremors and eliminating potentially dangerous effects [16]. This also enables fine and precise movements of the surgical instruments. The vision system cart is comprised of a processor, video monitor, lighting, and related endoscopic camera equipment. The camera is manipulated by a robotic arm that provides a steady view of the operative field for the surgeon [17].

Two to three surgeon-commanded robotic arms with wrist-like joints called EndoWrist® (Intuitive Surgical, Inc.) and a camera-manipulating arm are located on the patient-side cart. The multi-articulated EndoWrist® is capable of a wide range of motion superior to the human wrist and allowing complex maneuverability. The total number of robotic arms will depend on equipment model and options. More than 50 specialized EndoWrist® instrument tips are available to function as high-energy cautery instruments, forceps, needle drivers, scissors, and retractors. These detachable instruments can be exchanged as needed during the procedure, enhancing the diversity of tasks that can be performed during the surgery. The da Vinci® offers amenities, such as a dual console for an assistant surgeon, Firefly imaging for infrared angiography using fluorescent dye, and single-port equipment to perform

single-incision cholecystectomy as recently approved by the FDA [17].

Although the name da Vinci® Surgical System implies the label "robot," the da Vinci® is rather a computer-assisted telemanipulator. The term robot usually refers to a computer-controlled machine that is capable of independently performing preprogrammed tasks. Although the da Vinci® is capable of providing some feedback to the operator, the device does not perform autonomous tasks. Instead, each movement is dictated by the surgeon via the control console, similar to a master-and-slave-like manner [18]. Furthermore, the term telemanipulator or telesurgery suggests that there is distance between the surgeon and the patient; as previously mentioned, the console is located separately from the patient's bedside.

Similar to laparoscopic surgery, the da Vinci® creates small incisions through long instruments, uses the abdomen as a barrier, and requires a camera for visual assistance inside the body. However, the da Vinci® is designed to alleviate or eliminate problems that can be encountered with conventional laparoscopy: a two-dimensional video monitor that limits vision, surgeon fatigue due to constant standing and maneuvering of surgical instruments, and restricted range of motion.

- The da Vinci® utilizes high-definition three-dimensional video delivered to the viewer at the surgeon console with digital zoom capabilities, allowing true depth perception and high magnification. This immersive capability allows a virtual extension of the surgeon's eyes and hands within the surgical field and an intuitive handling of the manipulators.
- The da Vinci® is currently the only system allowing the surgeon to operate while in a seated position with four customizable parameters and multiple ergonomic adjustments, eliminating the need for operating while standing over the patient, thereby reducing surgeon fatigue and enhancing OR turnaround time.
- The da Vinci® arms have wrist-like joints containing various EndoWrist® instruments that have a range of motion far greater than the human wrist. EndoWrist® enhances dexterity, precision, and technique compared to long and straight conventional laparoscopic instruments. Modeled to be an improvement of the tendons found in a human wrist, EndoWrist® has internal cables which maximize responsiveness while eliminating the possibility of hand tremor. This design allows rapid yet sensitive manipulation with intuitive motion-scaling settings and fingertip control, allowing harmonious modification of hand-to-instrument movement ratios (Fig. 1.6).

Applications of the da Vinci®

The da Vinci® Surgical System is a computer-assisted surgical system designed to improve minimally invasive surgery. Equipped with true-to-life robotic arms and high-definition three-dimensional imaging, the robotic system facilitates training and accelerates mastery of minimally invasive tasks [19–21]. Additionally, the da Vinci® has proven useful in multiple specialties in surgery. The FDA has approved its use in general surgery and cardiac, colorectal, gynecologic, head and neck, thoracic, and urologic surgical procedures. The most common robotic-assisted procedures performed are cholecystectomy, hysterectomy, and prostatectomy [22–24].

Disadvantages of the da Vinci®

Performing robotic-assisted surgery is not without limitations. One obvious drawback of the current systems is the lack of tactile feedback to the operator (haptics). Although the system offers enhanced visual navigation with high-resolution three-dimensional imaging, the surgeon is left to rely on visual cues for position, velocity, and acceleration of the instruments. Besides absolute barrier hard stops, haptic sensory is inherently absent in robotic-assisted surgery. This limitation impacts judgment of force on internal structures and characteristics of manipulated tissues, such as compliance, texture, pulsatility, or elasticity [24].

In addition to the purchase price of approximately $1.5 million dollars per robot, upgrades and maintenance of the system are added expenses to consider as well. Possibly one of the largest challenges to operating the da Vinci® is the steep cost of time and money required for the

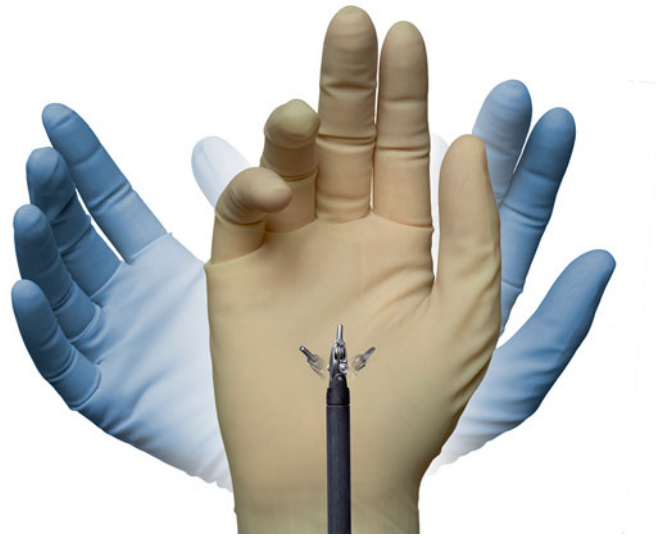

Fig. 1.6 EndoWrist®. Hand instrument articulation. Gloved hand showing range of motion and instrument showing range of motion (Copyright © 2014 Intuitive Surgical, Inc. Used with permission)

extensive hands-on training needed to safely master surgical technique and space especially if purchasing a dedicated training robot due to the high demand placed on equipment [24].

Disadvantages of the da Vinci® Surgical System also include possible injuries due to surgical complications, most commonly tissue burns from the high-energy instrument tips. Although many surgical complications go unreported, perforated intestine and colon injuries have been reported possibly due in part to the lack of tactile feedback. Also reported is possible nerve damage due to pressure from steep positioning on the operating table required for certain procedures, which has caused temporary postoperative weakness and immobility in extremities. As popularity of robotic surgery continues to flourish, it should be taken into consideration that some surgical complications will occur [25].

da Vinci® Impact

The benefits of minimally invasive surgery are well established. Compared to open surgeries, minimally invasive surgery results in decreased length of hospital stay, less pain, fewer wound infections and hernias, quicker return of organ function, and overall improved quality of life. For example, compared to the open approach, robotic-assisted prostatectomy is associated with more favorable outcomes, including better urinary continence and erectile function recovery and lower rates of positive surgical margin [19, 20]. However, the benefits of robotic surgery become less significant when a laparoscopic approach has been established. Nonetheless, procedures such as prostatectomy and hysterectomy have led surgical specialties such as urology and gynecology to adopt robotics in the operating room. In 2011, 31 % of the da Vinci® procedures performed were prostatectomy and 41 % were hysterectomy.

The explosion of the da Vinci® systems in today's field of surgery is reflected by increased sales and use worldwide. The 2012 Intuitive Surgical Annual Report states that 2,585 da Vinci® systems have been installed across the globe. The United States is currently the leading user of the da Vinci® Surgical System, possessing over 18,000 machines. In 2012, approximately 450,000 surgeries using the da Vinci® system have been performed. By 2013, the use of robotic surgeries has surpassed the previous year by 16 %, with approximately 523,000 procedures performed. The rapid increase of da Vinci® use is in part attributed to the growth of general surgery and gynecologic and urology procedures. Following the United States in the prevalence of robots are European countries with over 400 installed da Vinci™ systems; the remaining countries have nearly 300 total robots [23].

Fig. 1.7 Evolution of the da Vinci® Surgical System: *top*, full da Vinci® Surgical System; *center*, full da Vinci® S Surgical System; and *bottom*, full da Vinci® Si HD Surgical System—dual console (Copyright © 2014 Intuitive Surgical, Inc. Used with permission)

Modifications of Current Robots and Future Robots

With the rapid growth of technology, the da Vinci® system has evolved since the FDA approval and its initial release in 2000. Including the original system, there are now four models in the da Vinci® Surgical System family (Fig. 1.7). In 2006, Intuitive Surgical released the first successor, the da Vinci® S, followed by the Si version in 2009, and the single-site system in 2010. The da Vinci® S HD is enhanced with high-resolution display, integrated with critical patient information (e.g., superimposed radiographic images) called TilePro™. The HD system also includes telestration and a touch screen that permits an operator to draw over the displayed operative field, which facilitates teaching and team communication. The Si series has a more streamlined interface and the capability to utilize single-site instruments. The single-site system creates a keyhole incision through the navel, upon which is utilized as the single port for surgery, resulting in minimal scarring. The single-site system is FDA approved and has been demonstrated as feasible for cholecystectomies [23].

A new robotic system currently in development is the SPORT™ (Single Port Orifice Robotic Technology) Surgical System by Titan Medical Inc. in Canada. The system is comprised of a robotic platform and an interactive surgeon workstation to control the machine. The robotic platform includes collapsible instruments that are capable of performing a single incision and deploying into the body through the solitary orifice. The innovative design shows promise in surgeries which are conducted in small- to medium-sized surgical space. Current systems are mostly used in gynecologic and urologic surgeries. The SPORT™ will allow further expansion of the use of robots in general surgeries, as well as in ear, nose, and throat procedures. Potential applications of the SPORT system include cholecystectomies and appendectomies [25].

Supported by leading surgeons from institutions, such as Rochester General Hospital, University of Florida, Ohio State University, and Boston Children's Hospital, Titan receives direction and guidance from a medical advisory board for the development of SPORT™. SPORT™ has successfully completed phase one in research and development and has now progressed to phase two for tissue and cadaver testing. After completing phases three and four, SPORT™ will be commercially available in late 2015 [25].

Advancements in technology have indeed revolutionized medicine. Although the full potential of robotic technology has yet to be determined, these machines have already shown improvement in performing physically demanding tasks. In surgery, robots have proven useful in a range of tasks from holding the camera to tremor-free incision and manipulation of tissues. Current systems are still faced with many challenges; however, continuous research development may lead to overcoming those problems. More importantly, further research is warranted to assess the complete cost-benefit analysis of robotic surgery.

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Training and Credentialing in Robotic Surgery

2

Tomasz Rogula, Pablo A. Acquafresca, and Martin Bazan

Introduction

Achieving surgical competence is a complex process that involves the attainment of knowledge, judgment, professionalism, and surgical skill [1]. For this reason education and training have been a main matter of concern since the beginning of surgery as a specialty. In 1907 at the presidential address of the American Surgical Association, Dr. Dudley Allen described the ideal product of surgical training as someone who "…should limit his personal service strictly to those fields in which he is a master…" and the conclusion of this presidential address was a recommendation that surgeons be trained thoroughly and broadly [2]. What Dr. Allen was describing in his speech were the need to have a concentrated and continuous training experience and the need to attain and demonstrate competency through examinations carried out by a respected institution. As the field of surgery evolves, new technology and devices emerge. This makes it more difficult to stay up-to-date and creates the need for continuous education and training.

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The first big revolution in surgical education and training occurred with the emergence of laparoscopic surgery in the late twentieth century. In the 1980s Erich Mühe, a German, performed the first laparoscopic cholecystectomy [3], and Kurt Semm, also a German, completed the first fully laparoscopic appendectomy [4], despite being poorly accepted by the surgical community initially [5]. With the development of this new technology, surgeons had to learn a new method of operating due to the loss of both the third dimension and sense of touch. This paved the way for laparoscopic simulators and laparoscopic training boxes which allowed the surgeon to become acclimated to this new method of operating without compromising patient safety. Accreditation of surgeons using this new surgical technique became necessary in order to guarantee the best results and safety of patients. Thus, in 2009 the American Board of Surgery began requiring that all general surgery graduates provide documentation of successful completion of Fundamentals of Laparoscopic Surgery (FLS) – a validated and standardized education module designed to teach physiology, fundamental knowledge, and technical skills required for basic laparoscopic surgery, including simulation-based skills laparoscopy [6].

In the beginning of the 1990s came the emergence of the second revolution in surgery, robotic surgery. In 1992 the ROBODOC® (Integrated Surgical Systems, Sacramento, California) was introduced; this was the first computer-enhanced surgical instrument, allowing orthopedic surgeons to more precisely drill the shaft of the femur.

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Then, in 1994, the first surgical robotic instrument intended for abdominal surgery appeared; AESOP®, or Automated Endoscopic System for Optimal Positioning (Computer Motion, Santa Barbara, California), was designed to hold and manipulate the laparoscope during minimally invasive surgery. In 1997, in Brussels, the first integrated robotic surgical system for clinical application appeared, the da Vinci® Surgical System (Intuitive Surgical, Inc., Sunnyvale, California). The first clinical robot-assisted surgical procedure was performed in March 1997 by Drs. Cadiere and Himpens, using the da Vinci® Surgical System for a cholecystectomy. Following clinical trials, the da Vinci® Surgical System was FDA approved for surgery in the USA on July 12, 2000 [7].

Due to its characteristics, the da Vinci® robot has become the most popular and useful because it allows surgeons to overcome many of the difficulties of laparoscopy surgery: loss of depth perception, loss of natural hand-eye coordination, loss of intuitive movement, and loss of dexterity. Depth perception is restored with a stereo visualization by using a two-channel endoscope which sends both left and right eye images back to the surgeon. The alignment of the surgeon's hand motions to the surgical tool tip is both spatial and visual. To achieve spatial alignment, the system software aligns the motion of the tools with the camera's frame of reference. To achieve visual alignment, the system projects the image of the surgical site atop the surgeon's hands. Coupled together, spatial and visual alignment make the surgeon feel as though his hands are inside the patient's body [8].

All of this has led to a new way of feeling, seeing, and working in the surgical field. We are now operating through the eyes and hands of a robot which reintroduces the problem of how to teach, learn, train, and credential this new technique.

Training

Training is the key to mastering any surgical technique and should be emphasized even more so when it comes to robotic surgery. One must learn new skills regarding hand-eye coordination and also become accustomed to the loss of touch sensation. To overcome these difficulties, we must take advantage of several tools, which are simulators, mentored cases, robots with dual consoles, and robotic courses (which obviously must be designed using the aforementioned tools). This makes it possible to bridge the gap between early surgical skills and effective surgical performance when using a robot in a clinical setting without subjecting patients to unnecessary risks.

Simulators

A simulator is an educational tool which allows interactive performance of the trainee in an environment that re-creates or replicates a real-world clinical scenario, but is not identical to "real life." [9] They must be present in the initial training in robotic surgery because they ensure that some practice has taken place before trainees treat real patients; they improve the surgeon's performance within a safe training environment by providing a controlled re-creation of critical steps of any surgery. There are many simulators available for health-care training [10], with surgical simulators generally being divided into two categories: virtual reality simulators, in which the task is performed in an artificially virtual environment generated by a computer platform, and mechanical simulators, in which the robot is connected to a box trainer.

Currently there are four main different robotic surgery simulation platforms available on the market: da Vinci Skills Simulator® (dVSS, Intuitive Surgical), Mimic dV-Trainer® (MdVT, Mimic Technologies), Robotic Surgery Simulator (RoSS®, Simulated Surgical Systems), and SimSurgery Educational Platform® (SEP, SimSurgery). A fifth simulator worth mentioning, the ProMIS® (CAE Healthcare), is a laparoscopy simulator which can be adapted to the robot to convert it into a robotic surgery simulator [11]. All simulators except the SEP have shown an educational impact [12]. Of the aforementioned simulators, the only one using the da Vinci console is the da Vinci Skills Simulator®, which is manufactured by Intuitive Surgical, the same

Fig. 2.1 da Vinci® surgeon console (**a**) and da Vinci® Skills Simulator (**b**) (Copyright © 2014 Intuitive Surgical, Inc. Used with permission)

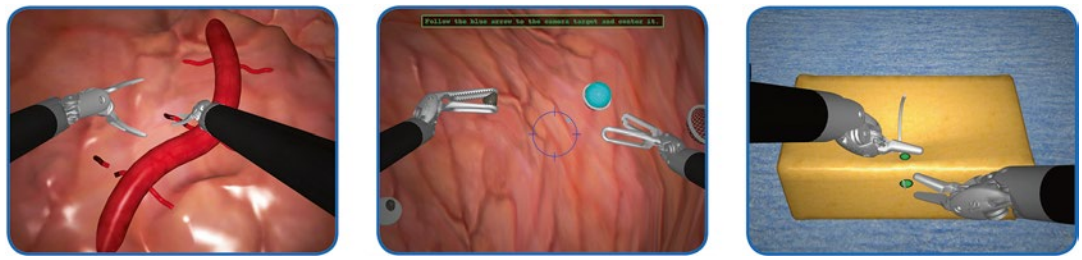

Fig. 2.2 da Vinci® Skills Simulator exercises (Copyright © 2014 Intuitive Surgical, Inc. Used with permission)

company that manufactures the da Vinci® robot. This gives it a potential advantage over the rest, because the surgeon trains in the same console that he or she will be using in live cases.

The da Vinci Skills Simulator® (dVSS) (Fig. 2.1a, b) consists of a small case which generates the virtual environment and is in turn annexed to an existing da Vinci surgeon console, transforming it into a practice platform. Some main features are built-in metrics which enable the surgeon to assess skills and to measure the improvement in a given exercise, real-time feedback and progress tracking, administrative tools which allow structuring of a training curriculum, and system software with an open architecture which allows integration of future development and incorporation of additional practice modules. The dVSS comes with a set of exercises (Fig. 2.2) ranging from basic to advanced and is designed to be relevant to surgeons from any specialty. Some of these are EndoWrist® manipulation exercises which help gain familiarity with the movement of the robot's instruments, camera and clutching exercises to improve camera control and effectiveness of clutch use, fourth arm exercises designed to promote instrument skill and to help users to think strategically about instrument placement during tasks, needle control and driving exercises designed to help users develop skill when manipulating needles (including a focus on how to effectively hand off and position needles while practicing with a range of geometries), and, finally, energy and dissection exercises which help gain familiarity with the foot switch

Fig. 2.3 Mimic dV-Trainer® surgery simulator (Copyright © 2014 Mimic Technologies)

panel during dissection tasks requiring application of monopolar and bipolar energy (the foot switch panel enables users to swap between different types of energy instruments) [13].

To detect whether a simulator is useful, we need to assess its validity, or whether an exam or test succeeds in testing the competence that it is designed to test [14]. The dVSS has shown face validity (how much the simulation resembles the situation in the real world), content validity (whether or not the intended content domain is being measured by the assessment exercise, in other words, if it is useful as a training tool), and construct validity (the extent to which a test measures the trait that it purports to measure; a test with high construct validity has the ability to distinguish between a novice and expert user). The dVSS has also shown an important educational impact, meaning the ability to improve the performance of the subjects. This was more pronounced in novice surgeons than in experienced robotic surgeons [15, 16] which makes this simulator more useful in the initial training stages. The weakest point of this simulator is the lack of cost-effectiveness due to its high market cost and the need of an existing da Vinci robot console, which makes feasibility difficult.

The Mimic dV-Trainer® (MdVT) (Fig. 2.3) is a stand-alone simulator built on a compact hardware platform which closely reproduces the look and feel of the da Vinci system and also replicates its behavior. Its software (Mimic's MScore™) allows objective performance evaluation due to its incorporated data collected from experienced surgeons to establish proficiency-based scoring baselines. The scoring is based on time to completion, economy of motion, instrument collisions, number of drops, missed targets, instruments out of view, blood loss, broken vessels, excessive instrument force, and misapplied energy. The simulator also comes with administrative tools for educators to create customized training protocols and allows uploading and sharing of these curricula via a collaborative online portal, in turn providing

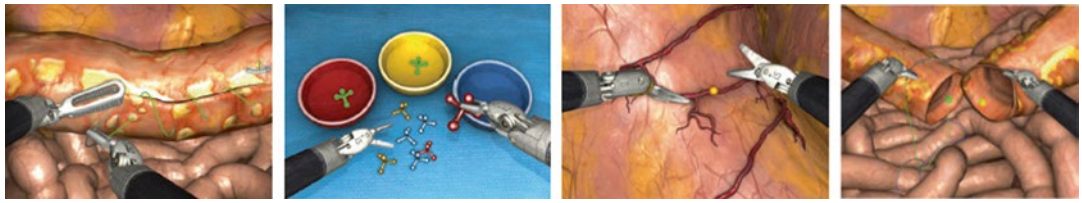

Fig. 2.4 Mimic dV-Trainer® exercises (Copyright © 2014 Mimic Technologies)

access to validated simulation curricula from other institutions.

The MdVT comes with two groups of training modules (Fig. 2.4): the da Vinci® overview and basic skills training and advanced surgical skills training. The first group allows the surgeon to become familiar with the da Vinci console, review the basic da Vinci functionality, train on EndoWrist® manipulation, learn how to use the camera and the clutch effectively, and understand some common da Vinci error messages and determine how to react to them. The second training module consists of needle control and needle driving exercises, suturing and knot tying (including tube anastomosis and tube closure), energy and dissection exercises to learn how to apply monopolar and bipolar energy, and finally exercises to practice dissection and manage bleeding. Lastly, there is an interesting game module which allows competing while developing robotic surgical skills at the same time [17].

Several studies have shown that MdVT has face, construct, and content validity as a training tool [18–20] and that it significantly improves technical skills in robotic surgery. Moreover, MdVT seems to be equivalent to dVSS in regard to improving robotic aptitude in skill domains related to object manipulation, camera movement, and clutching [21].

The weakest point of this simulator, as with the dVSS, is its high market cost which makes it less cost-effective. On the other hand, the MdVT does not require an existing da Vinci robot console.

The Robotic Surgery Simulator (RoSS®) (Fig. 2.5) is also a stand-alone simulator which can be easily transported; it uses virtual reality to generate the case scenario. RoSS® comes with a multilevel curriculum designed with various levels of difficulty that takes the surgeon through the basic skills required to perform a robotic surgery. This simulator can be distinguished from the previous ones in that it offers the opportunity to train while being guided through the operative steps of a real procedure (e.g., radical prostatectomy, hysterectomy, cystectomy, extended lymph node dissection, etc.). See Fig. 2.6a, b. This feature uses the principles of checklist-based learning, meaning the user can only proceed through the procedure after successfully learning and executing each step. The RoSS® also shares some characteristics of the previously mentioned simulators: system settings, EndoWrist® manipulation, camera and clutching exercises, fourth arm integration, needle control and needle driving, energy and dissection exercises, and performance feedback [22].

RoSS® has shown face validity and content validity [23, 24], but several studies could not demonstrate construct validity [23–25] which means it may be less useful in discriminating between various levels of expertise. The cost of this simulator is also a limitation that may reduce its feasibility.

The SimSurgery Educational Platform® (SEP) (Fig. 2.7) is another option available on the market, produced by the company SimSurgery. It lacks some features offered by the previous simulators; it offers EndoWrist® manipulation and performance feedback (stores data on performance measures). The simulator offers exercises to train on basic and advanced skills organized into three groups: tissue manipulation, basic suturing, and advanced suturing. It may be considered when training hand-eye coordination and suturing [26]. SEP has shown face, construct, and content validity, and its market price is relatively lower than the previously mentioned simulators [27].

Lastly is the ProMIS® (CAE Healthcare), a laparoscopic surgery simulator which can be

Fig. 2.5 Robotic Surgery Simulator (RoSS®) (Copyright © 2014 Simulated Surgical Systems)

connected to the robot in order to perform robotic surgery training. ProMIS® is a hybrid simulator which enables virtual reality simulation and mechanical simulation to be used together. The simulator has a laparoscopic interface which consists of a torso-shaped mannequin with a neoprene cover, all connected to a portable computer. Different trays are available, containing different training modules: suturing pads, knot-tying tasks, etc. These can be placed in the mannequin.

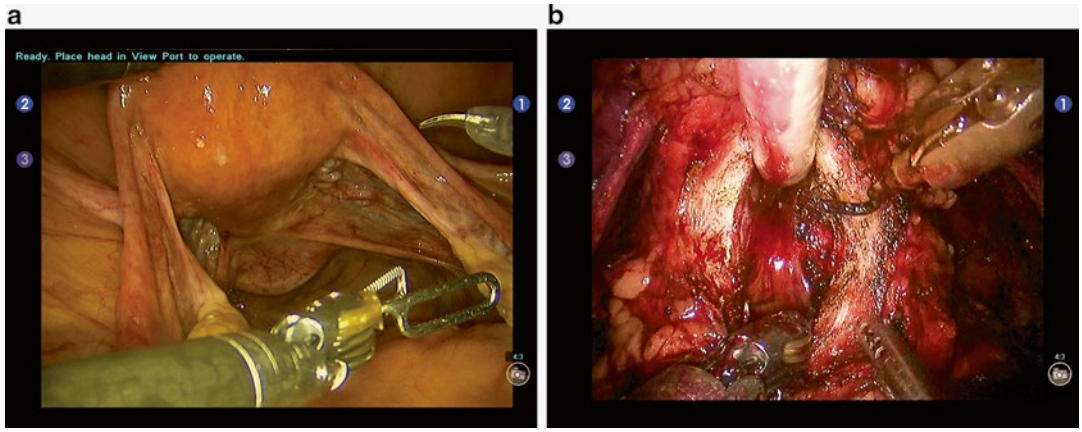

Fig. 2.6 Screen captures of Robotic Surgery Simulator (RoSS®) exercises (Copyright © 2014 Simulated Surgical Systems)

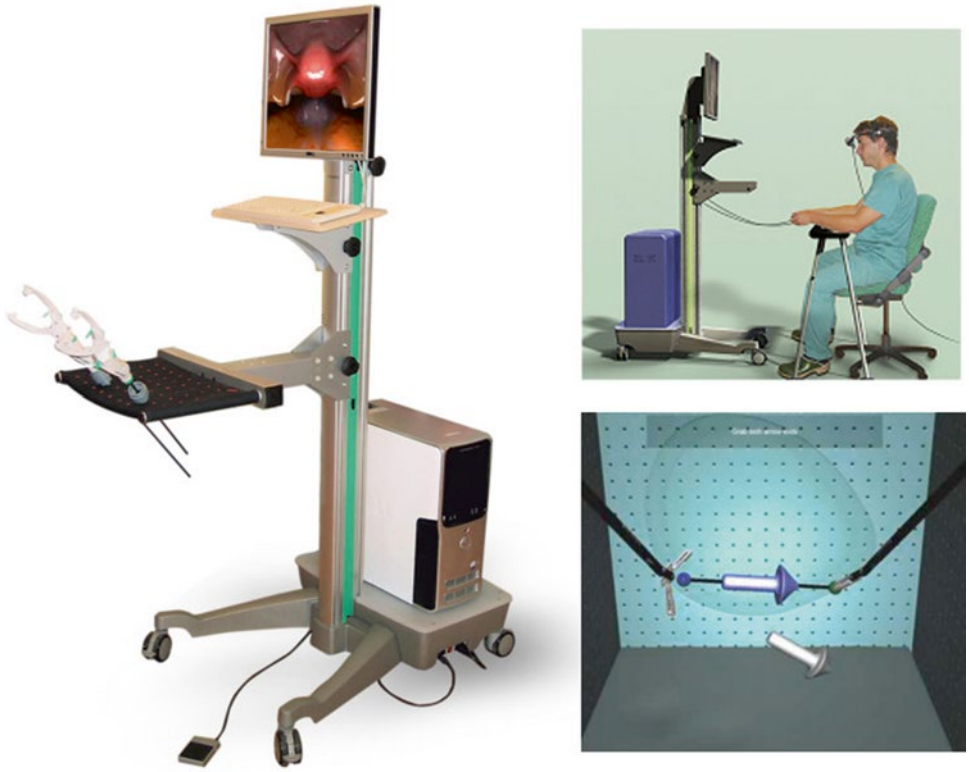

Fig. 2.7 SimSurgery Educational Platform® (SEP) simulator and exercise (Copyright © 2014 SimSurgery)

Three separate camera-tracking systems are placed inside the mannequin, arranged to record the three-dimensional position of the tip of the instruments. This way, instrument movement is recorded and stored in distinct sections based on the time the tips of the instrument are detected until they are removed from the mannequin. The ProMIS simulator analyzes three parameters:

time, path, and smoothness [11]. This robotic surgery simulator has shown face, content, and construct validity. It is the least expensive of all the mentioned simulators; however, it requires an existing da Vinci robot for use [28].

Given the lack of comparative studies between these different simulators, we cannot affirm that any of them is more effective than another for training in robotic surgery [12]. It is worth mentioning that simulation models have been shown to be valid and reliable for the initial phase of training and assessment in surgical procedures; however, this is not the case for advanced and specialist level skill learning [29]. Simulators should play a role alongside traditional training, especially in the initial phase of training. The main drawback of simulator training is still the cost, although this may decrease in the near future.

Mentored Cases

Mentoring can be defined as a form of training whereby an experienced surgeon scrubs in on or supervises the procedure with the intention of guiding the surgeon learner and assisting in the acquisition of new skills during the steep part of the learning curve. In terms of robotic surgery, mentoring can be the second stage of training after the learner has demonstrated competence in basic skills. The entrance of the trainee into this clinical training stage should be gradual. The first approach should be live case observation which will allow the trainee familiarization with the procedures and technique. Prerecorded operative footage also can provide the trainee with an opportunity to observe the execution of the various steps involved in completing a specific robotic procedure from start to finish [30]. A library of prerecorded operative video footage can be provided to trainees for reference so that they can review the specific steps of the procedure. Live case observation will allow interaction with the expert surgeon in real time while also allowing review of certain steps of the surgical procedure.

The second approach before immersing into the hands-on clinical training should be the participation on a live case as the bedside assistant to the main console surgeon. This should incorporate the knowledge acquired during the procedure-specific familiarization. The ability to assist effectively in live robotic procedures demonstrates that the trainee has gained the knowledge of the steps of the procedure, general proficiency in working in the robotic environment, knowledge of the functionality and limitations of the robot itself, as well as the strategies and techniques used by the console surgeon to complete the specific procedure. The importance of beginning the operative experience as a surgical assistant has been reinforced by several authors [31–33] and serves to strengthen the trainee's basic robotic knowledge and skills before commencing clinical training on the console. The number of cases recommended as the bedside assistant depends on which procedure the trainee is learning; there is still no general consensus in terms of this number.

Time on the surgeon console should represent the final approach of any clinical training. The procedure with which the trainee begins his clinical training at the console should be the type of procedure which constitutes the highest volume of cases at one's institution. This provides the trainee with plenty of opportunities to effectively work through the clinical components of the required techniques.

The specific procedure should be clearly defined by the steps required to complete the operation from the initial positioning of the patient to the final removal of ports and recovery of the patient. These steps should be ordered somewhat by the complexity of the surgical tasks involved and then be ordered from least difficult to most difficult, providing the trainee with a gradual progression in their curriculum. This allows the trainee to go through a stepwise progression of defined tasks and steps of the procedure based on the degree of difficulty, all under direct supervision of an expert robotic surgeon who is at the bedside or at the console with the trainee. This approach to robotic training has been emphasized by several studies [34–38] and allows the trainee to acquire skills through repetition of tasks based on specific skill.

When the trainee has demonstrated complete control of a predefined step, through formal

evaluation or based on an expert surgeon's judgment, he/she will be able to move on to the next sequentially difficult step of the procedure. Eventually the trainee will be able to integrate skills learned and practiced during each defined step into a comprehensive ability to complete the entire procedure. The learning process can be further enhanced through video recording and review of operative performance with a mentor or expert surgeon as it provides valuable formative feedback for the trainee [39].

Unlike traditional open surgical training where the mentor can be in close proximity to the trainee and facilitate hands-on teaching, in robotic surgery the mentor and trainee are separated in space, and the attending surgeon may not have full control of the operation as in open surgery. The fact that only one surgeon at the time can be at the console is an educational problem that has been previously documented [31, 36, 38], and the next training tool may be the one that brings light to this issue.

Dual Console

Intuitive Surgical has developed a da Vinci® model (Si) that has an available dual console which will potentially allow for expert surgeon direction and supervision for procedural robotic training and collaboration. The mentoring console has two collaborative modes [40]: (1) The swap mode allows the mentor and trainee to operate simultaneously and actively swap control of the robotic arms. (2) The nudge mode allows them to have control simultaneously, sharing the two robotic arms. Studies [40] have shown that the swap mode was most useful during parts of the surgical procedures that required multiple hands (e.g., isolation and division of vessels). The nudge mode, however, was more useful for guiding the resident's hands during the more crucial and precise steps of an operation (e.g., suturing).

The introduction of the dual console could shorten the learning curve and help trainees feel more comfortable when initially performing the procedure [41].

This new robotic system could lead to safer educational training and also opens the gate to a whole new way of training, termed "telementoring," defined as the use of audiovisual technology at any distance to provide mentoring or teaching.

Robotic Courses

Many guidelines have been published on how a robotic surgery course must be composed, but here we attempt to give general guidelines on the design of a robotic surgery course using the aforementioned tools. Whatever the course design, we believe it must be under the direction of an expert surgeon instructor (someone with substantial practical experience with the technology in clinical applications with reported results and reviews) and also, in the initial steps, an engineer from the company which designs the robots who can teach the basic knowledge about how the robot works.

Introduction and familiarization with the robot system itself must be the first step in any training course. The surgeon should learn about the robotic system components, draping the robot's arms, patient positioning, docking techniques, port placement strategy, inserting and exchanging instruments, and, importantly, basic system safety, emergency undocking procedure as well as dealing with troubleshooting errors and faults which may happen during the initial experience. This information should be provided first through lectures (which may be provided online) and then, after an examination of the surgeon's learned knowledge, transferred to the practical field through hands-on tutorials where the trainee can interact with the robot in a low-stress environment and apply what he has learned. This part of the course should allow a complete understanding of device function and technology, altered functional status, and device parameters and limitations.

Intuitive Surgical, the vendor of the robot, has created an online tutorial on the fundamentals of the da Vinci robot. It includes a technical overview of the robot, functional aspects of the system, as well as some troubleshooting tips. This online tutorial is available for the various robot models and includes a multiple-choice question-based examination that can be used by training

programs to evaluate trainee knowledge of the basic functional aspects of the robot [30].

After having successfully completed the first part of the course, the surgeon may move to the second step, learning the basic skills of any robotic surgical procedure: camera focus, movement, camera adjustment, clutching exercises, needle driving and wristed motions, precision cutting, dissection, suturing, and knot tying. These allow the surgeon to become familiar with the three-dimensional environment and will allow him or her to perform more complex procedural tasks. This step should have a theoretical component with lectures but also, more importantly, training on virtual simulation and dry labs with the robot. This will allow the surgeon to learn the basic components of any robotic surgical technique. A further step should be the application of these acquired skills in a live tissue lab (with animal or cadaver models) where the surgeon will be able to perform tissue dissection, hemostasis, and suturing.

Table 2.1 shows, in order of increasing complexity, exercises which will allow the surgeon to obtain the basic skills and become familiar with the 3D environment:

Module 1

- Instrument control: This task will allow the trainee to learn how to move the robot arms and familiarize themselves with the wrist movements of the arms.
- Camera control: This task teaches the trainee camera focus, movement, and camera adjustments.
- Fourth arm control: This task allows the trainee to learn how to use the fourth arm.
- Coordinate tool control: This task aims to integrate what the trainee had learned previously and will let him/her use the camera and the clutch together in a coordinated manner.

Module 2

- Ball placement: This task aims to develop accurate and precise control of instruments by picking up balls and placing them in a designated spot.
- Spatial control: This may be achieved, for example, by passing a ring along a curved wire.

Module 3

- Needle handling: This task should allow the trainee to handle a needle properly and to hand off a needle to a bedside assistant.
- Basic electrocautery: This task teaches the trainee how to use the electrocautery hook.
- Tissue cutting: With this exercise the trainee will learn how to use the scissors to cut tissue. It can be achieved, for example, by drawing a circle on a paper and soliciting the trainee to cut the circle in the most precise way.

Module 4

- Tissue retraction: This task combines the previously acquired skills and requires coordinated control of the fourth arm to retract tissue.
- Blunt tissue dissection: This task also combines the trainee's previously acquired skills and requires coordinated control of the instruments and the camera to separate two layers of tissue.
- Vessel dissection: This task requires coordinated control of the instruments and the

Table 2.1 Exercises that will allow the surgeon to obtain the basic skills and become familiar with the 3D environment, in order of increasing complexity

Module 1	Module 2	Module 3	Module 4
Basic console orientation	Psychomotor skills training	Basic surgical skills	Intermediate surgical skills
Instrument control	Ball placement	Needle handling	Tissue dissection
Camera control	Spatial control	Basic electrocautery	Blunt tissue dissection
Fourth arm control		Tissue cutting	Vessel dissection
Coordinate tool control			Knot tying
Knowledge	Technical skills	Integration of knowledge and technical skills	

camera to dissect the vessel. One possibility is through use of animal models.
- Knot tying: The trainee will have to coordinate the control of the instruments to effectively tie common surgical knots.

After completing the previously mentioned steps, the surgeon may move toward specific training in his or her area of competence. Through training and repeating the basic skill tasks on a virtual simulator, in a dry lab and on animal models, the surgeon will eventually master the key components of the surgical procedure and perform them fluently. Simultaneously, the surgeon may be present in the operating room to observe and assist in live cases using the robot. The observation of a complete procedure is an essential part of preclinical training. This should include procedure preparation, system setup, review of case selection, and intraoperative technical aspects.

After demonstrating mastery of the key components of the surgery on lab and virtual simulators, the surgeon will be allowed to perform them in a live surgery. They may begin with the easiest key steps and work up to more difficult steps, in an increasing level of difficulty and always under the supervision of an expert surgeon in the robotic field. At this point dual consoles can play a fundamental role. During conventional open and laparoscopic surgery, the mentoring surgeon is adjacent to the trainee and has the same view of the procedure, as well as being able to take over at any given moment. This is not the case in robotic-assisted procedures as only one surgeon can be at the operating console at one time. However, now, through an additional console, both the expert and novice surgeons may operate at the same time. The expert can control the third arm to help the novice, or they can simultaneously control both arms and switch between who is controlling them. In this way the expert can take control of the surgery at any time if the safety of the patient is at risk.

After completing the key components several times, the surgeon will be able to perform a complete procedure under direct supervision. The number of mentored cases required to master the technique depends on the type of procedure and its complexity and has not been well established yet. In every specialty this number is under discussion because its determination will facilitate coming to an agreement regarding the topic of accreditation.

Credentialing

Currently there are no governing bodies mandated for credentialing guidelines in robotic surgery. The requirement for acquiring credentials varies among hospitals. There is no standardized method, and more importantly, most of these requirements are not competency-based but rather require a number of proctored cases.

Robotic surgery credentialing should be the result of a standardized, competency-based peer evaluation system. It is important that this process be self-regulated by robotic surgery experts in a clear, comprehensive, and reproducible manner. It may be logical to follow the example set by the laparoscopic surgery and the Fundamentals of Laparoscopic Surgery (FLS) curriculum. The Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) has created the FLS curriculum, which serves as a set of guidelines for laparoscopic surgery training and credentialing. After having been validated as a means of training and credentialing trainees [42], the FLS curriculum is now endorsed by the American College of Surgeons. All general surgery certification candidates are required to have successfully completed the FLS training curriculum before being eligible for the American Board of Surgery certification.

At this point in time, there is no such curriculum in place for robotic surgery. Until such a curriculum is developed, we believe that several requirements should be considered as a bare minimum necessary to obtain robotic surgery credentialing, including:
- Proficiency in basic laparoscopy
- Technical certification for use of the da Vinci robot
- Proof of basic preclinical training in robotic surgery
- Clinical proficiency status obtained from an approved robotic surgery proctor

In order to reach this goal, the SAGES and the Minimally Invasive Robotic Association (MIRA) have taken a step forward by creating a consensus on robotic surgery which analyzes the credentialing topic in a general way [43]. The purpose of this type of consensus is to generate uniform standards which may be applied to all medical staff requesting privileges to perform procedures utilizing the robot and also to decrease the heterogeneity of concepts and to generate criteria universally applicable to all those wishing to obtain privileges. In our opinion surgical proficiency should be assessed for every surgeon, and privileges should not be granted or denied solely based on the number of procedures performed.

Having clarified these points, we will attempt to give an overview of the steps which should be required for credentialing in robotic surgery. The first step, although seemingly obvious, is important and necessary: the physician seeking these privileges should have a formal specialty training; this means that he or she should have a satisfactory completion of an accredited surgical residency with subsequent certification by the applicable specialty board (or an equivalent allowed by the institution).

For the second step, we find two possibilities: a physician with a previous formal training in therapeutic robotic surgery during their residency and/or fellowship programs or one without such training.

In the first scenario, the surgeon ought to have learned during his residency/fellowship minimal access procedures, general laparoscopic skills, use of therapeutic robotic devices, and techniques of accessing the body cavity/area of surgery. They should possess adequate clinical experience to move to next step.

Alternatively, physicians with residency and/or fellowship training who did not receive structured experience in therapeutic robotic procedures or without documented prior experience in these areas should complete a systematic training curriculum. Until a universal governing body is created, the curriculum should be defined individually by institution and should include a structured program using the tools mentioned earlier.

The third step may possibly consist of presentation of documented experience in the field, including an appropriate volume of cases with satisfactory outcomes. These cases would preferably be equivalent to the procedure in question in terms of complexity. A committee of experts on robotic surgery could be the one which determines the appropriateness of this experience. As mentioned before, the initial clinical experience with the specific procedure could be completed under review of an expert (mentor) and may include assisting.

An adequate number of cases to allow for proficient completion of the procedure should be considered by this expert review. This "adequate number" of mentored cases to be considered has been a matter of debate, and there is currently no consensus on this matter, even in the field of urology, where robotic surgery has shown an increasing presence. Taking the robotic-assisted radical prostatectomy (RARP) as an example, the current literature reveals a wide range in the recommended number of cases required to move beyond the initial learning curve. Some authors refer that surgeons without extensive laparoscopic experience can successfully adopt RARP in 8–12 cases [44], while others determined that a minimum of 250 RARP cases are required to achieve comfort and confidence comparable to open radical prostatectomy [45].

Therefore, we recommend that the criteria of competency for each procedure should be established in advance by the committee and should include evaluation of familiarity with instrumentation and equipment, competence in their use, appropriateness of patient selection, general safety, and successful completion of the procedure.

After having successfully completed the previously mentioned steps, a formal assessment of competency can be done. An applicant's abilities may be documented through validated measures of competency which include medical knowledge, decision-making abilities, and/or technical skill assessments. Certificates of completion of training or validation using assessment tools for competency and proficiency in a specific procedure (or set of similar procedures) could be accepted.

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Basic Setup, Principles, and Troubleshooting in Robotic Surgery

3

Chan W. Park and Dana D. Portenier

List of Abbreviations

MIS Minimally Invasive Surgery
RAS Robotic-Assisted Surgery

Introduction

In the late 1980s, the first laparoscopic cholecystectomy procedure heralded the era of minimally invasive surgery (MIS) [1]. With a greater focus on minimizing the invasiveness of open surgery, MIS surgeons substituted large laparotomy incisions with small incisions and cannulas and developed a systematic approach for establishing "triangulation" of the surgical target with video imaging and specialized laparoscopic surgical instrumentation. When compared to traditional open surgery, the MIS approach resulted in less postoperative pain, fewer wound complications, and improved patient recovery times. As a result, we have seen an evolution in the way that modern surgery is performed and for a large number of common procedures, the traditional "open" approach utilizing a standard laparotomy incision has been replaced by less invasive "laparoscopic" approaches.

In recent years, the evolution of MIS techniques and continued innovation of surgical technology have produced a sophisticated robotic MIS platform that incorporates high-definition imaging systems, powerful computer processors, and advanced robotic technology. Currently, the only commercially available robotic-assisted surgery (RAS) platform is produced by Intuitive Surgical, Inc. (Sunnyvale, CA) and is commonly referred to as the da Vinci® Surgical System. This RAS platform provides significant benefits over existing laparoscopic equipment such as high-definition, 3-dimensional visualization of surgical anatomy, precise and ergonomic control of "wristed" surgical instruments with 7 degrees of freedom, overcomes surgeon hand tremor, and more [2].

However, extra time and training for mastery of this technology are necessary in order to truly maximize these benefits [3]. In fact, credentialing for robotic surgery requires completion of a structured training program consisting of online didactic education followed by "hands-on" exposure to the equipment and dedicated time spent by the surgeon practicing surgical tasks with the RAS platform in a "dry lab" setting. In addition, the surgeon must coordinate an onsite mentoring experience with expert robotic surgeons in real-time clinical cases. There is a significant learning curve associated with becoming a proficient user of the RAS platform, and individual surgeons must overcome some of the complexities specific

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to RAS through their own personal experience [4–8]. It is with this in mind that we set out to provide a useful overview of the RAS platform and outline basic principles for proper setup and application of robotic surgical technology.

The Equipment

The RAS system is comprised of three major hardware components:

1. Surgical (aka patient) cart (Fig. 3.1) – contains the mechanical arms (1 camera arm, 3–4 surgical instrumentation arms) that interface with the patient directly at the operating table. Once "docked" to the patient, these mechanical arms will engage and articulate various surgical instruments ranging from graspers and needle drivers to electrosurgical dissectors and suction devices.
2. Vision cart (Fig. 3.2) – usually contains a video monitor (for bedside/assistant visualization), the video processor, a light source, insufflator for CO_2 gas, etc. This tower of equipment controls the video image utilized for RAS, and there are some key differences of this equipment when compared to standard laparoscopic equipment:
   (a) The camera – while similar in appearance to a standard laparoscope, the camera used for RAS contains two separate, high-definition internal cameras housed in a single tubular casing. This enables depth perception and the capture of a 3-dimensional image of the surgical field.
   (b) The vision cart monitor – this monitor does not project a 3-dimensional image; however, the monitor can be upgraded to a "touch screen" upon which the bedside assistant can draw special notes and markings. This ability to "telestrate" information

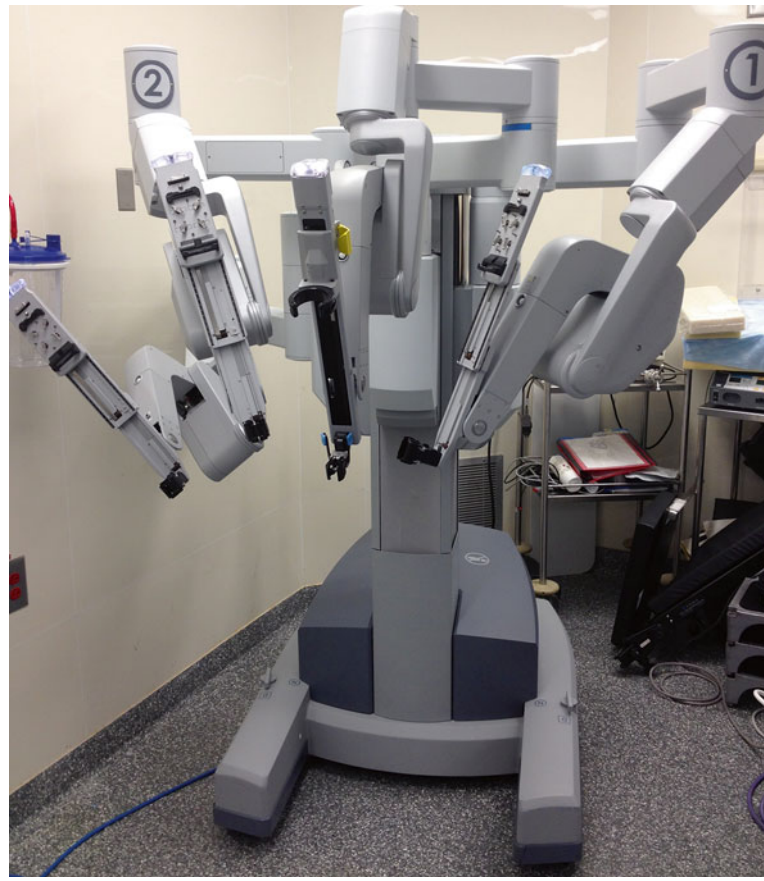

Fig. 3.1 Surgical cart (also known as the patient cart)

Fig. 3.2 Vision cart

on the monitor screen directly can help facilitate communication between the bedside assistants and the surgeon.

(c) Intercom system – facilitates verbal communication between the bedside surgical team and the surgeon working remotely from the surgeon console.

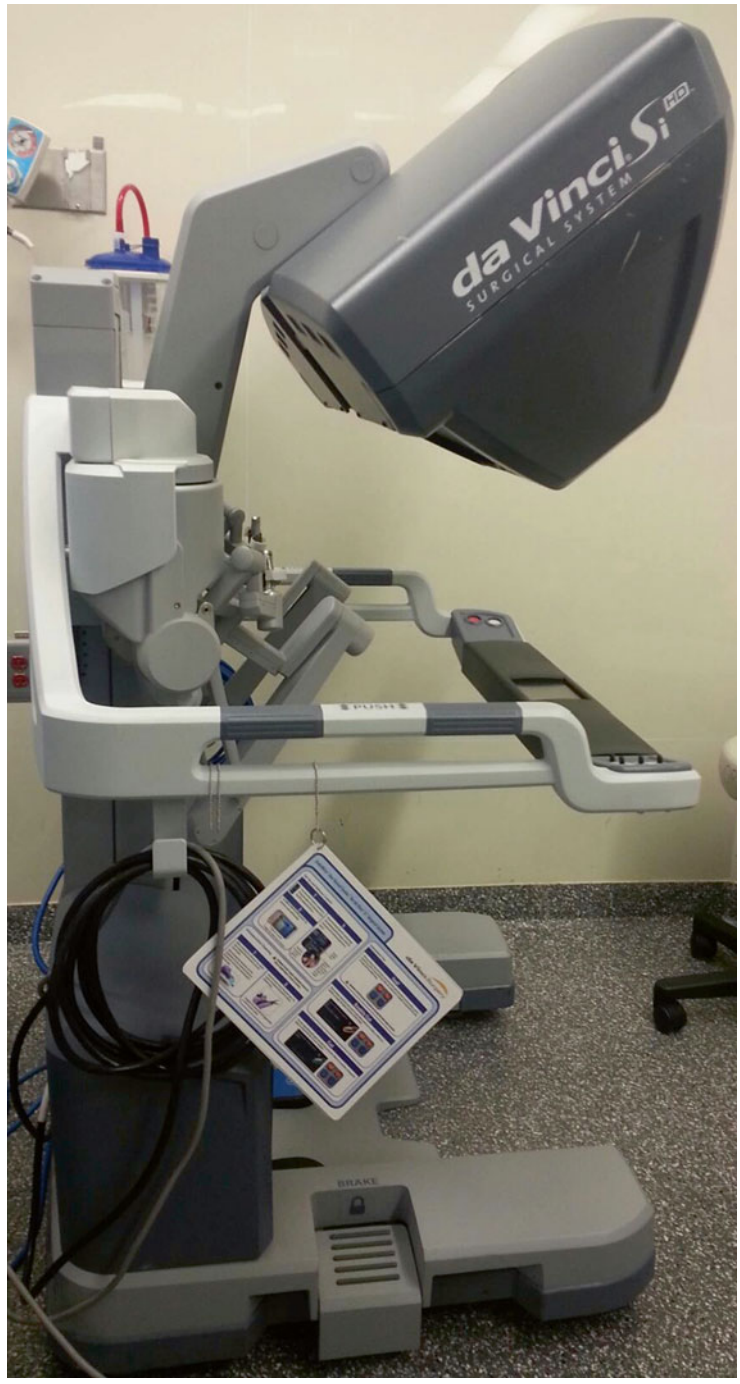

Fig. 3.3 Surgeon console

3. Surgeon console (Fig. 3.3) – contains a "stereoscopic" or binocular visual display that provides high-definition, 3-dimensional images with adjustable magnification and fine focus of the operative field as well as the master controllers. Foot pedals allow the surgeon to remotely control each arm of the surgical cart and utilize a wide variety of surgical instruments in order to conduct the technical steps of the procedure.

This complex, multicomponent setup requires knowledgeable staff specifically trained to set up and position the equipment appropriately with respect to the patient. Additional training for all team members is also a required component for developing a robust RAS program at any institution. Furthermore, proper surgical planning and greater attention paid to maximizing patient and equipment positioning can have tremendous impact on efficiency and on the overall surgical experience.

Patient Selection

While repetitive and frequent utilization of any technology can enhance efficiency and reduce operating times, RAS can be more time consuming and present formidable technical and complex surgical challenges especially early on in a surgeon's learning curve. As such, avoiding medically complicated patients and those who have a very low threshold for perioperative complications especially early on in a surgeon's RAS experience is always a prudent decision. All patients considered for RAS should undergo preparation for surgery in standard fashion and be carefully evaluated for perioperative risk factors. Furthermore, all patients must receive necessary prophylactic treatment with antibiotics and appropriate anticoagulation therapy, and an emphasis on ample patient education prior to surgery will prepare the patient for a more satisfying surgical experience.

From the physiologic perspective, RAS is similar to standard laparoscopic surgery since the creation of a surgical "working field" will require the development and maintenance of a pneumoperitoneum throughout the procedure. Thus, the surgeon must pay particular attention to the details gleaned from a thorough patient history and physical examination, and below are some specific questions that must be answered prior to any RAS operation:

- Can the patient tolerate the physiologic changes caused by establishing and maintaining a pneumoperitoneum?
- Do the benefits of a robot-assisted approach outweigh the perioperative risks?
- Are all components/equipment fully available for the procedure?
- Is there adequate support/staff to maximize the benefits of the robotic platform?

Once it has been determined that RAS is beneficial, safe, and appropriate, the next step will be to define a sound surgical strategy beginning with proper patient and equipment positioning.

Surgical Setup

Most institutions have specifically addressed the physical need for additional RAS equipment by outfitting and updating designated operating rooms as dedicated RAS operating suites. Greater square footage and an operating room environment free of excess clutter will facilitate easy positioning of the RAS hardware components. Once the patient has entered the operating room along with additional anesthesia and surgical staff, it may be cumbersome to reposition RAS equipment. Thus, it is imperative that the equipment be inspected and properly positioned prior to patient transfer, and it is the responsibility of the operating surgeon to ensure that all equipment necessary for the operation is available and properly positioned.

In preparation for surgery, first ensure that all three components of the RAS platform are functioning correctly:

- The surgeon console is designed to retain surgeon-specific settings so as to maximize ergonomics and enhance the overall surgeon-RAS interface experience. This initial setup should be completed well in advance of any scheduled surgical procedures (i.e., during initial training), but the surgeon-specific settings should be carefully reviewed/adjusted by the operating surgeon prior to each procedure.
- The vision cart must have properly functioning equipment (light source, video processor,

etc.), and particular attention should be paid to ensuring that there is an adequate supply of carbon dioxide gas for the entire procedure.
- The surgical cart must have properly functioning mechanical arms, and fresh, sterile drapes must be appropriately placed over each mechanical arm prior to surgery.

While these individual steps may be performed by surgical assistants as part of a preoperative "check list," we recommend that the operating surgeon directly supervise the positioning of each RAS component during the operating room setup.

In fact, one of the simplest ways to increase efficiency and decrease operating time is to have the surgical cart prepared and draped in a position that will allow direct docking of the surgical cart to the patient with minimal manipulation of the cart. Thus, anticipating patient positioning and the location of target surgical anatomy can help the surgeon direct the operating staff to prepare and drape the surgical arm cart in a position that will minimize extraneous movements of the heavy and cumbersome surgical cart during the "docking" process. In certain cases, anesthesia may be initiated and the patient prepared for surgery (Foley placement, skin/hair prep, etc.) in a "preliminary" position, and then the patient/operating table can be repositioned (with respect to the surgical cart) just prior to the actual operation.

Lastly, the surgeon must ensure that all necessary instruments are ready and available for the procedure. Unlike laparoscopic instruments, robotic surgical instruments will expire after a set number of clinical uses, and having an extra set of frequently used instruments (e.g., graspers, scissors, clip appliers, etc.) readily available in the operating room can minimize unnecessary delays during the procedure.

Initial Access and Cannula Placement

Once the patient is safely under anesthesia and properly positioned, gaining access to the target surgical anatomy is undertaken in a typical minimally invasive or non-robotic, laparoscopic fashion. In fact, some surgeons prefer to have an extra laparoscopic tower in the operating room with independent equipment (video monitor/processor, light source, etc.) setup for performing basic laparoscopy. This equipment may be used specifically for the initial access and preliminary survey of the intra-abdominal contents, and also as a security, "fall back" mechanism just in case the RAS platform is deemed incompatible with the planned surgical objectives. We recommend having this type of a setup readily available, especially early on in a surgeon's RAS experience.

According to individual surgeon preference, a Veress needle, an optical view trocar, or an open, "cut-down" approach is undertaken to gain access to the abdomen and initiate the pneumoperitoneum. We prefer a combination of Veress needle and/or an optical view trocar coupled to an independent 5 mm, 0° laparoscope for our initial access. At our institution, the open, "cut-down" approach is reserved for single-site RAS cholecystectomy procedures and in select patients who will need to have a larger final incision for whatever reason (i.e., large specimen extraction, etc.). Regardless of the initial access technique, upon establishing pneumoperitoneum, the intra-abdominal contents are surveyed and carefully assessed for signs of injury due to the initial access maneuver. Once this has been confidently excluded, we can begin placement of additional cannulas under direct visualization. While the robot camera may be used for the initial survey, this requires the placement of a larger caliber initial access trocar (large enough to facilitate an 8.5–12-mm camera). Thus, in most instances, we will achieve initial access with a 5-mm trocar and place all of our RAS cannulas while utilizing standard laparoscopic surgical equipment (5-mm laparoscope, standard laparoscopic graspers, etc.).

Specific locations and the number/size of the surgical cannulas will be determined by the demands of the surgical procedure and the characteristics of a patient's anatomy, but in general, there are some basic principles one must keep in mind during placement of RAS trocars. As in laparoscopic surgery, triangulation of the surgical target with respect to the camera and the bilateral working arms is preferred in most situations (Fig. 3.4).

Specific to RAS, visualization is maximized when the center column of the surgical cart is

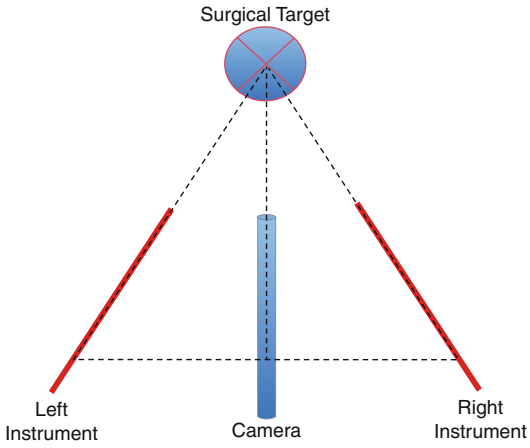

Fig. 3.4 Triangulation of the surgical target. Optimal approach angles are achieved when left and right instruments are positioned on either side of the laparoscope creating a triangulated approach toward the surgical target

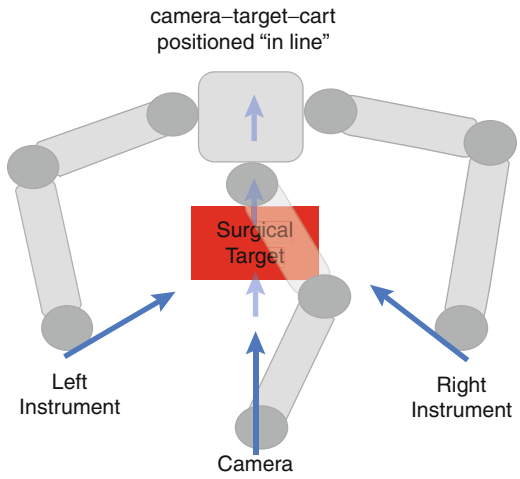

Fig. 3.5 Positioning the surgical cart. Aligning the surgical cart for a direct, straight-line approach toward the surgical target facilitates optimal "in-line" positioning of the camera, surgical target, and surgical cart and facilitates the docking process

positioned in a straight line behind the target tissue, and the camera is also lined up directly in front of the target tissue (Fig. 3.5). In most cases, the "left" and "right" working arms are then placed on either side of the camera, with particular attention paid to maintaining adequate working distance between each cannula/arm. It is generally recommended that a minimum of 8 cm of distance be maintained between the camera

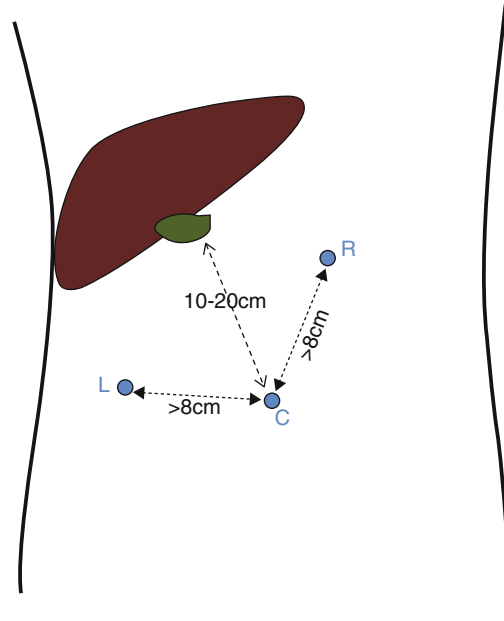

Fig. 3.6 Cannula placement. A minimum distance of 8 cm is recommended between instrument cannulas, and an ideal range of 10–20 cm between the camera port and the surgical target maximizes the surgical view

port and instrument cannulas, and an ideal distance of 10–20 cm is recommended between the instrument cannulas and the surgical target (Fig. 3.6).

The use of a 4th robotic surgical arm and the placement of additional bedside assistant port(s) are up to the discretion of the operating surgeon. Regardless of the number and size of the cannulas, it is imperative to maintain adequate spacing of cannulas so as to minimize mechanical interference of the robotic arms with each other. Robotic arms can crash into each other resulting in mechanical malfunction if these considerations are ignored. In addition, the bedside assistant may find it impossible to properly assist the operating surgeon, if the assistant's port is positioned in an inaccessible site or hidden behind actively working robotic surgical arms.

There are two standard lengths of reusable, metal RAS cannulas currently available. Both the 11-cm (standard length) and 16-cm (bariatric length) trocars come in various diameters. All RAS cannulas have external markings that define the optimum point of insertion. According to Intuitive Surgical, the black markings on these cannulas

represent the point that enables an axis of rotation that minimizes tissue trauma while allowing maximal surgical arm movement. Additional laparoscopic trocars may be utilized as assistant ports, and in most cases, a minimum diameter of 12 mm is necessary since staplers, sutures, and/or specimen bags must be introduced through these cannulas.

The caliber of the camera port is determined by the size of the robotic camera. Currently, there are two sizes of available RAS cameras: 8.5 and 12 mm in diameter. Both come in 0° and 30° varieties that offer high-definition, 3-dimensional, magnified visualization of the target tissue. The enhanced visualization is critically important, since the surgeon does not have any direct tactile resistance or "feedback" from the tissues. It is important for the surgeon to keep this in mind throughout any RAS procedure, so as to minimize inadvertent tissue injury. With the angled scope, the camera head may be loosened and repositioned to facilitate a 30° "up" or "down" perspective during the operation. Once docked, the surgical view can be easily adjusted and focused by the operating surgeon through simple movements performed at the surgeon console.

Docking the Robot

Once all of the cannulas have been placed, the operating table is adjusted into optimal position for the anticipated procedure. In this position, the individual arms of the surgical cart may be prepared for surgical maneuvers in a process called "docking the robot." First, the surgical cart is "driven" by a surgical assistant (and closely guided by the surgeon) into position. The surgical cart is heavy and cumbersome, and there is a built-in powered motor that allows the cart to be mobilized. The surgical cart's motorized movement is controlled by way of steering handles equipped with a rotary, hand-activated throttle and a brake release mechanism (Fig. 3.7). The surgical assistant (and surgeon) must be adept at utilizing these hand controls and safely engaging and disengaging the brakes for efficient movement of the

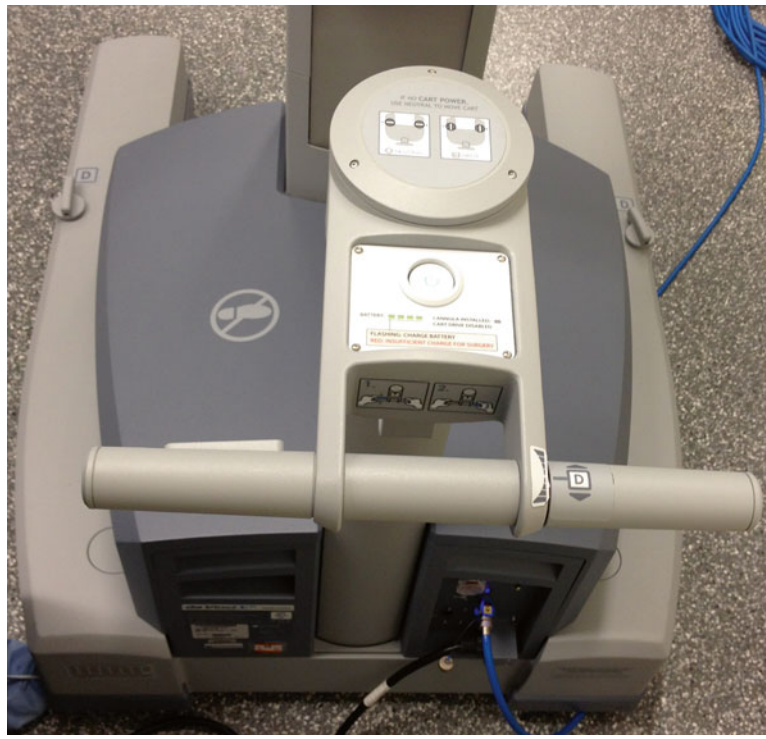

Fig. 3.7 Steering handles of the surgical cart motorized drive. Note the built-in rotary throttle and the brake release clutch on the right and left handles, respectively

surgical cart. Once the surgical cart has been positioned appropriately, the individual mechanical arms may be coupled to their designated cannulas and the docking process complete.

In order to maximize surgical view and intraoperative robotic arm movements, the surgical cart should first be positioned "behind" the anticipated surgical target. The surgical arms will then be extended over the patient's body and ultimately docked to their designated cannulas. This results in a final configuration with the camera and all instrument tips pointing directly toward the surgical target with the surgical cart standing directly beyond it (Fig. 3.5).

Following these simple principles can facilitate efficient docking of the RAS platform:

- First, position the patient so as to maximize target surgical site acquisition:
  - As an example: for a cholecystectomy procedure, the patient will need to be positioned in a reverse Trendelenburg position of about 45° with a slight rotation of the table toward the patient's left.
  - Once the robot is docked, it is time consuming and cumbersome to undock and reposition the patient or the robot. Thus, we will frequently utilize footboards and additional security straps to maintain proper patient positioning throughout the procedure.
- Prepare the robot in a location so as to minimize manipulation or "driving" of the robot.
  - It is easiest to "drive" the surgical cart in a straight line directly toward the patient from "behind" the anticipated surgical target.
  - As an example: for a cholecystectomy, the surgical cart is prepared in a location already aligned with the patient's right shoulder during initial setup. Once the patient is in final surgical position, the surgical cart is driven in a straight line toward the bedside, and the robot arms are individually docked. This results in the camera and all surgical instrument tips pointing directly toward the gall bladder with the surgical cart behind the patient's liver/right shoulder.
- When docking, engage the camera arm to its cannula first, followed by the surgical instrument arms and their respective cannulas.
  - There are markings on the setup joint of the surgical cart camera arm that designate a "sweet spot" for optimal camera arm positioning (Fig. 3.8). (The "sweet spot" of the camera arm is a range of possible arm positions that maximize RAS camera viewing angles and is predefined by the manufacturer and displayed on the camera arm as a blue-colored bar. Placing the camera arm anywhere along the blue-colored bar will ensure that camera viewing angles are maximized).
  - In order to manipulate any arm of the robot, the surgeon must press specific "clutch" buttons positioned in various points on the robot arm. (In certain cases, blinking-colored lights will depict errors and/or the status of the robot arm for repositioning. We refer the reader to the section on "Troubleshooting" for further explanation of common errors).
- Docking the working robot arms to the cannulas.
  - Visually inspect the internal cannula position with the camera so as to minimize inadvertent internal injuries.
  - Maintain proper distance between each cannula/robot arm and adjust position of robot arms/elbows to avoid mechanical interference between arms.
  - Anticipate the motion of the robot arms during the procedure, and ensure that there is ample clearance for the robot arms/elbows to move in space.
- Accommodate for positioning of an assistant port (if any) that will provide easy access to target tissues while maintaining freedom of space away from the movement of the operative robot arms.
- Select and install surgical instruments into each of the working robot arms.
  - Prior to insertion, each surgical instrument must be checked for signs of damage or malfunction. Some instrument tips have flexible "wrists" and the ability to bend and rotate in response to the surgeon's controls. Careful inspection of instruments, with particular attention paid to the wrist mechanism and instrument tip, is mandatory prior to use.
  - Ensure that there is unobstructed (by internal organs, tissues, etc.) passage for introduction/

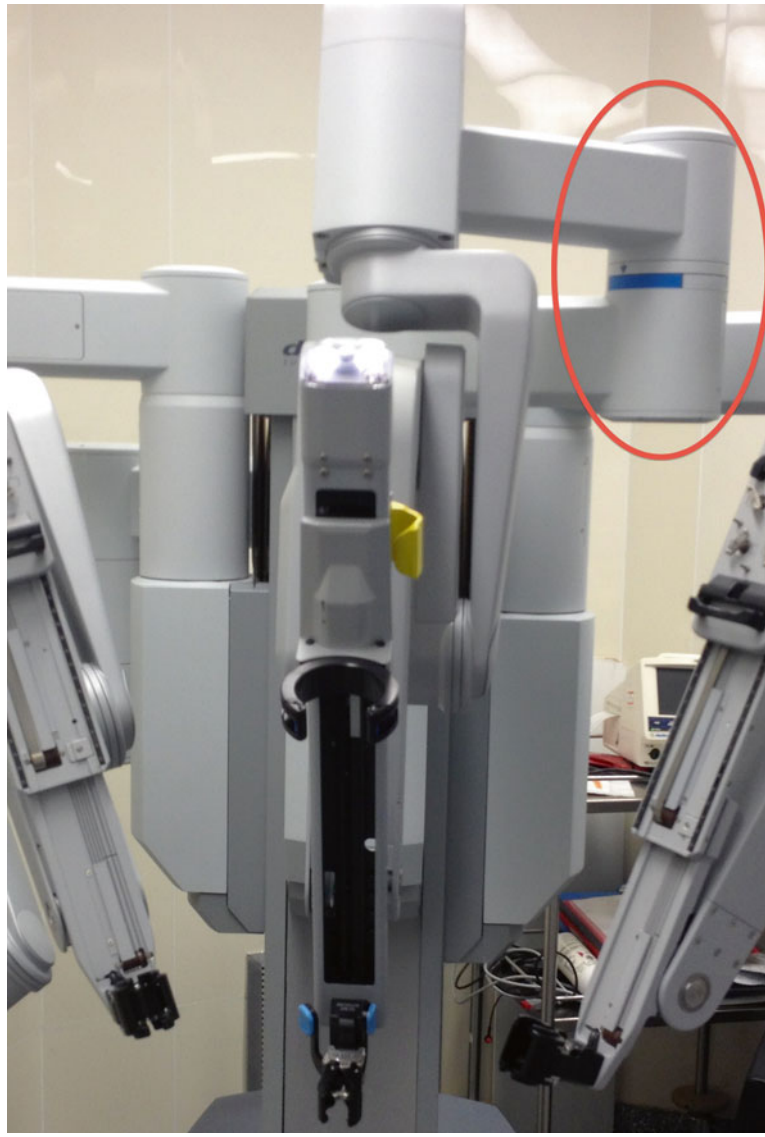

Fig. 3.8 The camera arm setup joint "sweet spot." Note the *blue* markings on the camera arm that designate ideal positioning of the surgical cart/camera arm during the docking process

retrieval of each instrument without risk of injury to surrounding tissues and organs.

- Each instrument must be placed tip first into a docked cannula and then "snap loaded" onto the mechanical rotors that are built into the sterile surgical drape cover the robot instrument arm. Once installed, the robot will perform an initial assessment and ensure the instrument has not expired. After several seconds, the RAS platform will display a ready signal on the monitors as well as a blinking light signal directly on the robot arm. The surgeon or assistant may then slowly advance the instrument into the surgical field while carefully monitoring the internal path of the instrument with the camera.

Once all of these steps have been completed, the surgeon may move to the surgeon console and begin the necessary steps of the operation. At first,

this physical distance and conducting the operation far away from the patient's bedside can lead to an unfamiliar sense of detachment for the surgeon. Expectedly, there may even be concerns about losing immediate access to the patient for emergency purposes. This feeling of remoteness from the familiarity and instant control accessible from the patient's bedside should serve to remind the surgeon of some of the key differences between standard laparoscopic surgery and RAS.

Differences Between Laparoscopic and Robotic Surgery

There are some key aspects of RAS that differ dramatically from standard laparoscopic and open surgery. As mentioned previously, the surgeon performs the key portions of the procedure remotely, several feet away from the patient's bedside. Thus, both the surgeon and the entire surgical team must be ready to initiate emergency maneuvers should such a need arise during the conduct of any operation. Having an emergency plan for the surgeon to move from the surgeon console to the bedside expeditiously in case there is unexpected bleeding or other critical issues and each member of the surgical team knowing their respective roles in undocking and mobilizing various RAS carts and surgical equipment is mandatory. If a patient must be converted from RAS to either laparoscopic or open surgery for whatever reason, the team must be able to quickly undock the robot and provide the surgeon with the necessary surgical equipment at a moment's notice.

Whereas, in laparoscopic surgery, the patient's position may be frequently changed to maximize visualization of target tissues, in RAS the patient's position must remain constant after docking of the robot. Any changes in patient position may require undocking and re-docking of the surgical cart, a process that can be time consuming and frustrating. Again, anticipating patient-specific factors (e.g., large amount of intra-abdominal fat or a large liver that may hinder RAS) and proper patient selection are important especially early on in a surgeon's experience with RAS.

In addition, the lack of tactile resistance or feedback must be respected and overcome. The only feedback that the operating surgeon experiences at the surgeon's console is purely visual. The enhanced visualization of the camera does provide exceptional visual feedback, but the surgeon must constantly maintain optimal visualization of both the target and surrounding tissues that may be at risk for inadvertent injury. Keeping all working instruments in direct and constant visualization is an absolute must for RAS. And, careful insertion and removal of surgical instruments by properly trained and knowledgeable assistants is critically important. Furthermore, the surgeon should make a conscious effort to reduce the number of instrument exchanges during the procedure to limit the risk of inadvertent injury and to maximize surgical efficiency.

It is also important to keep in mind that the high-definition, 3-dimensional images enjoyed by the operating surgeon are not what are visualized by the rest of the operating room staff on the 2-dimensional bedside control tower monitor. Sometimes, this can lead to inconsistencies in visualization of target tissues between the operating surgeon and the bedside assistant, and constant verbal communication between the surgeon and assistant is mandatory during any RAS procedure. In order to facilitate this communication, the bedside vision cart is equipped with an intercom and a monitor that may be upgraded to a touch screen that enables a surgical assistant to telestrate information directly onto the monitor screen in order to relay information to the surgeon at the console.

Finally, in certain instances, it may be necessary for the surgeon to return to the sterile field in order to complete necessary surgical tasks personally (e.g., firing a stapler, resetting an assistant retractor, etc.). Thus, an abundant supply of sterile gowns and gloves must be kept at the scrub table so as to allow easy access of the operating surgeon between the sterile bedside and nonsterile surgeon's console. In fact, the surgeon may wish to maintain sterility by wearing "over" gloves when moving to and from the surgeon's console or the bedside. This may eliminate the need to rescrub multiple times during a procedure and increase surgical efficiency and safety.

The Surgeon Console

The surgeon console is the main interface that enables the surgeon to visualize the surgical field and control each instrument/arm of the RAS platform. The console is comprised of three key components: the binocular viewing screens (Fig. 3.9), the master instrument controls (Fig. 3.10), and multiple buttons and foot pedals (Fig. 3.11) that control electrosurgical instrument activation, facilitate camera movements, and allow the surgeon to toggle control from one surgical arm to another.

One of the distinct advantages of the RAS platform is the surgeon's full control of the camera position and focus. By pressing a camera "clutch" and turning the instrument controls on the console, the surgeon can adjust the focus of the robotic camera. By pressing the camera clutch while pushing the console instrument controllers in and out, the surgeon can move the camera in space, zooming in and out of target fields. Likewise, by pressing the camera clutch while moving the instrument controllers in a "steering wheel" motion, the surgeon can easily adjust the horizon of the camera view.

The surgeon console master instrument controls can precisely manipulate the surgical instruments in use and replicate the hand movements of the surgeon's hands with precisely mimicked movements of the surgical instruments within the surgical field. The surgeon places the thumb and index finger of each hand into master controllers and can open and close instrument tips and can even bend and rotate wristed surgical instrument tips with great precision. The RAS platform affords up to a 90° articulation of the many varieties of wristed surgical instruments while allowing 7° of rotational freedom. In addition, the platform minimizes human hand tremor

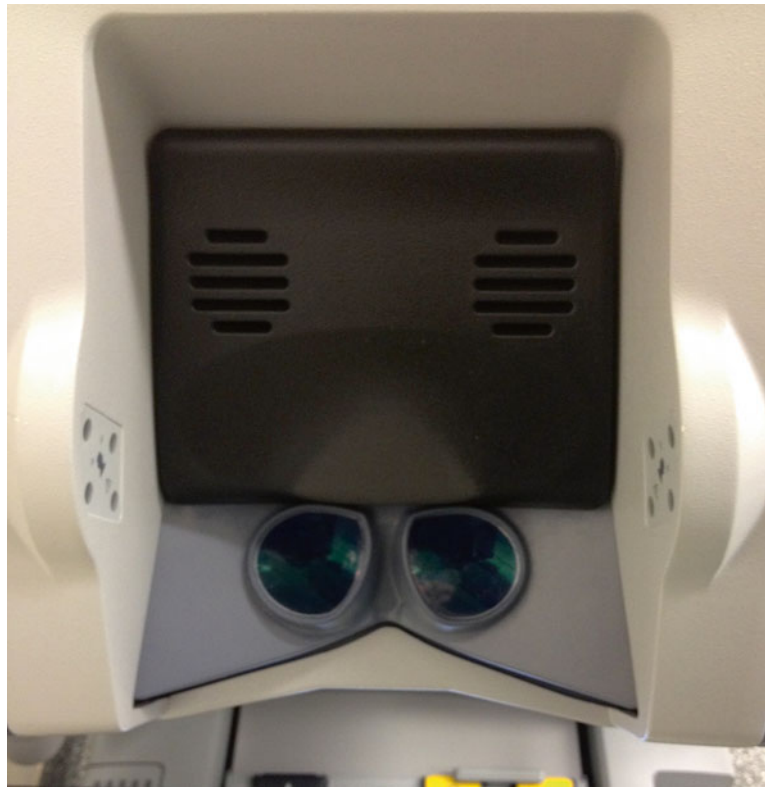

Fig. 3.9 Stereoscopic viewing display on the surgeon console

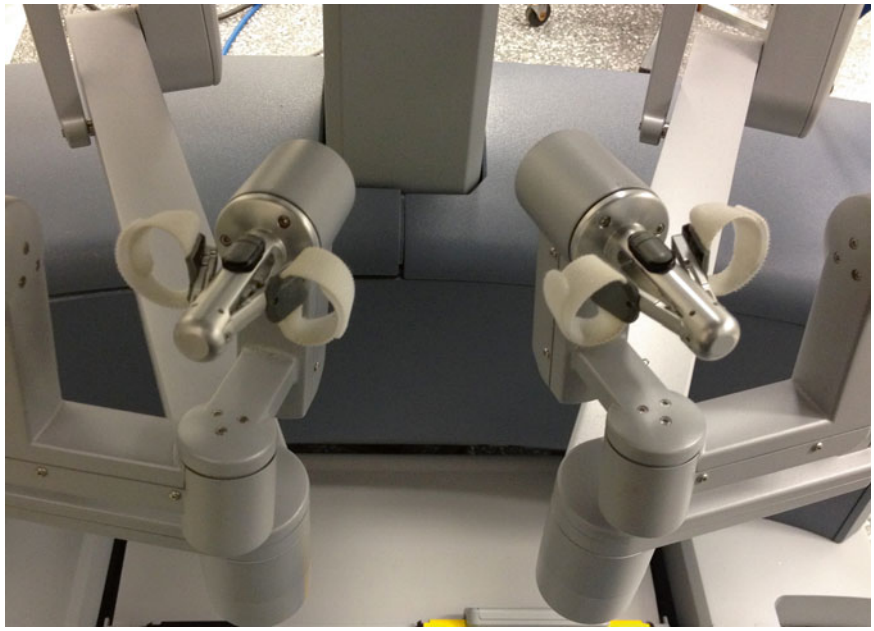

Fig. 3.10 Master controllers on the surgeon console

Fig. 3.11 Foot pedals on the surgeon console

and can "lock" an instrument in steady position for retraction purposes. As an operation continues, the surgeon may wish to adjust only the position of the instrument controllers at the console without affecting the actual surgical arms/instruments within the surgical field. This can be performed by pressing the instrument "clutch" button while moving the console instrument controllers freely without changing the actual position of the bedside surgical instruments.

Frequent and fine adjustments of the camera, the surgical instruments, and the individual controllers at the console are necessary. Thus, the operating surgeon must become familiar with every aspect of the console interface and be able to make these minute-by-minute adjustments as a procedure progresses. The ability to easily make these fine adjustments can help to overcome surgical difficulties and enhance the surgical experience for the surgeon. It has been the experience of the authors that one of the distinguishing characteristics between experienced and novice RAS platform users is that experienced robotic surgeons tend to make frequent, real-time adjustments and incorporate these fine movements and technical enhancements naturally throughout the procedure.

Troubleshooting

All mechanical devices have the potential for malfunction and failure. Fortunately, the failure rate of the Intuitive Surgical RAS platform is low, and recent reviews of failure rates were estimated to be as low as 0.5 % during robotic prostatectomy procedures and 3.5–4.5 % for robotic general surgery procedures [9–13]. Routine maintenance of the hardware components and software system updates are necessary for optimal performance of the RAS platform. Although a detailed description of all potential malfunctions of the RAS platform is beyond the scope of this chapter, we will discuss some common concerns and potential issues that a surgeon may encounter.

When utilizing the RAS platform, there are two major types of errors or "faults" that may be encountered: recoverable and non-recoverable. A recoverable fault simply means that the procedure may continue once the specific error detected has been appropriately addressed. In contrast, if a non-recoverable fault is encountered, there may be a serious malfunction of the RAS system, and the surgeon must completely shut down the RAS system and/or convert to either a laparoscopic approach or to open surgery in order to complete the operation. The RAS platform performs constant self-monitoring and surveillance in order to detect any technical or mechanical faults. Any identified errors will be communicated to the surgical team through visual and auditory alarms. Descriptions of the identified faults will be readily displayed on the monitors so that the team will be able to promptly address them. If a specific robotic arm triggers the fault, there will even be a flashing color light signal displayed directly on the arm to alert the surgical team. The RAS platform has the capability to communicate errors detected during an operation directly with the manufacturer via the internet for real-time troubleshooting. Finally, the system also has the capacity to store error data for review at a later date.

Here are some simple strategies for avoiding and/or troubleshooting commonly encountered difficulties during RAS:

- Electrical power: The RAS platform and all of its mechanical components are electrically powered with a backup battery reserved to maintain operations of the platform for a short period of time in case of a power outage. When not in use, the RAS platform must remain plugged into an electrical power source for proper battery charging. The power cables along with the multiple wires connecting the RAS carts and console must also be properly maintained.
- Surgical cart movement: In order to prevent inadvertent patient injury, the surgical cart may only be moved when the robotic arms are disengaged from the patient. Thus, docking a robot arm to a cannula will render the entire cart immobile.
- Robotic arm movement: Inappropriate movements of the robot arms may trigger an error message and render the specific mechanism immobile until the error has been acknowledged. Maintaining proper distance and

appropriate approach angles for all instruments/robot arms is necessary to avoid errors and to allow proper movement of individual surgical instruments/arms. In addition, extreme angulation causing unusual torque on the instrument arms may also trigger a similar, recoverable fault.

– Cannulas: The instrument arms are designed to engage appropriate RAS cannulas. Attempts to use noncompliant trocars may trigger an error.
– Instruments: When an instrument is first engaged by the RAS platform, the system will identify the type of instrument, the number of uses left prior to expiration, and the specific robot arm that it has been loaded onto. After a brief processing time of a few seconds, the system will superimpose all of this information directly onto the surgical image. Likewise, any errors detected during this process will trigger both an audible and visual alarm and display the error message on screen.
  - As mentioned previously, each surgical instrument may only be used for a set number of cases (10 uses) prior to expiration. If an instrument has "expired," it will simply need to be replaced.
  - When loading a surgical instrument, the instrument must be properly seated onto the surgical arm by first aligning the built-in grooves and then "snap loading" it into proper position on the robot arm instrument hub. Misalignment may lead to improper loading of the instrument onto the robot arm and trigger an error message. Sometimes, the built-in instrument hub on the sterile drapes covering the robotic arm may cause difficulty. When encountering an error for instrument installation, it is best to fully remove the instrument and to first ensure proper positioning of the drape/instrument hub prior to an attempt at reloading the surgical instrument.
  - Once an instrument has been properly loaded and used in a case, the RAS system will recall the position and orientation of the instrument tip and facilitate a "guided instrument exchange." This mechanism can help to avoid potential injury during passage of instruments into the surgical field. In order to perform a guided exchange, the assistant removes the surgical instrument by grasping the release levers and pulling the instrument out of the surgical field and the robotic arm. The RAS system will recall the spatial positioning (within the surgical field) of the previously used instrument and guide the newly inserted instrument tip back into position within 1 mm of the previous position.
– Camera: Blurred images may result from improper focus or debris/condensation on the surface of the camera lens. Prior to use, the surgical team must first align and focus the RAS camera, but the surgeon may further adjust the fine focus of the image at the surgeon console. If refocusing the camera does not improve vision, the camera tip should be cleansed with a soft cloth to ensure it is clean. Utilizing antifog emulsion solutions and/or endoscope-warming devices may also be helpful.
– Visualization: Inadequate visualization of target tissues may also result from less than optimal patient positioning. In such cases, the robot may need to be undocked and the patient repositioned.
– Positioning: The RAS platform is ideal for performing complex surgical maneuvers in one specific region or quadrant of the abdomen such as the deep pelvis, the diaphragmatic hiatus, etc. Surgical procedures that require frequent and multiple changes in patient position will likely require multiple docking and undocking of the robot. Thus, preoperative planning and strategies for efficient equipment utilization is extremely important for maximizing surgical efficiency.

Future Directions

Surgical technology is constantly evolving, and with each system enhancement, RAS platforms have provided the surgeon with more and more sophisticated surgical instruments with greater technical capabilities. With future development, the next generation of RAS platforms will likely overcome some of the bulkiness of currently

available equipment, the complexities of docking and patient positioning, and may even incorporate tactile feedback mechanisms. One recently introduced enhancement is the single-site robotic cholecystectomy platform. As with laparoscopic surgery, there has always been an interest in further minimizing the invasiveness of surgery by converting RAS procedures using multiple incisions into a "single-site" operation utilizing only one small incision. Whereas single-site laparoscopic surgery required a disoriented "crisscrossing" of surgical instruments, limited surgical views, and poor ergonomics, the RAS platform's capabilities such as the ability to designate control of individual surgical arms, enhanced surgical visualization, and improved ergonomics all help to overcome some of the challenges of single-site laparoscopic surgery. In fact, single-site robotic cholecystectomy has been gaining popularity in recent years, and even more complex operations are being undertaken with modified single-site robotic surgery approaches; the authors have even performed a single-site robotic adrenalectomy procedure utilizing a modified single-site robotic approach, and others have reported similar experiences with various single-site RAS procedures [14–26].

Regardless of what is in store for future technology enhancements, the fact remains that RAS technology is being utilized regularly in today's surgical arena and will likely become even more commonplace in the operating rooms of the future. Numerous surgical societies have created subcommittees dedicated to RAS, and the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) has even published a consensus statement to help guide surgeons in safely utilizing RAS platforms [3]. Robotic surgery training modules are now being incorporated into the curriculum for residents in training, and fellowship programs with greater emphasis on RAS are also becoming readily available [4, 23]. Thus, it is prudent for surgeons to remain engaged in the utilization and ongoing development of robotic technology since surgeons are responsible for ensuring that the use of surgical technology results in safer and better outcomes for patients.

Conclusion

The RAS platform provides the surgeon with advanced, minimally invasive surgical capabilities, but it does require additional training and a progressive accumulation of surgical proficiency. Proper patient selection and preoperative planning and optimal equipment setup are the fundamental keys to a successful RAS procedure. The strategies for avoiding and troubleshooting some commonly encountered challenges should facilitate efficient use of the RAS platform, and surgeons are encouraged to remain involved with ongoing technology development.

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Essentials and Future Directions of Robotic Esophageal Surgery

4

Umer I. Chaudhry and W. Scott Melvin

Introduction

The esophagus is a mucosa-lined muscular tube, 20–24 cm in length and devoid of a serosal layer, that traverses three compartments: the neck, the chest, and the upper abdomen, as it makes its way from the pharynx to the stomach. Throughout its course, the esophagus lies in close proximity to vital structures including the larynx, trachea, vertebrae, lungs, heart, the great vessels, thoracic duct, and both vagus nerves. Additionally, it is bound by fibrous membranes, both anteriorly and posteriorly, and confined by the diaphragmatic crura distally. Due to its anatomic location and intimate relationship to other vital structures, gaining access to the esophagus can be difficult, requiring thoracotomy in some procedures and blind dissection in others. Although dramatic advancements have been made since the first reported esophagectomy in 1911[1], surgery of the esophagus remains one of the most challenging operations with high morbidity and mortality.

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Minimally invasive techniques have truly revolutionized the field of general surgery. Many operations that were once performed open can now be successfully completed using a minimally invasive approach. The last two decades have seen a significant shift in the treatment algorithm of esophageal diseases, mainly due to the introduction and continuous development of laparoscopy. In most cases, minimally invasive esophageal surgery has now replaced open procedures as the standard of care.

Although originally intended to facilitate remotely performed surgery in the battlefield and other austere environments, potential applications of robotics in minimally invasive surgery were recognized in the 1990s. Subsequently, in 2000, the da Vinci Surgery System (Intuitive Surgical Inc., Sunnyvale, CA) became the first robotic surgery system to be approved by the FDA for laparoscopic surgery. Currently, few doubts exist that robotics provide superior optics, lighting, magnification, depth perception, range of motion, and dexterity compared with conventional laparoscopic technique. Robotics, perhaps, holds the most utility when the procedure requires fine dissection and movements in a confined space, such as esophageal surgery. For operations performed over a wide area and not requiring delicate dissection, the disadvantages of robotics usually outweigh any potential benefits. This chapter will explore the safety and feasibility of robotic applications in esophageal surgery.

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Esophagectomy

The most common indication for esophagectomy is esophageal carcinoma. Rarely, end-stage benign esophageal disorders, such as achalasia, may also require an esophagectomy. The incidence of esophageal cancer, mainly adenocarcinoma, has been on the rise, with greater than 17,400 new cases and 15,000 deaths expected in the USA this year [2]. However, significant advances have been made in the treatment of esophageal carcinoma as well, with overall 5-year survival rates approaching 47 % in patients receiving neoadjuvant chemoradiation, followed by an esophagectomy [3].

The classic open approaches for esophagectomy include a transhiatal resection [4], a transthoracic approach, such as an Ivor-Lewis esophagectomy [5], a "3-hole" McKeown-type technique [6], or a left thoracotomy or left thoracoabdominal approach [7], with each operation having its own advantages. The introduction of laparoscopy in the mid-1980s took the general surgery world by storm, and reports of minimally invasive esophagectomies (MIE) began to appear by the early 1990s. Collard et al. [8] were first to publish their experience with thoracoscopic esophagectomies in 10 patients in 1991. Subsequently, the first minimally invasive transhiatal esophagectomy was described by DePaula et al. [9] in 1995. Two years later, Swanstrom and Hansen [10] published the first series of totally laparoscopic esophagectomies. Since these initial reports, MIE technique has been modified several times and continues to gain acceptance [11–14]. In a population-based national study, Mamidanna and colleagues [15] reported that in 2009–2010, 24.7 % of all esophageal resections in the UK were performed via minimally invasive techniques, compared to 16 % in 2007 and less than 1 % in 1996 [16].

While utilization of minimally invasive surgery for esophageal resection has grown significantly, there still remains significant controversy when considering this approach for esophageal malignancies. In a recent survey of 250 international esophageal surgeons [17], an open technique was preferred by 78 %. Only 14 % preferred a minimally invasive approach and 8 % had no preference. Concerns have been raised regarding the adequacy of oncologic resection with MIE, when compared with the traditional open techniques. However, in a recent large single-institution series of over 1000 MIE, Luketich et al. [18] observed an R0 resection in 98 % of the patients, and median number of lymph nodes (LN) removed [21] were comparable to other open series. The authors concluded that in experienced hands, MIE can be performed safely and with good oncologic results. Nevertheless, long-term oncologic efficacy of MIE remains undetermined.

Although 20 years have passed since the first description of MIE, the operation remains technically complex. The dissection at the hiatus and within the mediastinum can be especially difficult and time consuming. Robotic approach to MIE allows surgeons to overcome many of these technical and ergonomic barriers, although there is a steep learning curve with the surgeon approaching near proficiency after 20 cases [19].

The first report of a robotic-assisted esophagectomy was published in 2003 [20]. Authors described a transhiatal approach for an early stage adenocarcinoma of the distal esophagus. Majority of the abdominal portion of the case was performed using standard laparoscopic techniques. The esophagus was resected using the robot and a cervical esophagogastrostomy was created via a gastric pull-up. Formal mediastinal lymphadenectomy was not performed. The total operative time was 246 min, with robotic portion taking 52 min, and estimated blood loss was 50 ml. At the time, the authors concluded that robotic application in esophageal malignancy was best suited for patients with early stage disease, since an adequate LN dissection required for advanced stage disease was not yet feasible with the robot and the transhiatal approach. Typical abdominal port placement (Fig. 4.1) and finished incisions (Fig. 4.2) are shown.

A year later, in 2004, Kernstine and colleagues [21] described the first robotic-assisted transthoracic and transabdominal esophagectomy, with a cervical esophagogastrostomy. The procedure lasted for 11 h, with the robotic portion taking 4 h 20 min, and estimated blood loss was 900 ml.

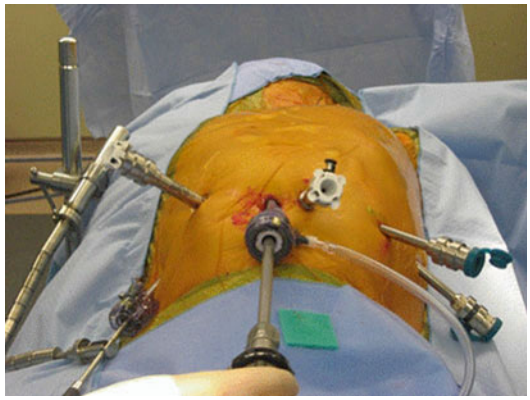

Fig. 4.1 Abdominal port placement (Used with permission from Abbas AE, Dylewski MR. Robotic Assisted Minimally Invasive Esophagectomy. In Kim DC (ed): Robotics in General Surgery. New York: Springer Science + Business Media; 2014)

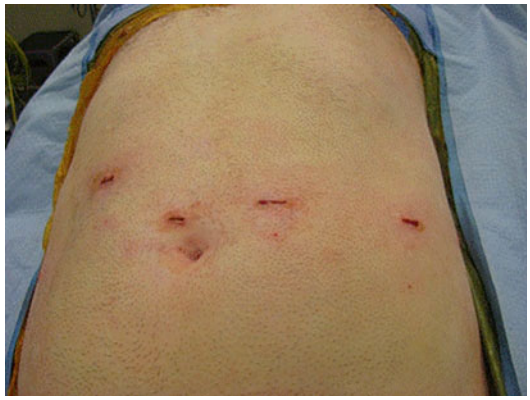

Fig. 4.2 Incisions upon completion (Used with permission from Abbas AE, Dylewski MR. Robotic Assisted Minimally Invasive Esophagectomy. In Kim DC (ed): Robotics in General Surgery. New York: Springer Science + Business Media; 2014)

The resection included periesophageal, peritracheal, and both hilar nodal groups, as well as the thoracic duct. Final pathology results were not reported, although the patient was determined preoperatively to have stage T3N0 disease by imaging.

The authors determined that a combined transthoracic and transabdominal robotic-assisted approach can be applied to a much broader group of patients, when compared to a transhiatal technique.

Since these initial case reports, many cases series have been published on utilization of robotics for esophageal resection, with great variation in techniques. Several groups have described a transthoracic approach [22–26], while others have published on transhiatal technique [27–29], all with variable assistance from the robot. A single publication exists of a totally robotic esophagectomy [30]. The most recent series are summarized in Table 4.1. Oncologic outcomes such as recurrence- or disease-free survival are difficult to interpret, as all the studies suffer from small sample sizes, short follow-up intervals, and variable disease stages among the patients. At the time of this publication, no randomized trials exist comparing these different techniques.

In the robotic-assisted transhiatal approaches, the abdominal portion of the operation was completed in standard laparoscopic fashion, while the robot was employed for the transhiatal mediastinal dissection. In 2008, Galvani and colleagues published a case series of 18 patients with early stage esophageal malignancy [27]. The mean operative time was 267 min and estimated blood loss was 54 ml. There were no perioperative deaths. All patients had an R0 resection and mean LN retrieval was 14 (range 7–27). At mean follow-up of 22 months, 17 % of the patients had recurred. More recently, the same group published their results on a series of 23 patients with advanced-staged esophageal cancer [29]. Based on preoperative endoscopic ultrasound, nodal involvement was present in 65 % of the patients, and 74 % had tumor invading into the adventitia (T3). Eighty-three percent of the patients had received neoadjuvant chemoradiation. Median operative time was 231 min (range 179–319) and estimated blood loss was 100 ml (range 25–400). There was one 30-day mortality (4 %) and two patients experienced an anastomotic leak (9 %). All but two patients (91.3 %) had an R0 resection, and mean LN yield was 15 (range 5–29). At median follow-up of 7 months (range 1–29), 18 (78 %) patients were alive and metastases had developed in 6 (26 %).

Dunn et al. [28] recently published their experience with 40 robotic-assisted transhiatal esophagectomies over a 3-year period. Ninety percent of the patients had esophageal cancer of

Table 4.1 Summary of case series on utilization of robotics for esophageal resection

Author	Year	Patients	Approach	Conversion rate (%)	Operative time (min)	Blood loss (ml)	ICU stay (days)	Hospital stay (days)	Mortality (%)	LN yield	R0 resection (%)
Kemstine et al.	2007	8	TT + TH	0	11.2 (9.5–13.0)	275 (50–950)	1 (0–72)	NR	NR	18 ± 7	100
Galvani et al.	2008	18	TH	0	267 ± 71	54 ± 35	1.8 ± 1.2	10 (4–38)	0	14 (7–27)	100
Kim et al.	2010	21	TT	0	410 ± 100	150 (50–2,300)	2 (1–3)	21 (11–45)	0	38 ± 14	95.2
Puntambekar et al.	2011	32	TT	0	210 (180–300)	80 (40–200)	NR	9 (5–20)	0	20 (9–28)	NR
Weksler et al.	2012	11	TT	0	445 (306–536)	150 (50–600)	4 (1–9)	7 (5–16)	0	19 (10–47)	100
Dunn et al.	2013	40	TH	12.5	311	97	1 (0–16)	9 (6–36)	2.5	20 (3–38)	94.7
Sarkaria et al.	2013	21	TT	24	556 (395–807)	300 (200–500)	NR	10 (7–70)	5	20 (10–49)	81
de la Fuente et al.	2013	50	TT	0	445 ± 85	146 ± 15	2 (2–23)	9 (6–35)	0	20 ± 1.4	100
Coker et al.	2014	23	TH	0	231 (179–319)	100 (25–400)	NR	9 (7–37)	4	15 (5–29)	91.3

Hours values reported as median (range) or mean ± standard deviation, when applicable
ICU intensive care unit, *LN* lymph node, *NR* not reported, *TT* transthoracic, *TH* transhiatal

varying stage and 42.5 % had received neoadjuvant therapy. The median operative time was 311 min and estimated blood loss was 97 ml. There were 5 (12.5 %) conversions to open technique and a single 30-day mortality. Complication rates were high with 25 % of the patients experiencing an anastomotic leak and 35 % suffering temporary recurrent laryngeal nerve palsy. The median LN yield was 20 (range 3–38) and R0 resection was achieved in 94.7 % of the patients. Median disease-free survival was 20 months (range 3–45).

For series describing robotic-assisted transthoracic approaches, esophagus is mobilized transthoracially with robotic assistance, and abdominal portion of the operation is completed via laparotomy, laparoscopically, or robotically. In a recent series of 21 patients from Memorial Sloan-Kettering Cancer Center [26], 17 patients underwent a robotic-assisted Ivor-Lewis esophagectomy, and the remainder had a "3-hole" McKeown approach. The median operative time was 556 min (range 395–626) and median estimated blood loss was 300 ml (range 200–500). Five patients (24 %) required conversion to an open approach and another five patients had to be converted to a non-robotic laparoscopic and thoracoscopic approach. Reasons for conversion were several and included excessive operative time, poor visualization, questionable anastomotic integrity, extensive adhesions, positive margin on frozen section, and robotic console failure. There were three (14 %) anastomotic leaks and three patients developed airway fistulas. A single perioperative mortality was reported. The authors concluded that robotic-assisted MIE may offer some advantages over standard MIE, but critical evaluation of complications and subsequent refinement of technique is paramount for future applications.

Recently, de la Fuente et al. [25] published a series of 50 robotic-assisted Ivor-Lewis esophagogastrectomies, the largest series of robotic-assisted esophageal resection to date. Mean operative time and estimated blood loss were 445 ± 85 min and 146 ± 15 ml, respectively. Statistically significant improvement in operative time was noted in the last 20 patients (410 ± 60 min; $p = 0.003$). One patient (2 %) had an anastomotic leak and another suffered a conduit staple-line leak. There were no perioperative deaths and all patients had an R0 resection, with median LN yield of 18.5 (range 6–63). These results are comparable to other series of robotic-assisted transthoracic approaches [22, 23].

Albeit hampered by selection bias and small sample size, a study by Weksler et al. [24] showed that robotic-assisted transthoracic esophagectomy ($n = 11$) was equivalent to traditional thoracoscopic MIE ($n = 26$). Authors noted no significant differences in operative time, blood loss, LN yield, R0 resection rates, perioperative complication rates, length of ICU or hospital stay, or mortality between the two approaches.

A 2011 review by Clark and colleagues [31] evaluated oncologic, operative, and functional outcomes of all robotic-assisted esophageal resections published up to April 2010. Nine case series with 130 patients were included in the analysis. There were variations in technique, with majority of the patients undergoing a transthoracic approach. Indications for surgery also varied from high-grade dysplasia to adenocarcinoma and squamous cell carcinoma. Sixty-two percent of the tumors were located in the distal esophagus, 14 % in the middle and upper esophagus, and remaining 24 % were not defined. Mean operative time was 377 min, and estimated blood loss was 226 ml. Average hospital length of stay was 15 days. Perioperative complications included a 30-day mortality rate of 2.4 %, an anastomotic leak rate of 18 %, a vocal cord paralysis rate of 13 %, a pulmonary complication rate of 25 %, and a cardiac complication rate of 11 %. An R0 resection was achieved in 90 % of the cases and average LN yield was 21 (range 12–38).

Although the review by Clark et al. [31] and subsequent case series by Weksler et al. [24] and de la Fuente et al. [25] are convincing that robotic-assisted esophagectomy can provide adequate oncologic resections with similar perioperative outcomes as laparoscopic or thoracoscopic approaches, the heterogeneity of techniques and variable extent of robotic assistance, along with short postoperative follow-up, reduce the impact of the data. Additional shortcomings of the

approach include its high operational costs, need for more personnel and space, and an additional learning curve.

Currently, there is no evidence in the literature to support that robotic assistance offers better oncologic or perioperative results than conventional MIE techniques, and, thus, its wide dissemination beyond specialized high-volume centers cannot be justified. However, in 2012, a randomized controlled trail comparing robotic-assisted minimally invasive thoraco-laparoscopic versus open transthoracic esophagectomy (ROBOT trial) was initiated in the Netherlands [32]. The study will randomize 112 patients with surgically resectable esophageal cancer to each arm, with overall complications representing the primary endpoint. Short-term and 5 years' follow-up results will be published as they become available and provide the much needed data to determine the efficacy of robotics in esophageal resection.

Esophagogastric (Heller) Myotomy

Achalasia is a rare idiopathic primary motility disorder of the esophagus with an estimated incidence of 1 per 100,000 individuals [33]. It is characterized by absent peristalsis of the esophageal body and failure of relaxation of the lower esophageal sphincter. Surgical esophagogastric myotomy, or Heller myotomy, when combined with an antireflux procedure is the most effective treatment for symptoms related to achalasia, with a success rate of greater than 90 %, compared to 41 % for endoscopic botulin toxin injection and 68 % for endoscopic balloon dilation [34].

Basic principles of esophagogastric myotomy have not changed much since Heller's initial description in 1913 [35]. However, the surgical approach has evolved dramatically over the last 20 years. Since the first report of laparoscopic Heller myotomy in 1991 by Cuschieri [36] and a thoracoscopic approach by Pellegrini in 1992 [37], minimally invasive approach has become the gold standard for the treatment of achalasia. The literature supports minimally invasive technique over an open procedure with comparable or improved outcomes and better quality of life measures [38]. As it offers superior results over a thoracoscopic approach and is technically more feasible, laparoscopic Heller myotomy with partial fundoplication has now become the preferred approach by most surgeons [39–43].

Melvin et al. [44] published the initial report of robotic Heller myotomy in 2001. The patient was a 76-year-old female with a 10-year history of achalasia. A myotomy with Toupet fundoplication was performed successfully using the robot throughout the operation. The procedure lasted 160 min and the patient was discharged on postoperative day 1. The authors determined that the robot had application in operations that required fine dissection, such as Heller myotomy. Additionally, they concluded that the added benefit of increased magnification and three-dimensional optics would prevent iatrogenic esophageal perforation and identify residual circular fibers.

Several years later, in 2005, a multicenter retrospective review of 121 patients, comparing robotic-assisted Heller myotomy with laparoscopic Heller myotomy was published [45]. The study represented operations performed between 1995 and 2004 at three institutions in two countries. Operative time for the robotic group was significantly longer during the first half of the experience (141 ± 49 vs. 122 ± 44 min; $p < 0.05$), but showed no statistical difference during the latter half. However, the laparoscopic cohort experienced a 16 % rate of intraoperative esophageal perforation, compared to 0 % in the robotic group. Outcomes were similar at short-term follow-up with 90 % and 92 % of the patients in robotic and laparoscopic group achieving symptomatic relief, respectively. Although hindered by selection bias inherent to a retrospective study, this was the first publication to suggest that robotic Heller myotomy confers an advantage over conventional laparoscopic approach. These results were later confirmed by Melvin et al. [46] in a prospective multicenter study evaluating 104 patients who underwent robotic Heller myotomy with partial fundoplication. Operative time averaged 141 min for the cohort, but decreased from 163 min during the initial 2 years of the study to 114 min in the final 2 years ($p < 0.001$). There were no esophageal perforations.

Seventy-six percent of the patients completed a postoperative symptom survey and all reported significant improvement in daily symptoms.

Superior safety and efficacy of robotic Heller myotomy was further supported by Huffman and colleagues [47] in a prospective, nonrandomized, single-institution study of 61 patients. Over a 6-year period, 37 patients underwent laparoscopic Heller myotomy and 24 had robotic myotomy. There were no esophageal perforations in the robotic group, compared to 3 (8 %) in the laparoscopic cohort. All patients completed a global (Short Form-36) and disease-specific (Gastroesophageal Reflux Disease Activity Index) quality of life questionnaire preoperatively and at postoperative follow-up. Both groups experienced improvements in quality of life indices, with the robotic group showing better outcomes overall.

Using the University Health System Consortium (UHC) database, Shaligram et al. [48] analyzed 2,683 patients who underwent open (418), laparoscopic (2,116), or robotic (149) Heller myotomy between 2007 and 2011. Not surprisingly, results showed that perioperative outcomes for both laparoscopic and robotic approaches were superior to those of the open procedure. However, comparison of laparoscopic and robotic methods yielded no statistically significant differences in perioperative patient outcomes. Laparoscopic technique did, however, generate lower hospital costs ($7,441) versus open ($9,802) and robotic ($9,415) approaches.

Published studies thus far, albeit small and suffering from biases, have established that robotic Heller myotomy is comparable to the laparoscopic technique in regard to safety and efficacy. Series by Melvin et al. [46] and others [45, 48, 49] have shown lower esophageal perforation rates with the robotic approach, but this finding was not corroborated by Shaligram and colleagues [48] in their recent analysis of the UHC database. With increasing surgeon experience, operative times have decreased significantly but still remain higher than the laparoscopic approach. This and the considerably increased operative costs associated with the robotic operation continue to plague its widespread use.

Other Esophageal Applications of the Robot

Resection of Benign Lesions

Benign lesions of the esophagus are rare, with historical autopsy studies reporting a prevalence of less than 1 % [50, 51]. Leiomyomas and polyps comprise up to 80 % of these benign lesions, while hemangiomas, duplication cysts, and papillomas are more rare. Robotic enucleation of leiomyomas has been described in several case studies [52–54]. Additionally, few case reports exist of robotic-assisted excisions of esophageal cysts and epiphrenic diverticulum [55–58]. All studies have shown the robotic approach to be safe and feasible, although operative times seem to be longer compared to conventional techniques. It is difficult to discern how much of this difference is due to surgeons' lack of familiarity with the robotic system versus inherent shortcomings of the approach itself. Larger studies are needed to address these concerns.

Paraesophageal Hernia Repair

True prevalence of hiatal hernia in the overall population is unknown, as most patients are asymptomatic. Majority (95 %) of hiatal hernias are type I or sliding hernias, while the remainder are paraesophageal hernias (PEH) [59]. Although they make up only a small fraction of hiatal hernias, PEH are associated with serious morbidity and mortality [60, 61]. Laparoscopic approach has become the gold standard treatment for PEH, with multiple series showing improved perioperative outcomes, versus open technique, and excellent symptomatic control and patient satisfaction on long-term follow-up [62–67]. Only a handful of reports exist describing robotic-assisted PEH repairs [68–70]. Collective conclusion from these studies shows that robotic-assisted PEH repair is superior to the open approach but comparable to the laparoscopic approach. Larger, randomized, comparative studies are needed to objectively evaluate the benefits of robotics over conventional laparoscopy.

Conclusion

Robotic surgery has ushered in a new era in the minimally invasive surgical field. While this innovation has been met with extreme enthusiasm and adaptation in several specialties, its widespread use in the realm of general surgery has been plagued by concerns related to increased cost, lengthy operative times, and lack of benefit over conventional laparoscopic techniques.

Robotic-assisted esophageal surgery has been a slowly evolving field, with many theoretical advantages over conventional laparoscopic methods. In most cases, the robotic approach to esophageal surgery has exhibited comparable outcomes to conventional laparoscopic techniques. However, large prospective, randomized, controlled trials are still missing. As competition arises and further research and innovation is conducted, robotic systems will become smaller, less expensive, more capable, and widely available. This, in turn, will allow surgeons to become more adept at performing robotic procedures and, hopefully, will encourage publications of the Level I evidence so desired.

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Essentials and Future Directions of Robotic Gastric Surgery

5

Pornthep Prathanvanich and Bipan Chand

Introduction

Laparoscopic gastric surgery remains one of the most technically challenging operations. Attempts to improve upon some of the major limitations of standard laparoscopy include improved wrist articulation and the dimensional field with the introduction of robotic surgical systems in the late 1990s. The current commercially available robotic platforms allow for seven degrees of wrist freedom, improved dexterity, tremor filtration, motion scaling, stable operative platform, and stereoscopic vision (3D imaging system). This chapter reviews much of the technical aspects of robotic gastric surgery including outcomes and future directions. We chose to focus on current accepted platforms; however, in this ever-evolving field, these systems will continue to change.

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Malignant Aspects

Gastric Cancer

Clinical Practice and Oncological Indications

The diagnosis of early gastric cancer (EGC) has increased worldwide in recent years. Diagnosing gastric cancer requires tissue sampling often performed at endoscopy. Depth of invasion and presence of lymph node metastasis are currently performed by ultrasonography, computed tomography, and endoscopic ultrasonography. In 1994, Kitano et al. [1] reported the first laparoscopy-assisted distal gastrectomy for gastric cancer. The indication for laparoscopic gastrectomy (LG) is typically limited to early gastric cancer (EGC) [2] because of perceived limitations of laparoscopic lymphadenectomy when compared to conventional open surgery. According to the Japanese Gastric Cancer Association (JGCA), LG is recommended for only EGC patients with a preoperative stage IA (cT1N0M0) and stage IB (cT1N1M0 and cT2N0M0) [3, 4]. There has been an overall increase in the detection of early gastric cancer from 15 % to 50 % and 10 % to 20 % in Eastern and Western countries, respectively [5]. Rates of early detection remain higher in the East secondary to well-established nationwide screening programs.

The Japanese Laparoscopic Surgery Study Group reported on the oncological outcomes of LG for EGC [5]. This multicenter study included

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1,294 patients undergoing LG and found that the 5-year disease-free survival rate was 99.8 % for stage IA and 98.7 % for stage IB (median follow-up of 36 months). However, demonstrating an advantage with LG with D2-lymphadenectomy remains controversial. In recent years, studies have provided evidence that performing a LG with D2-lymphadenectomy can be safe and effective [6]. In general, most studies have demonstrated an improved early postoperative course (when compared to conventional open gastrectomy (OG)) while demonstrating similar long-term outcomes. For this reason, some authors have suggested routine D2-lymphadenectomy, even in cases of EGC. Douglass HO Jr et al. [7] reported the risk of understaging in up to 25 % of patients diagnosed with mucosal EGC at preoperative workup. On histological examination, 7.5 % had AGC and 17.5 % had submucosal EGC. Therefore, they suggested that until the accuracy of preoperative staging is 100 %, routine performance of all gastric cancer surgery with standard D2 dissection remains justified. This meticulous dissection may be improved upon with the use of robotic surgical systems. Advanced gastric cancer (AGC) is more often discovered in Western countries and may be a reflection of screening practices. Treatment often focuses on palliation from bleeding, pain, and obstruction. Yet attempts at surgical cure still remain a priority. Laparoscopic resection of AGC has shown no differences in oncological adequacy, recurrence rates, and survival when compared to open surgery [8–10, 12]. However, Song et al. performed a retrospective multicenter study (Korean Laparoscopic Gastrointestinal Surgery Study Group), evaluating patterns of disease recurrence [11]. With a mean follow-up of 41 months, the incidence of disease recurrence was 1.6 % in patients with EGC and 13.4 % in patients with AGC. Advanced T-classification and lymph node metastasis were risk factors for disease recurrence. In 2011, a multicenter, prospective, randomized study was designed and initiated in Korea (KLASS-02 study) with the goal to compare laparoscopic and open gastrectomy with D2-lymphadenectomy for AGC [13]. Results have not been reported.

The first reported robot-assisted gastrectomy (RAG) was published by Giulianotti et al. [14] and Hashizume et al. [15] in 2003. Initial studies focused on the safety and feasibility and subsequently demonstrated a shallower learning curve with robot-assisted surgery when compared with laparoscopic surgery. Heemskerk J et al. [16] compared learning curves of robot-assisted laparoscopic surgery with conventional laparoscopic surgery between eight inexperienced participants. Basic and advanced laparoscopic tasks, using both conventional laparoscopy and the da Vinci® Surgical System (Intuitive Surgical, Inc.), were compared for accuracy and time. Robotic assistance resulted in faster times with greater accuracy, suggesting robotic assistance may benefit inexperienced subjects. Kang BH et al. [17] demonstrated that after the initial twenty cases of RAG, an inexperienced laparoscopy surgeon could achieve results similar to an experienced laparoscopic surgeon performing LG.

Indications for RAG are similar to those of LG. The benefits may include greater ease at the dissection required in extended lymphadenectomy. Current indications of RAG with limited lymphadenectomy are in preoperative stage IA and stage IB-IIA [6, 18, 19]. Using the robotic approach in AGC should be performed only in the context of controlled studies at experienced centers. Most Western studies on RAG have reported few cases of AGC in their series of RAG [20–23]. In 2011, D' Annibale A et al. reported on 24 consecutive robot-assisted gastrectomies with extended D2-lymphadenectomy for AGC. Median operative time was 267 min (255–305) with median intraoperative blood loss of 30 mL. Median number of harvested lymph nodes was 28 (23–34) with negative resection margins in all cases. No conversions occurred. Surgery-related morbidity was 8 % with no 30-day mortality. Long-term results are not reported.

Technical Advantages of RAG

Skill Improvement

Conventional laparoscopy presents limitations including two-dimensional vision, physiologic tremor, limited manipulation, and ergonomic discomfort. These limitations pose challenges in

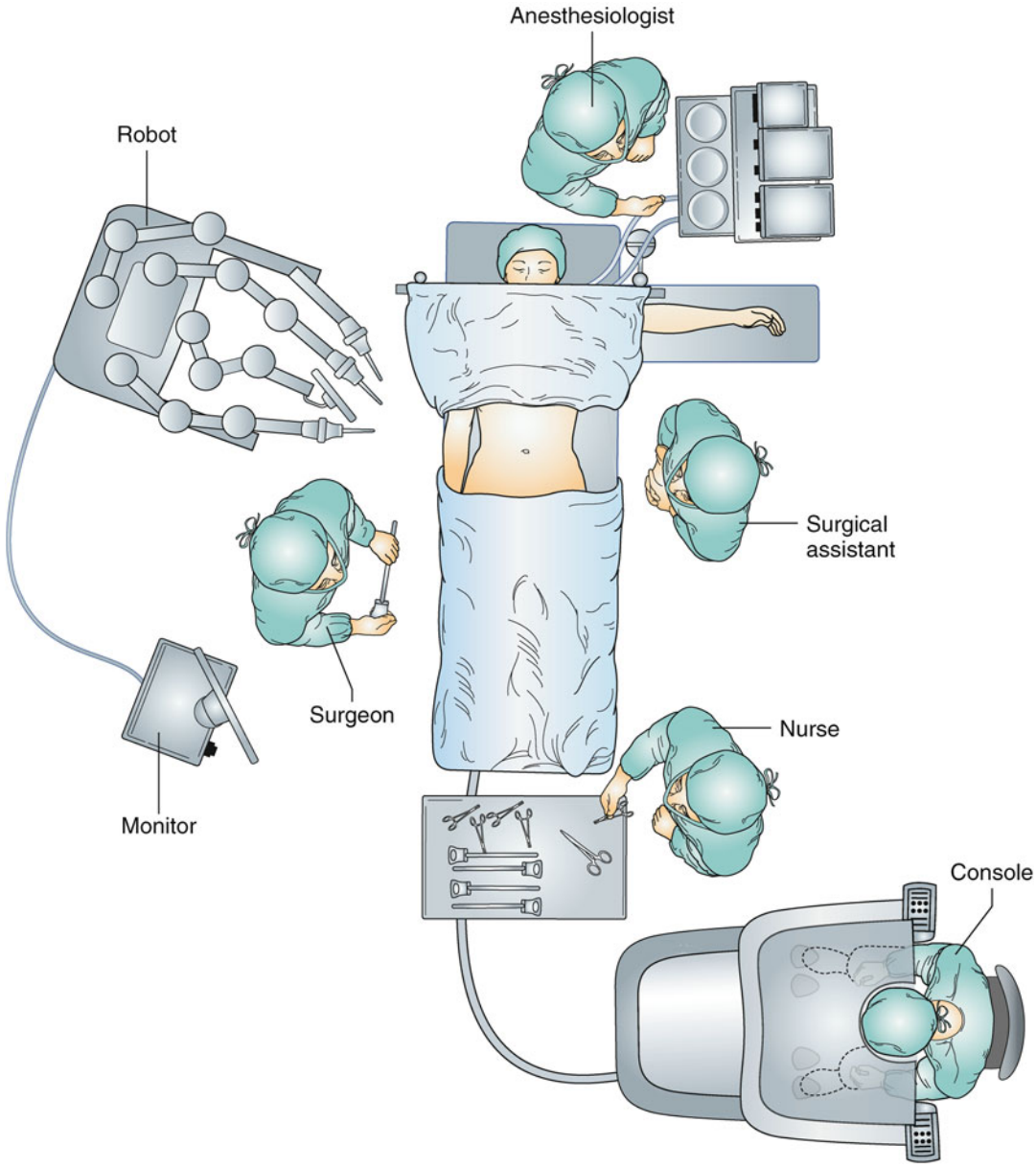

Fig. 5.1 Operating room: The surgical cart with active robotic arms and camera holder is placed on the right side of the patient. The console in front of which the operator sits and operates is put at the foot of the patient. It is important that the operator and the surgical assistant can see the same monitor from the same direction to share the same optical information

complex abdominal surgical procedures including extended lymphadenectomy and intracorporeal anastomosis performed in laparoscopic gastrectomy. Studies have shown that the robotic surgical system enhances the ability to perform difficult dissections and suturing [24]. The surgeon is able to identify smaller anatomical structures, thereby reducing mistake manipulations. Beyond three-dimensional vision, another benefit of the view system is the stability of the camera platform. The camera is held by a robotic arm and controlled directly by the surgeon (Fig. 5.1). In robotic

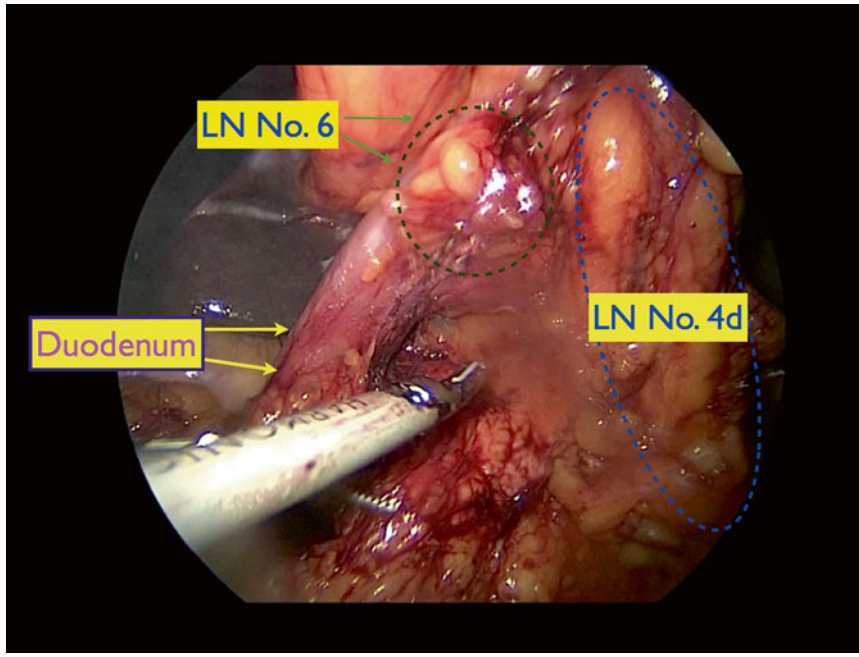

Fig. 5.2 Laparoscopic dissection of lymph nodes around the infrapyloric area (LN group 6) and lymph nodes along the right gastroepiploic vessels (LN group 4d)

surgery, it is possible to lift up the abdominal wall ("tent effect"). This simple maneuver, performed by the camera arm and 30-degree laparoscope, improves the angle of vision and provides an excellent view of the celiac trunk and esophageal hiatus. Finally, the robotic console reduces ergonomic discomfort and maintains a comfortable position for the surgeon.

Dissection of Splenic Vessels

Image magnification, tremor filtering, and fine circumferential robotic arm movements allow precise vascular dissection around splenic vessels for clearance of lymphatic tissue with minimization of vascular injury and decreased intraoperative bleeding [20, 25]. This makes a pancreas-spleen-preserving D2 lymph node dissection possible.

Isolation of Diaphragmatic Crura

With wristed instrumentation, en bloc dissection of cardia lymph nodes and complete encircling of the distal esophagus are possible [20, 21]. Moreover, the robot-sewing technique allows in performing a hand-sewn esophagojejunostomy often in the deep and narrow space of the abdominal cavity [26].

Lymphadenectomy

Laparoscopic dissection of lymph nodes around the infrapyloric area (LN group 6) (Fig. 5.2), splenic artery (LN group 11) (Fig. 5.3), and superior mesenteric vein (LN group 14v) is the most frequent source of intraoperative bleeding [27, 28]. This is one of the major reasons that LG is recommended only for EGC. However, if dissection along these vessels can be safely conducted, the risk of bleeding can be reduced. Reports have shown the benefit of the robotic surgical system in allowing for accurate lymph node and vessel dissection [29]. Some authors have recently reported a new integrated robotic approach for suprapancreatic D2 nodal dissection [30] (Fig. 5.4a, b). Lymph node dissection around the infrapyloric and suprapancreatic areas is often difficult in the obese patient [31]. Robotic technology has been shown to facilitate laparoscopic extended lymphadenectomy in this situation [22, 29].

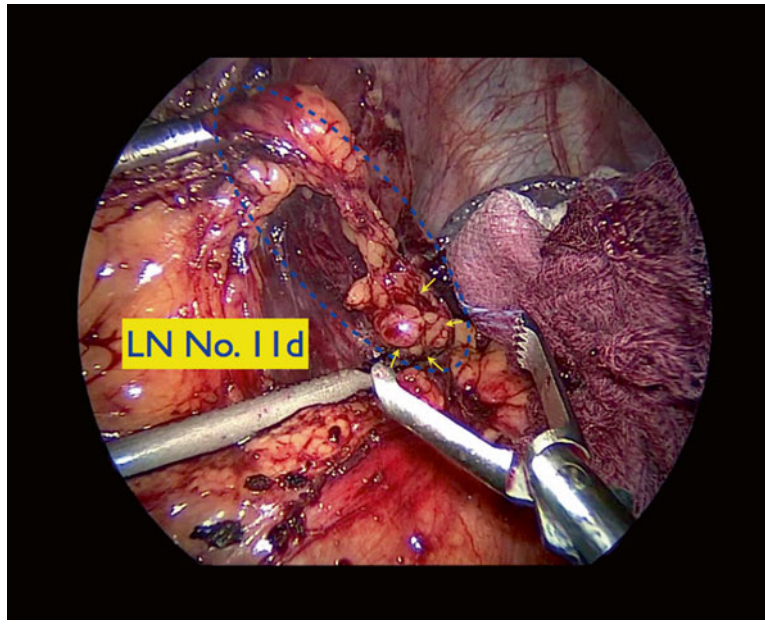

Fig. 5.3 Laparoscopic dissection of lymph nodes along the distal splenic artery (LN group 11d)

Digestive Restoration

Digestive restoration is often more demanding when following total gastrectomy (TG). Anastomotic techniques range from a hybrid-open approach to a full robotic procedure. In several studies, the technique is often performed extracorporeally through the minilaparotomy used for specimen removal [32–34]. This hybrid-open technique has been used in gastrojejunostomy or gastroduodenostomy creation following distal gastrectomy, as well as in esophagojejunostomy following TG. Song J et al. [35] reported this approach in patients with low BMIs. However, in cases with higher BMIs, it is very difficult to perform an extracorporeal anastomosis unless the incision is extended [36, 37].

In order to improve on perioperative outcomes, including less pain, decreased wound morbidity, and better cosmetic results, a shift from extracorporeal to intracorporeal anastomosis has occurred [17, 38]. Giulianotti et al. described a full robotic hand-sewn ("robot-sewn") technique of anastomosis following gastric resection. Recently, Eastern groups [17, 39, 40] have reported their preliminary experience with robot-sewn esophagojejunal anastomosis following TG. Hur H et al. [41] presented results of a pilot study in which the anastomosis after gastrectomy was successfully achieved by a robot-sewing technique as a gastroduodenostomy (Fig. 5.5), gastrojejunostomy, and esophagojejunostomy. They were able to be performed in deep and narrow spaces with the abdominal cavity. Liu XX et al. [42] reported successfully completing robot-assisted gastrectomy with intracorporeal robot-sewn anastomosis in a total of 104 gastric cancer patients. Robot-sewn anastomoses were successfully performed for 12 proximal subtotal gastrectomies with esophagogastrostomy, 38 distal subtotal gastrectomies with gastroduodenostomy ($n=22$) and gastrojejunostomy ($n=16$), and 54 total gastrectomies with esophagojejunostomy. The average surgical time was 272.52 ± 53.91 min and average bleeding was 80.78 ± 32.37 mL. The number of harvested lymph nodes was 23.1 ± 5.3 with adequate surgical margins in all. Hospitalization was 6.2 days. Prior to this clinical trial, more than 100 cases of robot-assisted gastrectomy with minilaparotomy were undertaken [43].

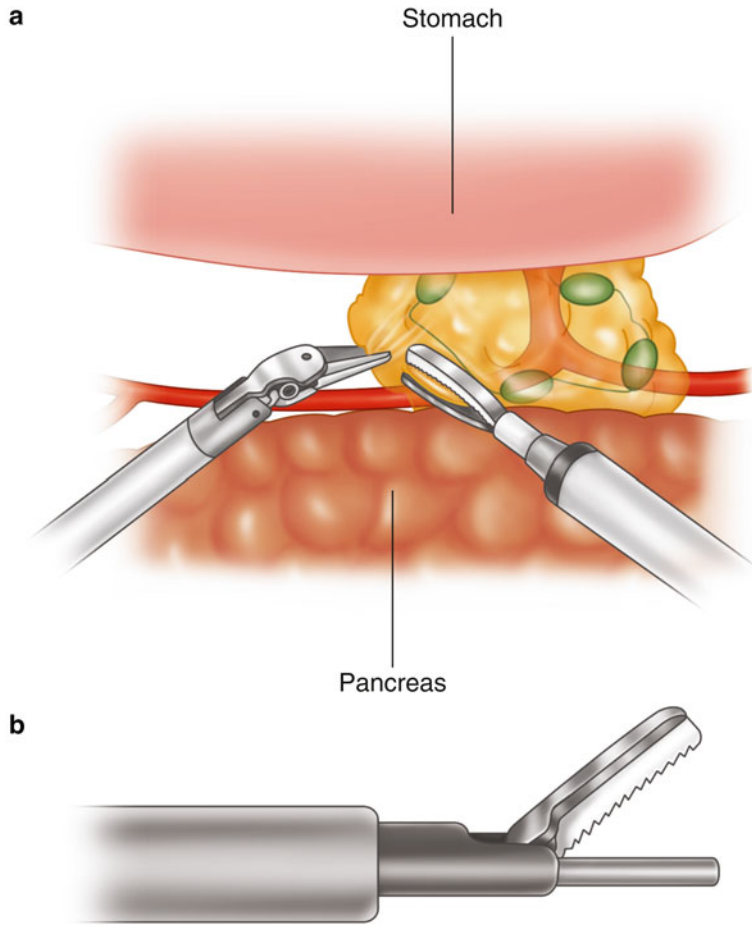

Fig. 5.4 Lymph node dissection. (**a**) A lymph node dissection is easily performed under a magnified, clear vision. An ultrasonically activated coagulating dissector (**b**) is a very useful tool for both dissecting the gastrointestinal tract and for performing lymph node dissection

In their experience, RAG with full intracorporeal anastomosis led to one less hospitalized day when compared to their first 100 patients.

Perioperative Outcomes

A recent meta-analysis was performed of all articles published between 2010 and 2013 (Table 5.1) [44–48]. All were nonrandomized retrospective studies comparing RAG to OG and LG for treatment of gastric cancer. The results of the meta-analysis showed that RAG was associated with a significantly longer operative time (+84.54 min and +61.09 min) when compared with OG and LG, respectively. The mean operating time is commonly longer in robotic surgery than in conventional laparoscopy. Some reasons are as follows: first, most of the studies comparing RAG and LG were performed by Eastern surgeons who have a greater experience with conventional LG. It also is important to note that the number of LG procedures included in these papers is typically greater than the number of RAG procedures. This may take into account the learning curve of RAG. A more accurate analysis should be performed at the beginning of a surgeon's experience with LG and at the beginning of their experience with RAG. Previous studies report the mean robotic setup was 62.9 ± 24.6 min [49]. With experience, Iranmanesh et al. reported that setup time was reduced rapidly without having a significant increase on overall operating room time [50]. Huang KH et al. showed a median docking time reduction by 30 min after 25 cases (52 min versus 22.5 min from initial RG and recent RG, respectively) [51].

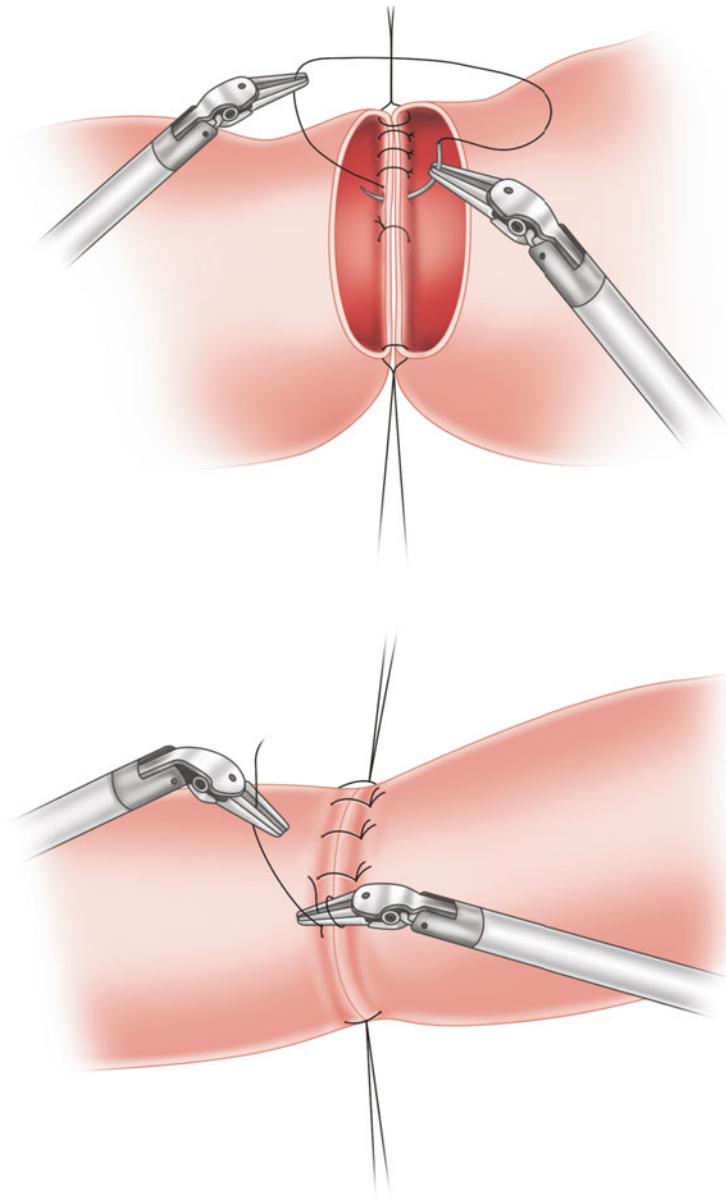

Fig. 5.5 Suturing. Distal gastrectomy with a reconstruction by Billroth I method. Suturing in all directions (*left*) is performed as easily as in open surgery. Whole layer suturing or seromuscular layer suturing is smoothly done in a manual fashion. The ligature technique is also performed as easily as in open surgery (*right*)

Multiple studies have similar reports (Kang et al. 2012 [17] and Huang et al. 2012 [51]). Second, operative time can also be reduced by upgraded robotic instruments. Many of the studies have various iterations of the surgical systems. A third explanation involves the change in digestive restoration techniques, as described earlier. While robotic surgery favors a shift from extracorporeal to intracorporeal anastomosis, the latter is known to be a more time-consuming technique. Fourth, also as discussed earlier, robotic surgery is typically associated with a more meticulous dissection than conventional laparoscopy. Often a greater degree of extended lymphadenectomy is performed in RAG.

The most common finding is a reduction of blood loss in the RAG group. RAG was associated with a significantly lesser intraoperative

Table 5.1 Meta-analysis of perioperative outcomes involving RAG

Authors	Year	Subject	Type of approach	Total	OT (min)	Blood loss (mL)	Number of resected LN	Hospital stay (days)	MB (%)	MR (%)
Hyun MH et al. [44]	2013	RAG vs. LG vs. OG	RAG = 663 LG = 1,236	7,200	RAG > LG, $p < 0.001$* (285.2 > 223.21)	RAG < LG (121.31 < 127.39) $p = 0.54$	RAG < LG (35.47 < 35.72) $p = 0.89$	RAG < LG (8.43 < 9.03) $p = 0.14$	RAG > LG (12.77 > 11.81) $p = 0.44$	–
			OG = 5,301		RAG > OG, $p = 0.001$* (286.78 > 221.05)	RAG < OG (107.58 < 261.76) $p = 0.002$*	RAG < OG (34.82 < 35.95) $p = 0.10$	RAG < OG (8.8 < 10.98) $p < 0.01$*	RAG > OG (8.6 > 3.84) $p = 0.12$	
Liao G et al. [45]	2013	RAG vs. OG	RAG = 520 OG = 5,260	5,780	RAG > OG, $p < 0.0001$* (301.3 > 208.93)	RAG < OG (90.72 < 216.80) $p < 0.001$*	RAG < OG (35.32 < 36.1) $p = 0.27$	RAG < OG (7.3 < 10.17) $p < 0.0001$*	RAG > OG (11.92 > 11.9) $p = 0.60$	RAG < OG (0.59 < 0.62) $p = 0.97$
Liao G et al. [46]	2013	RAG vs. LG	RAG = 762 LG = 1,473	2,235	RAG > LG, $p = 0.00$* (+50.00)	RAG < LG (− 46.97) $p = 0.02$*	RAG > LG (+1.61) $p = 0.26$	RAG < LG (−0.50) $p = 0.09$	RAG < LG (11.74 < 12.46) $p = 0.38$	RAG < LG (−0.6) $p = 0.45$
Marano A et al. [47]	2013	RAG vs. LG vs.	RAG = 404 LG = 845	1,967	RAG > LG, $p < 0.00001$* (295.58 > 231.88)	RAG < LG (91.72 < 127.25) $p = 0.03$*	RAG > LG (35.01 > 34.1) $p = 0.80$	RAG < LG (8.46 < 9.06) $p = 0.26$	RAG < LG (11.52 < 13.22) $p = 0.46$	–
		OG	OG = 718		RAG > OG, $p < 0.00001$* (321.70 > 225.87)	RAG < OG (107.26 < 332.84) $p = 0.08$	RAG < OG (33.7 < 36.33) $p = 0.09$	RAG < OG (7.66 < 10.58) $p = 0.005$*	RAG > OG (21.42 > 19.35) $p = 0.81$	
Xiong B et al. [48]	2012	RAG vs. LG	RAG = 268 LG = 650	918	RAG > LG, $p < 0.0001$* (+68.7)	RAG < LG (−41.8) $p = 0.006$*	NS $p = 0.82$	NS $p = 0.42$	NS $p = 0.19$	NS $p = 0.52$

OT operative time
*Statistic significantly ($p < 0.05$)

blood loss (−168.61 and −32.59 mL) when compared with OG and LG, respectively. The reason may be secondary to improved magnification, improved dexterity for better vascular control, and a greater degree of precise dissection. A reduction of perioperative transfusions may allow for improved oncological results. Kamei et al. demonstrated that blood transfusion was associated with poor survival in patients with resectable gastric cancer [52]. Another recent study demonstrated that perioperative blood transfusion increased cancer recurrence [53].

There were no differences in the number of retrieved lymph nodes and overall morbidity and mortality. The removal of at least 15 lymph nodes allows for proper staging and prognostication. This is important because it favors greater rates of survival [54, 55]. RAG was associated with a significantly less length of hospital stay when compared with OG; however, it was not significantly different with the LG group.

According to oncological results and survival in robotic gastric surgery, the longest follow-up to date was reported by Pugliese [56], with a mean observation of 53 months. In that report, the 3-year overall survival rate was 85 % for the laparoscopic group and was 78 % for the robotic group, although it was not statistically significant, based on the log-rank test.

Gastric Submucosal Tumors

Gastrointestinal stromal tumors (GISTs) are rare mesenchymal tumors that occur throughout the smooth muscle layer of the gastrointestinal (GI) tract. GISTs represent less than 1 % of all GI tract malignancies. The most common location of these tumors is the stomach (70 %). Curative therapy is surgical resection with entire tumor removal without breaking the tumor capsule. GISTs do not infiltrate into the gastric wall, like adenocarcinoma; therefore, a wide normal mucosal margin is not needed. Only microscopic negative margins are sufficient to ensure R0 resection [57]. Tumor spillage or hemorrhage is associated with high locoregional recurrence and/or development of peritoneal metastasis. Regional lymphadenectomy is not routinely performed because lymphatic metastases are rare.

The size of the tumor cannot be the sole indicator for laparoscopic approach. Current guidelines and consensus favor the tight principles of surgical resection without limiting the indications for laparoscopic surgery by size [57, 58]. Many authors report the superiority of laparoscopic wedge resection over open surgery by demonstrating faster oral intake, less pain, less inflammatory lab results, less blood loss, and shorter hospital stay [59–61]. Long-term results in terms of recurrence and survival rates were also comparable to open surgery.

Resection techniques (69–80) include:

1. Laparoscopic "wedge" resection or full-thickness partial gastrectomy is an effective strategy for tumors that are located along the lesser or greater curvature of the stomach [74] (Fig. 5.6).
2. Laparoscopic anatomic gastrectomy (i.e., subtotal or total gastrectomy) is reserved for large tumors that involve a significant portion of the stomach. When the tumor is located near the pylorus, distal gastrectomy can be performed [62]. The published reports of minimal invasive surgery for gastric GIST are summarized in Table 5.2 [63–69]. Most operations include wedge and anatomic resections. The data suggests reasonable operative times, acceptable complication rates, and few conversions to open operations.
3. Laparoscopic transgastric resections are reserved for tumors located at the posterior wall especially near the gastroesophageal (GE) junction. GISTs near the GE junction are more challenging when compared to prepyloric lesions, secondary to potential narrowing of the lumen. A proximal gastrectomy can cause severe gastroesophageal reflux. Laparoscopic trocars can be used to penetrate the gastric wall, and laparoscopic forceps and linear staplers can be inserted in the so-called transgastric route. Either an endoscopic view or a laparoscopic camera, which is inserted into the stomach via a transgastric trocar, can be used for visualizing the surgical field. To prevent retraction of the trocars, balloon trocars are preferably used.

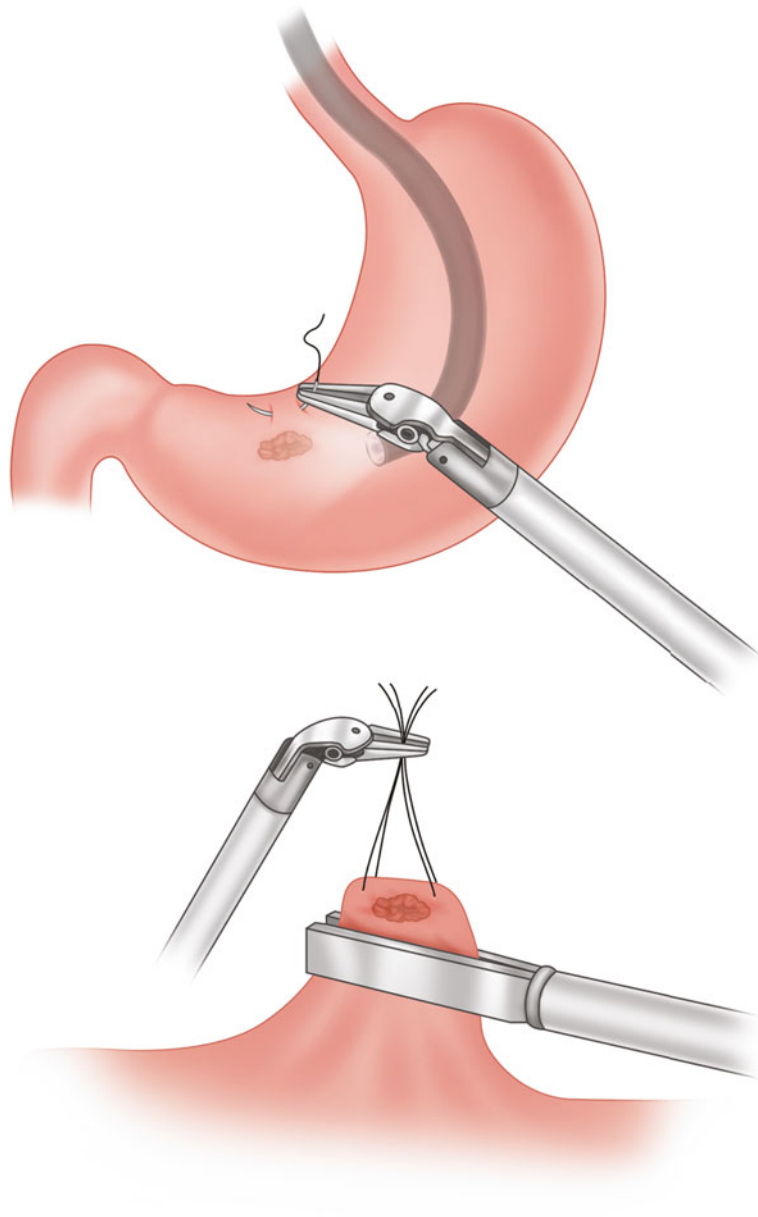

Fig. 5.6 Schematic drawing of a laparoscopic wedge resection: Under direct vision via an endoscope in the stomach, a few stitches through the whole layer of the stomach are placed as a marker to obtain a definite cancer-free margin (*left*). While holding the sutures with the tip of the forceps, the lesion is cut with an endoscopic stapler (*right*)

4. In 1995, Ohashi S [70] presented laparoscopic intragastric surgery (LIGS) that was well accepted as a minimally invasive procedure for mucosal or submucosal gastric lesions. In 2003, Walsh RM et al. [71] reported the technique of combined endoscopic/laparoscopic intragastric resection of gastric stromal tumors in 13 patients with a mean age of 57 years (range 34–72). All patients were asymptomatic, and no lesions had mucosal ulceration. Eight lesions were located at the gastroesophageal junction, two each at the incisura and posterior body and one each in the fundus and anterior wall of the corpus. All lesions were predominantly intraluminal, and three were transmural. The laparoscopic/endoscopic technique included two or three, 2 or 5 mm intragastric trocars. The advantage of using 2 mm instruments is the elimination of

Table 5.2 Perioperative outcome of minimal invasive surgery for gastric GIST

Authors	Type of surgery	Total	Size (cm)	OT (min)	Complications (%)	Conversion (%)	R0 (%)	Intermediate/ High risk (%)	Recurrence rate (%)	Median/U (mo)
Buchs NC et al. 2010 [63]	RAG	5	5.5 (4.2–7)	192 (132–285)	0	20[a]	100	80	0	18 (11–27)
Moriyama H et al. 2012 [64]	RAG	1	NR	190	0	0	100	NR	NR	NR
Oshiro EO et al. 2012 [65]	RAG	1	3.5	230	0	0	100	NR	NR	NR
Desiderio J et al. 2013 [66]	RAG	5	5 (4–7)	240 (210–300)	0	0	100	NR	0	13.5 (12–15)
Sexton et al. 2008 [67]	LG	61	3.8 (±1.8)	151.9 (±67.3)	16.4	2	98	25	5	15 (0–103)
Wilhelm et al. 2008 [68]	LG	63	2.6 (0.3–6.5)	90.7	7.5	6.5	100	13	0	40 (2–99)
Sasaki et al. 2010 [69]	LG	37	3.2 (1.6–7.4)	100 (30–240)	2	2	100	24	0	74 (1–81)

OT operative time, *NR* not reported

[a]One patient had a conversion to open surgery because of a suspicion of diffuse adenocarcinoma on fresh frozen section and necessitated a total gastrectomy with a radical lymph node dissection

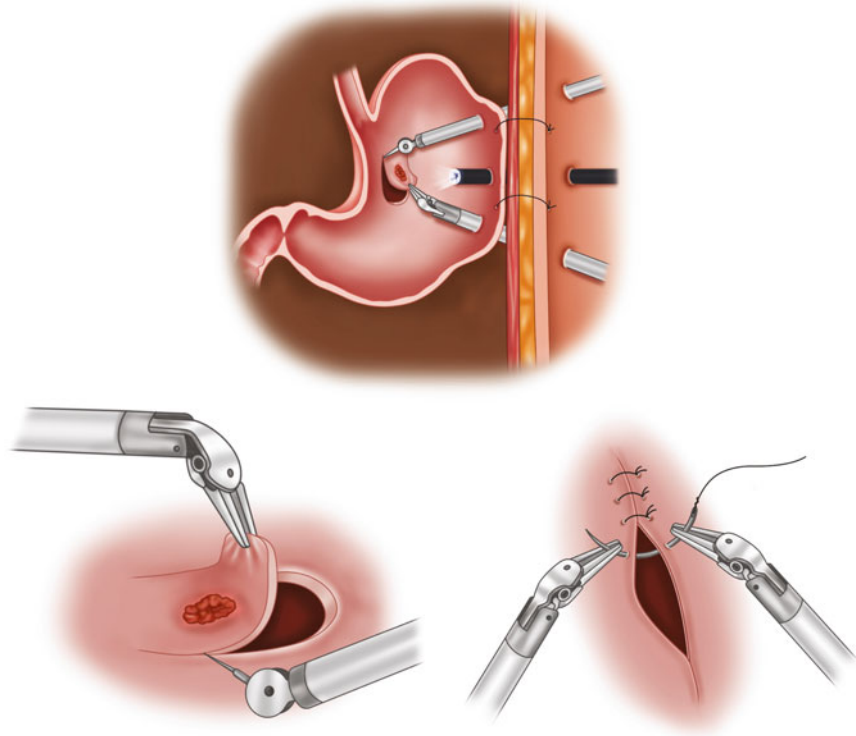

Fig. 5.7 A schematic drawing of an intragastric resection: The early gastric lesion that is located within the mucosal layer at the cardia, antrum, or posterior area of the stomach is easily resected in this manner (*upper*). A sufficient area with tumor and a tumor-free margin is removed (*left*), and the remnant mucosa is approximated and sutured if necessary (*right*)

closure of the gastric wall port sites. The mean operative time was 186 min. The mean size of the resected specimens was 3.8 cm (range 1.5–7.0). There was no mitotic activity on histopathology, and all were considered pathologically benign. The median length of stay was 3.8 days (range 3–8). There was no mortality or operative morbidity. At a mean follow-up of 16.2 months (range 1–32), there had been no local recurrences.

5. In 2007, Hoya Y et al. [72] reported a new technique, laparoscopic intragastric full-thickness excision (LIFE) under flexible endoscopic control. The lesion of the posterior gastric wall is pulled inward and removed under endoscopy and laparoscopy guidance. Only one trocar is placed into the anterior gastric wall, and the lesion is removed with several laparoscopic stapling fires. They described this surgical technique in three pigs. In 2011, Sahm M et al. [73] reported their experience with combined laparoscopic and endoscopic approaches in seven patients. The tumor was located in the posterior gastric wall near the cardia and pylorus. For this approach, one trocar was placed into the stomach to intragastrically introduce the endostapler. They used 2 trocars (5 mm) into the abdominal cavity for laparoscopy. Tumor size was 38 ± 7 mm (28–48 mm) and histology revealed 6 gastrointestinal stromal tumors and 1 leiomyoma.

The advantage of robotic arms in inaccessible areas is also applicable for gastric submucosal tumors (SMTs) near the gastroesophageal junction or pylorus [63–65] (Figs. 5.7 and 5.8a, b) (Table 5.2). In 2007, Hirano Y et al. [75] reported the first successful robotic intragastric surgery in a porcine model. They performed intragastric

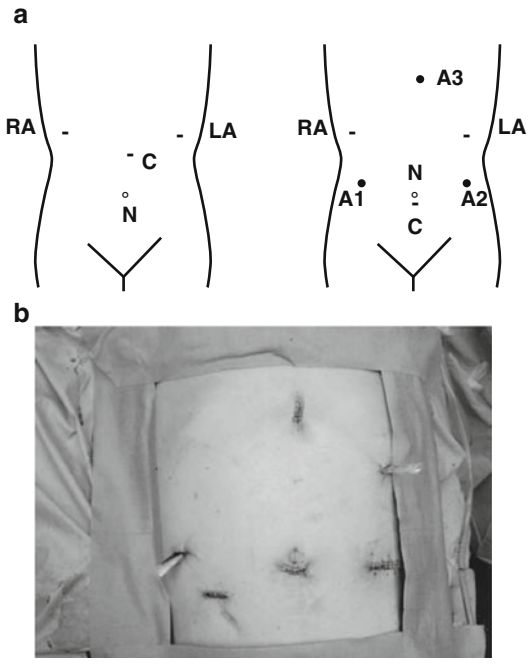

Fig. 5.8 Skin incision: (**a**) The *upper* shows the position of the skin incision for intragastric resection, while the *lower* shows the position for a laparoscopic distal gastrectomy (**b**). *C* camera, *RA* right robotic arm, *LA* left robotic arm, *A1, A2, A3* assistant trocars, *N*, navel (Used with permission from Hashizume M, Sugimachi K. Robot-assisted gastric surgery. Surg Clin N Am. 2003;83:1429–1444)

mucosal resection of a tentative lesion near the EGJ: Esophagogastric Junction using the da Vinci Surgical System. The average size of the resected mucosa was 6.3 cm and mean duration was only 11 min. They also successfully performed closure of the defect after mucosal resection and subsequent closure of the intentional gastric perforation. The time for these was 8.28 min. However, this technique of robotic intragastric surgery in humans has yet to be published. Further studies need to be undertaken to prove its practical feasibility.

Benign Aspects

Peptic Ulcer Disease (PUD)

Minimal invasive surgery for PUD, such as laparoscopic repair of perforated peptic ulcer (PPU), was first reported with the introduction of laparoscopy. Nonetheless, routine practice has been rather limited, largely because of the low incidence of PUD after identification of *Helicobacter pylori.* In 2013, Antoniou et al. [76] reported a meta-analysis of four randomized trials, with a total of 289 patients. The study reviewed the outcome of a laparoscopic approach compared with open sutured repair of PPU. Analysis of outcomes did not favor either approach in terms of morbidity, mortality, and reoperation rate. Although the odds ratio seemed to consistently support the laparoscopic approach. The largest available randomized trial, which enrolled more than 100 patients, demonstrated a lower morbidity rate for a laparoscopic approach (5 % vs. 14 %), but the data was not statistically significant [77]. This finding correlates with a cumulative evaluation of prospective and retrospective studies reported in 2005 [78]. Growing interest in the laparoscopic approach may encourage the design of additional randomized trials to analyze its efficacy compared with the open approach. No robotic studies have been published in benign peptic ulcer disease management.

Gastric Dysmotility

The major type of gastric dysmotility is gastroparesis, defined as delayed gastric emptying leading to symptoms of nausea, vomiting, bloating, early satiety, weight loss, dehydration, and electrolyte imbalance. Surgical therapies may be indicated in severe cases. Recently, most articles have reported the benefits of gastric electrical stimulation (GES). GES involves electrical stimulation of the lower stomach with a system consisting of a generator implanted deep within the tissues of the abdomen and two electrical leads which are implanted in the wall of the stomach. In 2013, Timratana P et al. [79] reported on the outcomes of laparoscopic GES (Enterra Therapy System, Medtronic, Minneapolis, MN) for diabetic and idiopathic gastroparesis. Primary operations were completed laparoscopically in 110 of 111 cases, with one conversion to laparotomy due to severe adhesions. At a mean follow-up of 27 months (1–113), symptom improvement was

achieved in 91 patients (80 %) and was similar for both the diabetic and idiopathic subgroups. The need for supplemental nutrition (enteral and/or parental) decreased in both groups. No robotic systems have been reported for gastroparesis management.

Future Prospects

Robotic System-Assisted in Natural Orifice Transluminal Endoscopic Surgery (NOTES)

Endoscopic submucosal dissection (ESD) is an advanced therapeutic technique which may be considered the ultimate "minimum" invasive treatment for early stage gastric cancer. Previous studies have reported the incidence of lymph node (LN) metastases in early gastric cancer ranging from 3 % to 5 % in mucosal cancers and 16 % to 25 % in submucosal tumors [80]. The optimal lesion for ESD is thought to be an intramucosal well-differentiated-type adenocarcinoma without ulceration or scarring and less than 20 mm in size. Patients at risk of LN metastasis should undergo gastrectomy and lymph node dissection for T1 cancer. Finally, much of the histological information supporting the performance of ESD is available only after the primary lesion has been resected. NOTES might be able to build a bridge between ESD and standard gastrectomy and LN dissection. NOTES may provide for endoscopic sentinel node (SN) biopsy as a complement and oncological augment to current ESD technique. If SN theory is clearly proved, the following procedures are theoretically feasible as a new standard treatment for extended indication of ESD (i.e., sm2, sm3, sm1 with undifferentiated-type or ulcer). If NOTES sentinel node biopsy is negative, the treatment can include ESD, EMR, wedge resection, or pylorus-preserving gastrectomy. If NOTES sentinel node biopsy is positive, convert the operation to RAG. In 2008, Cahill RA et al. [81] have proven the technical feasibility of lymphatic mapping and SN biopsy by NOTES in a stomach pig model. A major large-scale clinical trial of SN mapping for gastric cancer in conventional open surgery has recently completed. The Japan Society of Sentinel Node Navigation Surgery study group conducted this multicenter prospective trial for SN mapping by combined blue dye and radioactive tracer (Technetium99 m tin colloid) injection [82]. They reported at ASCO 2009 that in this trial 433 early gastric cancer cases (≥4 cm cT1N0M0 or cT2N0M0) were enrolled at 12 major hospitals. The false-negative rate was 7.0 %, while the sensitivity of metastasis detection based on SN status was 93 %, and the accuracy of metastatic status based on SN was 99 % (383/387). NOTES could supplement ESD is by providing direct sampling of SN from the perigastric lymph basins.

NOTES may develop into a full-thickness gastric wedge or sleeve resection for early adenocarcinoma and other lesions including small gastrointestinal stromal tumors. However, the main limitations include a reliable gastric wall closure. Tissue anchors, endoscopic clips, suction-based prototype suturing device, and other instruments have all been reported. However, no one method has yet been universally accepted or adopted. Phee SJ et al. [83] developed a master–slave robotic prototype system that is a cable-driven flexible robotic manipulator that can be attached to an endoscope. This system could allow for two-handed endoscopic manipulation with 9–12 degrees of freedom. It consists of a long and flexible body that allows it to follow an endoscope through human natural orifices. The trial demonstrated that the slave manipulator had enough force and dexterity to perform an essential surgical procedure on the slippery gastric walls of a live pig. This has the potential to allow for performing tasks such as grabbing, picking, cutting, and suturing. Future work will include incorporating force sensors and haptic devices into the robotic system. The aim is to enable the endoscopist to "feel" as though the slave manipulators are his or her own hands.

Flexible robotics has been reported by Aron M and Desai MM [84]. They used a flexible robotic system in performing ureteroscopy.

Robotic flexible ureteroscopic examinations using the Hansen Medical Inc. system were

performed in 18 patients who had 5–15 mm renal calculi. They found an 89 % complete fragment clearance at 3 months. Future robotic endoscopes, with an ability to create stable fixation points while maintaining precise tip maneuverability, might allow for an enhanced degree of precision to perform intraluminal therapeutic endoscopy and NOTES. Accessory instrumentation (e.g., graspers, scissors, biopsy forceps, and suction catheters) could be introduced and exchanged within working channels at the push of a button or even integrated within the flexible assembly.

Dexterous Robot

The dexterous miniature in vivo robot for NOTES is a multifunctional robot with the ability for tissue retraction and manipulation, stereovision imaging, cautery, and tissue grasping capability. The design of the micro-robot consists of two arms, grasper and cautery end effector arms connected to a central body [85]. This robotic device can be used in both intraluminal and intraperitoneal cavity. Each quadrant of the abdomen can be imaged and surgically accessed through this technique without requiring additional incisions. This robotic device has been endoscopically deployed in the peritoneal cavity through a gastrotomy incision. Onboard video feedback from the robot enabled visualization of the small bowel for further manipulation. In 2009, this miniature robot was used to perform a cholecystectomy and small bowel dissection in a porcine model [86]. The surgeon control interface was in a remote location and comprises of two controllers, a display, and a foot pedal. Each robot arm movement is controlled by the movement of the controllers. Grasper and cautery extensions can be activated when required, at the push of a button. The video feedback from a standard laparoscope is displayed on a screen between the two controllers. Using the surgeon interface console, positioning of the dexterous robot arms with adequate workspace can be performed remotely. This system has yet to be reported in the field of gastric surgery.

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Essentials and Future Directions of Robotic Bariatric Surgery

6

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Introduction

The rates of obesity continue to rise exponentially and represent one of the major health challenges for physicians, surgeons, health-care systems, and economies. Especially concerning is the rate of increase of patients with morbid obesity (body mass index (BMI) over 40), which increased over 70 % from 2000 to 2010 [1]. The health consequences of obesity have been recognized since the 1900s, and the development of surgical approaches to treat the obesity epidemic has paralleled the growth in both the recognition of the health consequences and the increase in the magnitude of affected patients [2].

Initial approaches included wiring of the jaw, which predictably did not enjoy widespread success. Considering today's understanding of the complex pathophysiology of obesity, this is not necessarily surprising. However, this initial observation prompted the realization that a surgical solution to obesity required more than simple restriction of oral intake [2]. Modern-day bariatric surgery started arguably with Payne et al., who performed jejunocolic and later jejunoileal bypass [2]. The evolution of the initial modern bariatric procedures has been remarkable and now includes commonly adjustable gastric banding, longitudinal sleeve gastrectomy, roux-en-Y gastric bypass, and biliopancreatic diversion with and without duodenal switch as well as an expanding field of revisional bariatric surgery. With the increasing recognition of the metabolic effects and benefits of bariatric surgery, there has been an expansion of indications and the principles of bariatric and metabolic surgery, in certain cases, such as in difficult to control diabetes in patients with lower BMIs, with promising results [3]. In the present climate of evidence-based medicine, the rate of growth of bariatric surgery has paralleled the literature supporting the notion that bariatric surgery is an effective and economically viable solution for durable weight loss as well as improvement and remission of diabetes and the comorbidities that describe metabolic syndrome [4, 5].

The past 20 years have seen an explosion of the application of minimally invasive principles to surgery for morbid obesity. Catona reported placing a nonadjustable gastric band via laparoscopy in early 1992. Broadbent et al. is credited with publishing the first report of laparoscopic surgery for obesity, also implanting a nonadjustable

This chapter contains video segments that can be found on the following URL:

Electronic supplementary material Supplementary material is available in the online version of this chapter at 10.1007/978-3-319-09564-6_6. Videos can also be accessed at http://www.springerimages.com/videos/978-3-319-09563-9.

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gastric band [6]. In 1993, laparoscopic adjustable gastric band placement, vertical banded gastroplasty, and roux-en-y gastric bypass were reported [6]. Today, the majority of bariatric surgery is performed in a minimally invasive manner.

Robotics and Bariatric Surgery

Since the initial report of robotic bariatric surgery in 1999, there has been increasing interest and adoption of robotic surgery to the field of bariatric surgery [7]. This has been driven by a variety of factors, including ergonomic issues, patient-related factors (abdominal wall size, subcutaneous and intraperitoneal fat), and the superior visualization and degrees of freedom offered by robotic platforms. Of increasing interest within our group in particular are the application and superb outcomes of robotic surgery to revisional bariatric surgery. Oftentimes, the biggest proponents of robotic surgery are surgeons who have adopted it as part of their practice. There is, to date, limited data with regard to outcomes and comparison with traditional laparoscopy. In 2014, A PubMed search using the terms "robotic" and "bariatric" returns less than 100 published manuscripts. We will discuss the essential principles as well as future directions of robotics in the field of bariatric surgery.

Robotics and Training

As with safe adoption of any new technology, it is imperative that surgeons who use robotics as part of their bariatric surgery practice are adequately trained in the safe application of robotics to laparoscopic bariatric surgery. Training is not only important for the surgeon but for surgical assistants, surgical technologists, and circulating nurses. It requires an investment from hospitals/health systems for maintenance for robotic platforms and team training. There are a number of tools to assist surgeons who wish to adopt robotics, including a defined curriculum created by Intuitive Surgical, Inc., (Sunnyvale, CA) as well as skills labs to introduce the robotic platform, surgical simulators, and wet labs. In addition, the first cases done should be proctored by an experienced robotic surgeon. After training and adoption of robotics, it is imperative that surgeons continue to use robotics regularly in their practice, not only to hone skills but also to increase the efficiency of the entire surgical team [8]. An increasing number of hospitals are defining milestones for robotic credentialing to ensure safe outcomes for patients. Similar to the Fundamentals of Laparoscopic Surgery curriculum now required for credentialing by the American Board of Surgery, and additionally the developing curriculum for flexible endoscopy, it is anticipated that a curriculum for robotic surgery will be required in the near future [9]. For experienced laparoscopic surgeons, the learning curve for robotic gastric bypass, for example, to achieve a significant decrease in operative time can be fewer than 10 cases, as compared to almost 100 cases (per some published reports) for laparoscopic gastric bypass surgery [10].

Robotics and Port Placement for Bariatric Surgery

Port placement for robotic-assisted laparoscopic bariatric surgery is similar to that of the laparoscopic equivalent operation and typically consists of five to six ports. The technique used by our group for nearly all bariatric and foregut surgeries is as follows. Initial entry is in the right upper quadrant with a 5 mm port using optical viewing technique. This port is later exchanged to a 5 mm robotic compatible trocar. Additional ports are placed as follows. A 12 mm camera port is placed periumbilically. In larger BMI patients, in order to reach the angle of His, this may need to be placed supra-umbilically. A 5 mm robotic compatible trocar is placed in the left upper quadrant in the anterior axillary line at the level of the periumbilical port. An additional 5 or 8 mm left upper quadrant robotic compatible trocar is placed midway between the periumbilical and lateral left upper quadrant port. A 12 mm or 15 mm assistant port is placed midway between the right upper quadrant and periumbilical port. A 15 mm port is used for adjustable gastric band placement and may facilitate specimen extraction with sleeve gastrectomy; additionally, the larger port is necessary for certain

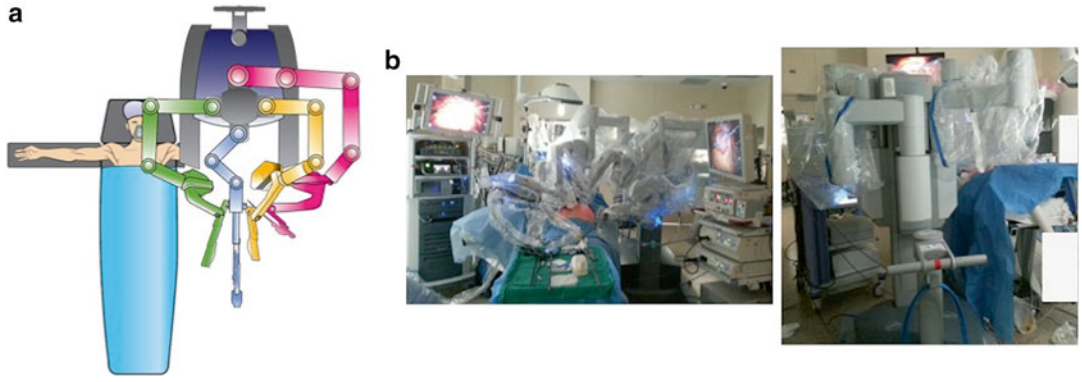

Fig. 6.1 Schematic for robotic docking for foregut surgery. (**a**) We utilize a parallel side dock technique in which the patient cart is parked parallel to the operating table next to the left shoulder. The left arm is tucked. (**b**) Intraoperative photographs demonstrating the parallel side dock technique. This technique affords functionality while leaving space at the head of the bed for access to the airway as well as for intraoperative endoscopy

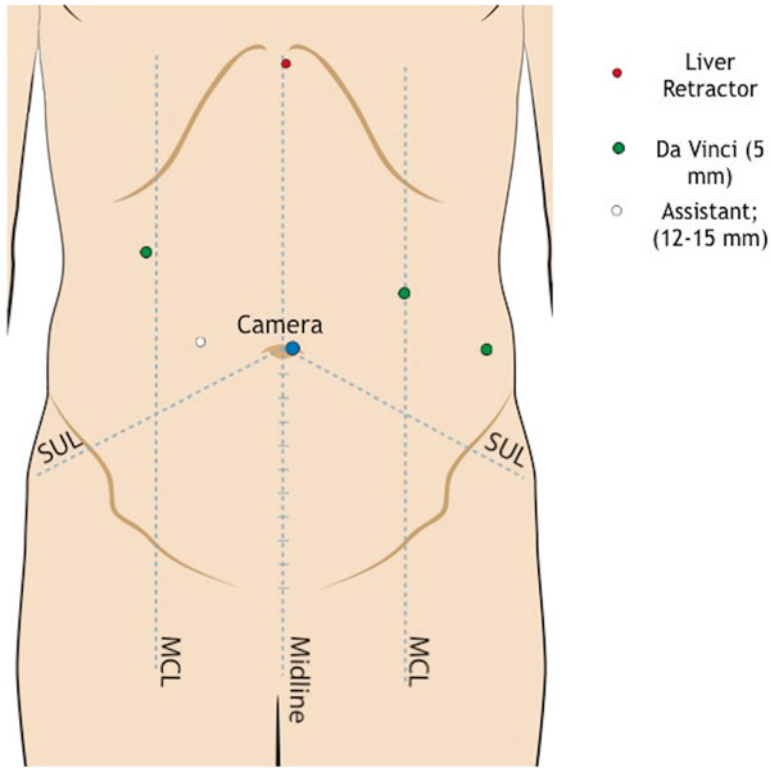

Fig. 6.2 Port placement for robotic-assisted sleeve gastrectomy

gastrointestinal staplers. Lastly, a subxiphoid incision is made to accommodate a liver retractor. In anatomically favorably situations, an internal liver retractor with sutures with or without a Penrose drain may be utilized. Our approach has been published previously [11]. The setup for biliopancreatic diversion differs slightly, and the reader is encouraged to review the references noted later in this chapter regarding this procedure. When docking the patient cart for foregut

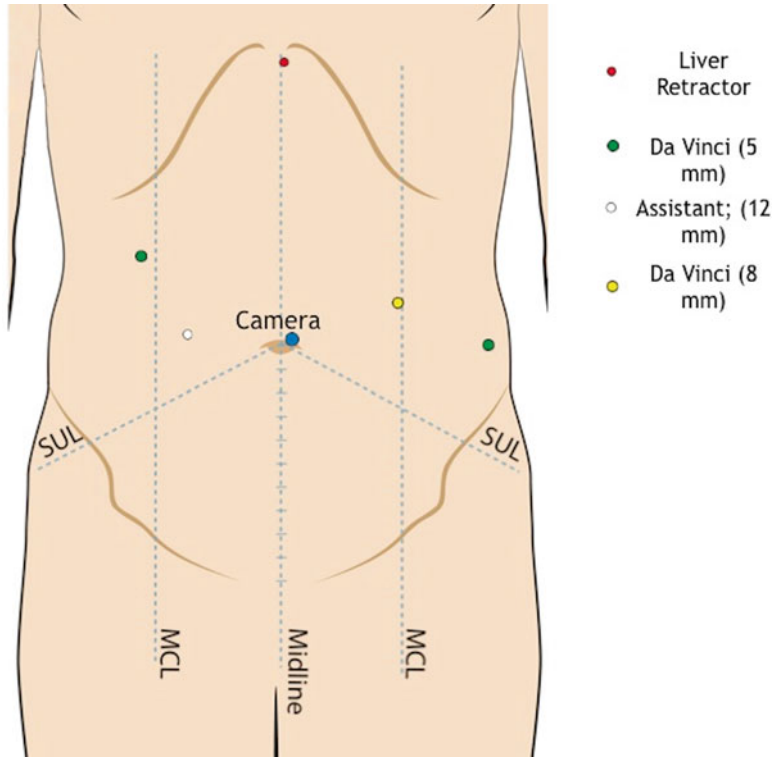

Fig. 6.3 Typical port placement for robotic-assisted roux-en-y gastric bypass

surgery, we utilize a parallel side dock technique (schematic and intraoperative figures are demonstrated in Figures 6.1a, b). Please refer to Figures 6.2 and 6.3 for our typical port placement for robotic-assisted laparoscopic sleeve gastrectomy and roux-en-y gastric bypass.

Robotics and Adjustable Gastric Bands

As the bariatric surgery climate continues to evolve, the frequency of placement of adjustable gastric bands has continued to decrease for a number of reasons, including relatively low excess weight loss, long-term surgical complications including band slip and erosion, as well as the not insignificant rate of revisions of gastric bands to another weight loss operation [12]. Today, most robotic surgeons would argue that the platform is most useful when revising patients with previous adjustable gastric band to another operation. However, there may still be some utility in primary placement of adjustable gastric bands. Edelson et al. published the largest (407 patients) comparison of robotic-assisted (287 patients) to conventional laparoscopic (120 patients) placement of adjustable gastric bands and noted no difference in hospital stay or operating time for everyone except those with a BMI greater than 50, in which there was a time advantage with the robotic approach [13].

Robotics and Longitudinal Sleeve Gastrectomy

The fall in the number of adjustable gastric bands being placed by surgeons has been relatively paralleled by the increase in patients and surgeons choosing longitudinal sleeve gastrectomy as the initial weight loss operation [12]. Diamantis et al. reported a series of 19 patients undergoing robotic-assisted sleeve gastrectomy and reported equivalent operative time when compared to the laparoscopic approach [14].

The technique reported to have used only three of four robotic arms and employed two bedside assistants (including one to hold a liver retractor). With the port technique used by our group, there is only one bedside assistant needed for stapling. A representative robotic-assisted sleeve gastrectomy (with the bedside assistant firing the staplers) is demonstrated in Video 6.1. With the introduction of robotic staplers, it is possible that the entire operation can be performed without the use of an assistant port. Ayloo et al. reported a comparison of 30 robotic-assisted sleeve gastrectomies to 39 laparoscopic sleeve gastrectomies in patients with an average BMI of over 55. The robotic technique was longer by 21 min; however, all patients in the robotic group had their staple lines oversewn as opposed to none of the patients in the laparoscopic group. There were no differences in complications between either group [15]. Vilallonga et al. reported their experience of 100 robotic and 100 laparoscopic sleeve gastrectomies, noting increased operative time in the robotic group [16]. Similar results were noted by Romero et al. comparing 134 robotic-assisted sleeve gastrectomies to a literature review of 3,148 laparoscopic sleeve gastrectomies noting increased surgical time but a shorter hospital length of stay [17]. A robotic technique for vertical sleeve gastrectomy without the use of staples has also been described. In this technique, the stomach is divided between two laparoscopic clamps; the stomach is then sewn shut with a running absorbable suture. There is a learning curve for robotic-assisted laparoscopic sleeve gastrectomy. Sequential cases improve efficiency and decrease docking and operative times. Vilallonga et al. reported that the learning curve was about twenty cases [18, 19].

The limitation of all of the studies describing robotic-assisted laparoscopic sleeve gastrectomy includes all the limitations of nonrandomized clinical trials. It is a legitimate debate as to the usefulness of the robotic platform for sleeve gastrectomy. Several reasons to adopt a robotic technique may include increasing surgeon and operative team experience with the robotic platform with a relatively straightforward procedure in preparation for more complex procedures. Robotics offers a distinct advantage in situations requiring suturing, including patients with large hiatal hernias requiring repair. The utility of routine crural repair during sleeve gastrectomy is currently the subject of a clinical trial (NCT01554553, www.clinicaltrials.gov).

Robotics and Roux-en-Y Gastric Bypass and Biliopancreatic Diversion/Duodenal Switch

Perhaps one of the most obvious benefits of robotics in bariatric surgery is in operations requiring a large degree of suturing, as in gastric bypass and related operations in which surgeons may be using hand-sewn techniques for anastomoses. A number of studies have been published evaluating the utility of robotics in roux-en-y gastric bypass. Mohr et al. reported one of the first series of totally robotic roux-en-y gastric bypass procedures. When comparing 10 robotic to 10 laparoscopic procedures, they noted a decreased median surgical time for the robotic procedures [20]. Multiple additional series have been performed, most noting similar outcomes with the robotic platform as compared to laparoscopy. Most series note increased operative time with the robotic platform, with decreased time as institution and surgeon experience increases [21–24]. Certain series have noted a lower leak rate with robotic-assisted laparoscopic roux-en-y gastric bypass [25]. A two center report with one of the largest reported experiences in the world (1,100 robotic gastric bypasses) noted 1 leak (0.09 %) in the entire series [26]. A review of seven studies and 1,686 patients demonstrated a significant reduction in anastomotic strictures with robotic gastric bypass as compared to the laparoscopic approach with no other differences noted [27].

Robotic biliopancreatic diversion with duodenal switch was initially reported in 2007 in a published series of 47 patients. There was an 8 % incidence of leaks (4/47 patients) with three patients requiring conversion to open operation. This initial series demonstrated the feasibility of robotic biliopancreatic diversion [28].

One advantage to the robotic technique for roux-en-y gastric bypass is that most studies indicate that the learning curve for the robotic approach is significantly less (reported by some authors as being <20 cases) [29–31]. In surgeons starting to do gastric bypass, the robotic approach leads to shorter operative times during the learning curve, with the difference magnified as BMI increases [32]. In an operation in which complications, specifically leaks, can be disastrous, the robotic platform has been shown to allow for excellent outcomes during the learning curve [33]. The rate of leak during the learning curve for laparoscopic roux-en-y gastric bypass has been reported as high as 10 % [28]. The learning curve for robotic-assisted biliopancreatic diversion with duodenal switch has been reported to be about 50 cases [34].

As documented by most studies which evaluated this variable, costs are higher with the robotic approach. A systematic review of 10 studies (2,557 patients) noted that the expected costs for robotics as compared to laparoscopic roux-en-y gastric bypass was about $3,500 more expensive [35, 36]. This is likely to decrease with the introduction of new robotic platforms and increased competition. With the ability to more easily perform hand-sewn anastomoses, the lower learning curve, decreased leak rate during the learning curve, the avoidance of staplers, as well as the likely continued decrease in costs of robotic platforms with increasing competition, some suggest an actual cost advantage to robotic gastric bypass as compared to laparoscopic or open procedures [37]. An example of a robotic-assisted laparoscopic roux-en-y gastric bypass is noted in Video 6.2.

Robotics and Revisional Bariatric Surgery

As the number of primary bariatric procedures continues to increase, the number and complexity of revisional cases will also increase. Commonly, patients undergo revision from an older generation of bariatric procedures such as vertical banded gastroplasty and fixed gastric bands as well as revisions from adjustable gastric bands (Video 6.3), sleeve gastrectomies, and failed gastric bypass. Particularly relevant to the field of robotic bariatric surgery is the enormous opportunity to achieve excellent outcomes and low conversion and complication rates with robotic-assisted revisional bariatric surgery as compared to a totally laparoscopic approach. There is limited literature on this topic, but it suggests superiority of the robotic approach.

Snyder et al. published a series of 99 revisional bariatric operations over a 7-year period and noted zero leaks and an average hospital length of stay of 2.3 days. There were no conversions to open operations [38]. Buchs reported a series of 60 revisional operations, including open, laparoscopic, and robotic approaches. The robotic approach was noted to have no conversions to an open procedure (14.3 % for the laparoscopic group) with significantly less complications and a shorter hospital length of stay [39]. One of the largest series (154 patients) of laparoscopic revisional bariatric surgery reports a 10.4 % rate of conversion to open operation [40]. Although more studies are needed, in the area of revisional bariatric surgery, the robotic platform appears to have the most promise, especially when it comes to decreasing the rate of conversion to an open procedure.

Robotics and Bariatric Surgery in Adolescents

The role of bariatric surgery in morbidly obese children and adolescents is sometimes a controversial topic to discuss. We do not wish to delve into the many issues that surround this topic; rather, we would just like to note robotics has been used successfully when performed in children and adolescents. Alqahtani reported a comparison of laparoscopic adjustable gastric banding as compared to a robotic-assisted approach. There were no significant differences between the two approaches except that the robotic approach took longer (24 min longer on average) [41]. As the number of bariatric procedures performed in morbidly obese adolescents continues to increase, we should expect more data on robotic approaches to pediatric bariatric surgery.

Conclusions

Since the initial report in the literature in 1999, there has been a significant increase in the number of surgeons using robotics in the field of bariatric surgery [7]. With that, the literature surrounding this topic, albeit still limited, has increased. The promise of robotics likely has yet to be fully realized. Almost all will agree that, especially in the field of revisional bariatric surgery, it offers much promise.

Current and future platforms may also increase the complexity and scope of endoscopic and natural orifice surgery. With the continued evolution of augmented reality and the ability to assimilate imaging and other technologies, the robotic console has the promise to integrate the patient's medical information seamlessly with the surgical procedure. It is easy to see how the ability to evaluate radiological imaging and the actual surgical field concurrently at the console can make for a more efficient and safer operation, especially with difficult dissections around vital structures. Although there are divergent opinions regarding the use of robotics for bariatric surgery, it is important to objectively evaluate the evidence and published data while laying a framework for true randomized comparative trials. The superior visualization, increased degrees of movement, technological promise, and ergonomic advantages exist, but these strengths alone have not led to more widespread adoption of this technology.

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Essentials and Future Directions of Robotic Colon Surgery

7

Emre Gorgun

Key Points

- Minimally invasive surgery reduces operative trauma and postoperative hospital stay.
- Laparoscopic surgery is now widely used in performing colectomies both for benign and malignant conditions.
- Laparoscopic colorectal surgery has short-term benefits over open colorectal surgery.
- da Vinci robotic surgical system has fundamentally changed the minimally invasive approach in the field of colon and rectal surgery.
- Adding robotic system provides high-definition three-dimensional vision, surgeon motion filtration, articulating movements of the instruments, stable camera control, and better ergonomics.
- Robotic colon and rectal surgery can be technically demanding, but, if performed by experienced surgeons, operative trauma remains minimal with enhanced dexterity and improved visualization.

This chapter contains video segments that can be found on the following URL:

Electronic supplementary material Supplementary material is available in the online version of this chapter at 10.1007/978-3-319-09564-6_7. Videos can also be accessed at http://www.springerimages.com/videos/978-3-319-09563-9.

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Introduction

Since the introduction of laparoscopic surgery for the management of symptomatic cholelithiasis, the surgical approach for many intra-abdominal diseases has dramatically changed. Laparoscopic colectomy, for both benign and malignant conditions, is now widely performed. The collective experience with laparoscopic colon surgery has demonstrated that patients who undergo laparoscopic procedures have less pain, decreased incidence of ileus, and shorter hospital stay. These trends have led some surgeons to use newer minimally invasive approaches, in an attempt to decrease operative trauma and hospital stay as well as improve operative visualization and dexterity. The introduction of the da Vinci® robotic surgical system (Intuitive Surgical, Inc., Sunnyvale, CA) has revolutionized the field of minimally invasive surgery. Robotic assistance in colon and rectal surgery continues to expand with ever-growing indications. Extensively utilized in urology and gynecology, the use of robotics in colorectal surgery is still in its relatively early stages. Robotic colorectal surgery has been increasingly adopted for both benign and malignant resections since first reported in 2002.

Laparoscopic colon surgery is technically demanding due to intraoperative anatomical difficulties and requires special training to master the technique. The technical challenges in laparoscopy can lead to longer operative time and a

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potential increase in complications, if such procedures are performed by inexperienced laparoscopic surgeons. Adding robotic system provides high-definition three-dimensional vision, surgeon motion filtration, articulating movements of the instruments, stable camera control, retraction, and better ergonomics [1]. The fatigue that is associated with unnatural positions during laparoscopy [2] is also eliminated by the use of robotic technology. These advantages may ultimately overcome the limitations of laparoscopic surgery and may shorten the learning curve in minimally invasive colorectal surgery [3]. Despite its advantages over conventional laparoscopy, robotic surgery has its own limits. Data in regard to long-term oncological outcomes of robotic colon cancer surgery are still not available. Additionally, increased cost of the robotic technique remains a major drawback that limits its extensive implementation.

As more surgeons consider the advantages and restrictions of the robotic platform, there is increasing discussion regarding its role in the field of minimally invasive colorectal surgery. In this chapter, I will discuss technical aspects of robotic colon surgery and provide a framework to facilitate best practices using the most up-to-date information, as well as highlight future directions of robotic colon surgery.

Preoperative Planning

Proper patient selection is crucial to preoperative planning, and patients should be both medically fit and able to tolerate laparoscopy. All patients should undergo a detailed history and physical examination.

Preoperative colonoscopy and flexible sigmoidoscopy are recommended for patients especially with left-sided colon or rectal lesions. Flexible sigmoidoscopy reveals useful information in left-sided pathologies regarding the distance from the anal verge to the lower edge of the tumor, thus facilitating operative planning. As part of the preoperative preparation for colon and rectal surgery, patients should undergo a mechanical bowel preparation with oral antibiotics. In our practice, mechanical bowel preparation and oral antibiotics are enforced to sustain low postoperative surgical site infection. Preoperative intravenous antibiotics are given within 30 to 60 min of the incision time, to ensure adequate concentration at the outset. Deep venous prophylaxis should include the use of sequential compression devices, as well as chemical prophylaxis (preoperative heparin).

Procedure

Setup

After informed consent is obtained, IV induction is given, followed by endotracheal intubation. A Foley catheter and an orogastric tube are placed. The patient is routinely placed in the modified lithotomy position (Fig. 7.1), which allows access to the anus. This position also allows an intraoperative CO_2 colonoscopy to be performed with ease, when required. The lithotomy position provides additional space for the surgical team, especially when operating in the upper quadrants of the abdomen, by standing between the patient's legs (Fig. 7.2). Padded stirrups or yellow fins are used and attention is given to preventing peroneal nerve injury. Both arms are tucked at the patient's sides. A gel pad on the operating table can provide additional decubitus support and stability against gravity with tilting. Additionally, we prefer to secure patients on the operating table with a strong tape over the chest, to prevent patients from sliding during steep Trendelenburg and right or left tilt. Two monitors on both sides of the table should be routine in laparoscopic surgery (Fig. 7.2) and robotic view should be added on these monitors via wire connection for the bedside assistant. This setup is also helpful in hybrid procedures where part of the operation is performed using laparoscopic approach.

Robotic Right Hemicolectomy

- *Initial access, surgical technique, and operating time*: A 12 mm incision is made left to the umbilicus and used as the camera site. Usually

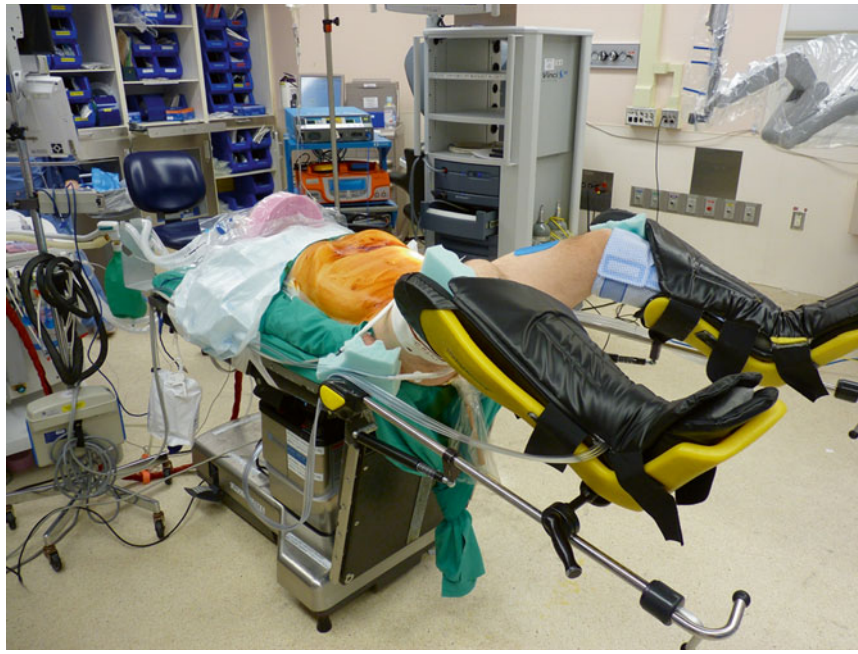

Fig. 7.1 Modified lithotomy position in robotic surgery

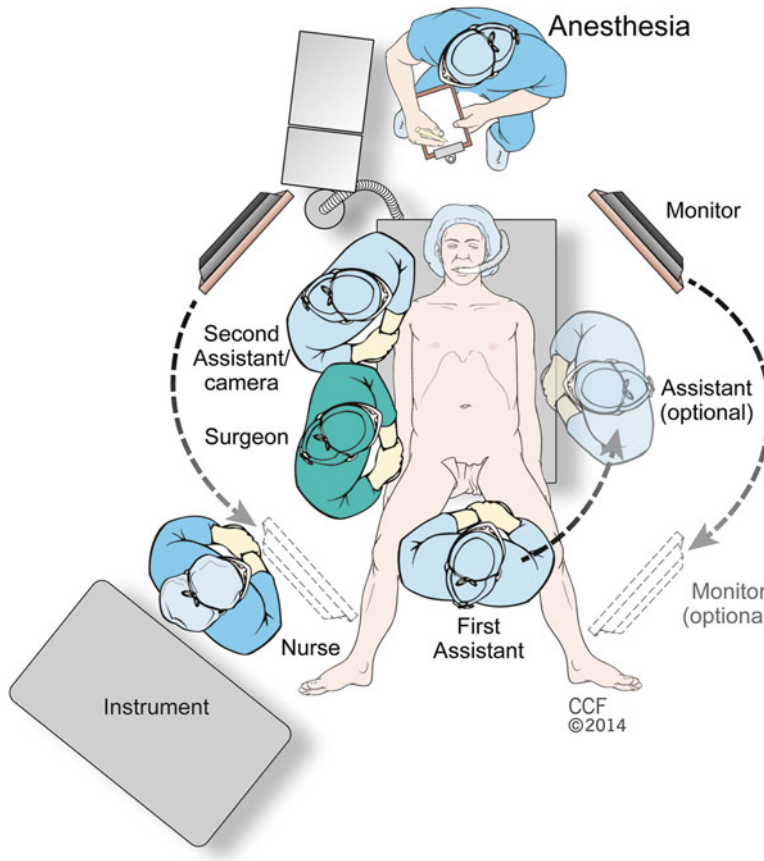

Fig. 7.2 Room setup in minimally invasive colorectal surgery (Reprinted with permission of the Cleveland Clinic Center for Medical Art & Photograph © 2014. All Rights Reserved)

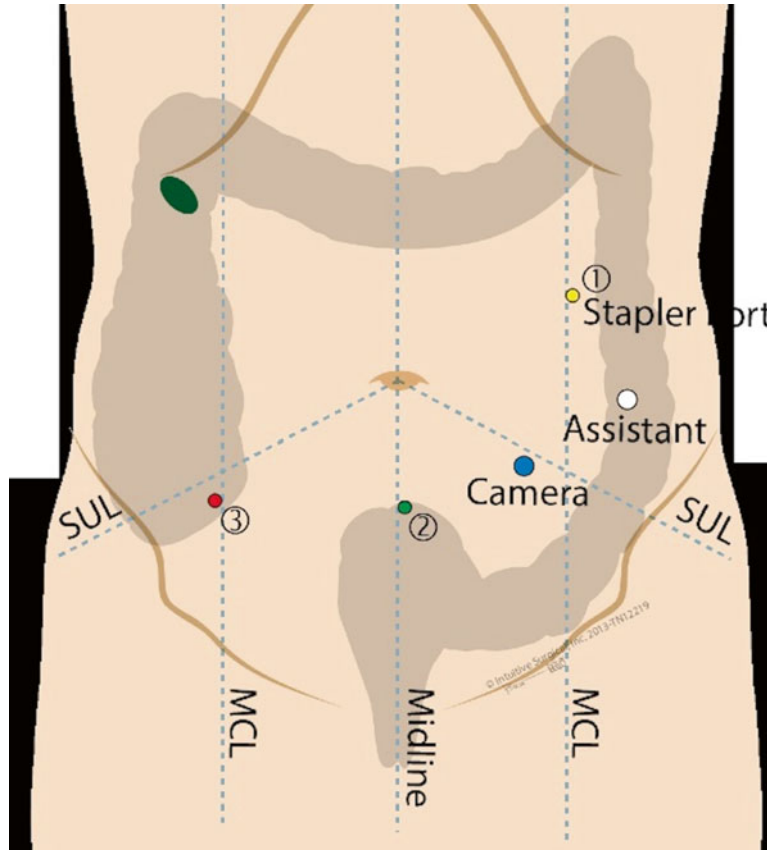

Fig. 7.3 Port placement right hemicolectomy (Copyright © 2014 of Intuitive Surgical, Inc. Used with permission)

a balloon trocar functions well for this purpose in the camera port location. The reported port numbers for robotic right hemicolectomy varies from 4 to 5 trocars according to different reports [4–9]. Preferred trocar placement for robotic right colectomy is shown in Fig. 7.3. The basic concept in port placement is to have the camera in the middle, with one working arm superior and one inferior to the camera. One 5 mm assistant port is added in the left abdomen for additional retraction. Additional third arm is usually placed on the right side of the abdomen and improves traction/countertraction. The initial dissection is done with the hook cautery or monopolar scissors in the right arm and a bipolar fenestrated forceps or Cadiere forceps in the left arm. Either a medial-to-lateral or lateral-to-medial dissection is carried. The ileocolic pedicle can be taken with Hem-o-lok clips or using any of the vessel-sealing energy devices. The colon is then dissected from the fascia of Gerota and retroperitoneum, preserving the duodenum, ureters, and gonadal vessels. Finally, take down of the hepatic flexure is performed using sharp dissection [4–8].

- *Prolonged operating time* is one of the major drawbacks of robotic surgery. The only randomized clinical study comparing robotic to conventional laparoscopic right colectomy for colon cancer showed that the operative time was significantly longer in the robotic group [4]. Similarly, in a case-matched study by Luca et al., robotic right colectomy was found to be associated with longer operating time compared to open right colectomy in colon cancer [6]. On the other hand, a study comparing the first 30 laparoscopic and robotic right

colectomy cases performed by the same surgeon suggested that operating times for both groups were statistically comparable [7]. However, earlier studies investigating patients with both benign and malignant diseases showed either prolonged [10] or similar [11] operating time for robotic right colectomy. D'Annibale et al. reported that docking time, surgeons' experience (learning curve), and intracorporeal creation of anastomosis affect the prolonged operating time for robotic right colectomy. Indeed, a gradual decline in operating time with increasing surgical volume for robotic right colectomy was observed and reported [5]. Shorter operating time was achieved by increasing surgeon's as well as robotic operating room team's experience and volume.

- Some recent studies did show similar *estimated blood loss* during robotic and laparoscopic right colectomy [4, 7]. On the other hand, robotic surgery was found to have significantly reduced blood loss compared to open right colectomy in earlier publications [6]. Reduced blood loss is an advantage of robotic colectomy compared to open surgery, but laparoscopic colectomy may offer comparable outcomes in terms of blood loss.
- *Intracorporeal anastomosis* with non-articulated rigid instruments has been a challenge for most colorectal surgeons, and extracorporeal creation of anastomosis during conventional laparoscopic colectomy is usually the preferred option to reinstitute intestinal continuity. However, one of the most important advantages of robotic surgery is the improved dexterity and superior suturing capabilities compared to conventional laparoscopic technique which makes creation of intracorporeal anastomosis technically less demanding. Robotic-assisted intracorporeal creation of anastomosis was reported to be safe, feasible, and have fewer wound and anastomotic complications according to the recently published studies [12, 13].
- Although *conversion rates* between laparoscopy and robotic surgery seem to be similar when studies are reviewed [4, 7] in a case-matched study comparing laparoscopy to robotic surgery by D'Annibale et al. [14], no conversions to open surgery were required in the robotic group consisting of 53 patients. However, in this group two patients were converted to standard laparoscopy and four were converted to a hand-assisted procedure for radical treatment of advanced cancer. There are no reported conversions to open surgery during robotic right colectomy in the literature up to date. This finding may be related with better ergonomics, visualization, and dexterity provided by the robot that may help surgeon to feel physically and mentally better during the surgery.
- Shorter *length of hospital stay* seems to be another benefit of minimally invasive techniques and robotic approach. Robotic right colectomy for colon cancer offers shorter length of hospital stay compared to open surgery [6]. However, similar results were reported for robotic and laparoscopic right colectomy in terms of length of hospital stay [4, 7]. Additionally, robotic right colectomy provides similar overall morbidity and mortality compared to conventional laparoscopic right colectomy in the early and long-term postoperative period [4, 7].
- Robotic right colectomy for colon cancer is feasible with no compromise in the *oncological outcomes*. Studies reported that specimen quality regarding the length of the resected specimen, harvested lymph nodes, and distance from the ligated vessels were comparable between laparoscopic, open, and robotic right colectomy procedures [4, 6, 7]. 92 % overall and 90 % disease-free survival rates were reported after robotic right colectomy for colon cancer at a median follow-up of 36 (6–96) months [5]. Previously reported 30 months overall survival rates by the American Joint Committee on Cancer (AJCC) were 89.2 % for stage II and 72.7 % for stage III colon cancer [15]. These results indicate that robotic right colectomy may offer similar 3-year survival rates for patients with colon cancer compared to open and conventional laparoscopic surgery.

Table 7.1 Outcomes of robotic right colectomy for colon cancer

	No. of patients	Operative time (minutes)	Blood loss (ml)	Conversion	No. of harvested lymph nodes	Anastomosis leakage	Length of stay (days)
Park JS et al. 2012	35	195	35.8	0	29.9	1	7.9
Shin JY 2012	6	342.5	185	0	25.8	0	10.7
Park SY et al. 2012	15	201.4	41.7	0	24.2	0	7
Luca F et al. 2011	33	191.7	6.1	N/A[a]	26.6	0	5
D'Annibale et al. 2010	50	223.5	20	0	18.8	0	7

[a]No data included for conversion

- Intraoperative findings and pathological and short-term outcomes for robotic right colectomy among various studies are summarized in Table 7.1.

Robotic Left Colectomy/Sigmoid Resection

In order to perform a robotic left colectomy or sigmoid resection, five to six ports are required including camera and assistant ports [16]. Figure 7.4 shows the port placement for three robotic arms, one camera, and two assistant ports. A 12 mm camera port is placed in the supraumbilical area, and this step is accomplished using open technique. Insufflation through umbilical port is achieved and pneumoperitoneum obtained. Following pneumoperitoneum, the camera is inserted and additional trocars are placed as shown in Fig. 7.4. A right upper quadrant robotic port is used for the purpose of the splenic flexure mobilization. Once the robot is re-docked for the pelvis, this port in the right upper quadrant is released from the robotic arm and can be used as the second assistant port. An additional 5 mm assistant trocar is placed in the left mid-abdomen, lateral to the edge of the rectus muscle staying in equal distance both from right upper and lower quadrant trocars. The assistant ports are used for small bowel/colon retraction and suction irrigation. We generally prefer a medial-to-lateral approach; however, depending on the comfort level of the surgeon, a lateral approach can also be utilized. The superior rectal/inferior mesenteric vessels can be identified and ligated after the left ureter is visualized and preserved. This can

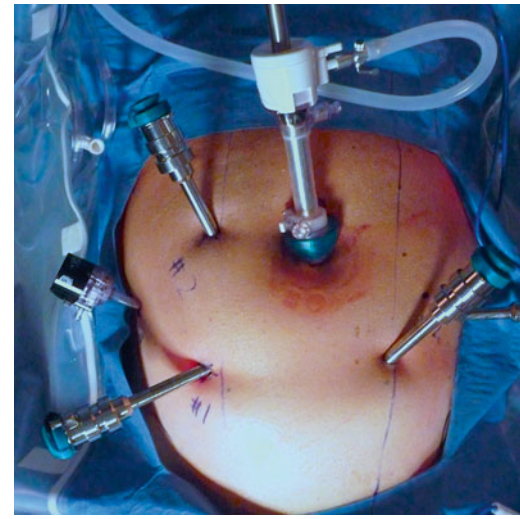

Fig. 7.4 Port placement for left/sigmoid resection

be performed using either Hem-o-lok clips (Video 7.1) or robotic vessel sealer (Video 7.2). Ligation of the inferior mesenteric vein just below the level of the pancreatic body gives additional mobility to the proximal colon segment. There are several described techniques for robotic left colectomy: *hybrid* (laparoscopic splenic flexure mobilization), *single-docking* (mobilizing the second and third robotic arms for different parts of the surgery) (Fig. 7.5), and double-docking (first docking from left upper quadrant for splenic flexure mobilization and then docking to the left lower quadrant for the rest of the procedure) [17]. The author of this chapter uses the single-docking approach and flips arm 3 from the right upper quadrant trocar to the left lateral trocar for the pelvic part. In this approach, the robot does not need to be moved or repositioned except the

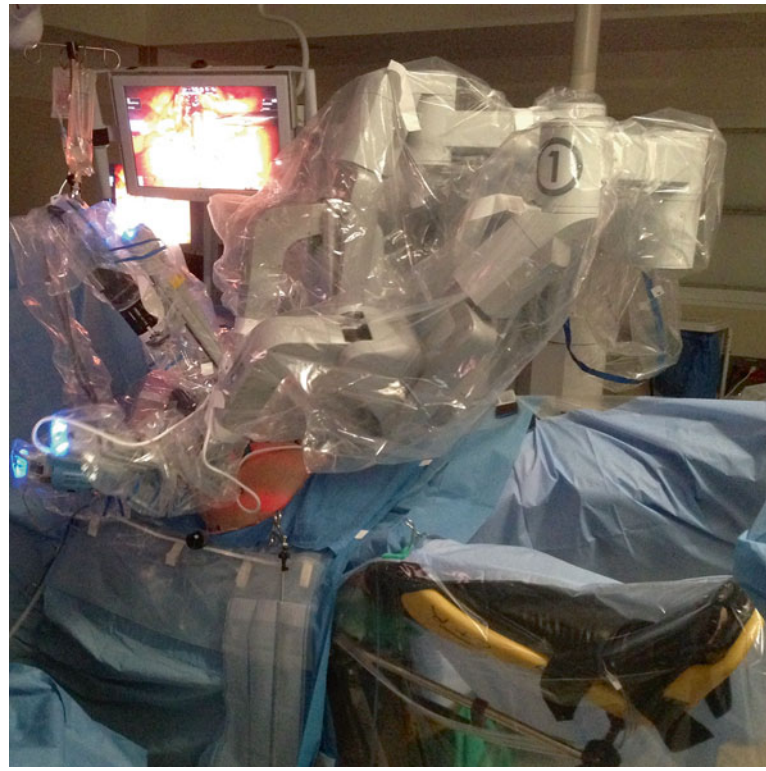

Fig. 7.5 Left-sided docking

described arm change. After the colon has been completely mobilized, bowel distal to the pathology is transected with a laparoscopic linear-cutting stapler. Endocutter stapler can be introduced through the right lower quadrant trocar after upsizing to a 12 mm port. This site can ultimately be used as the specimen extraction as well as the stoma location in cases where a diverting ileostomy be needed. Usually, one firing of the stapler is satisfactory to staple and cut across the bowel depending on the level of the transection. This step can also be achieved using the robotic EndoWrist 45 mm stapler (Fig. 7.6). This is a 54 degree-wristed articulating robotic stapler and may provide advantage in confined spaces such as deep in the pelvis. After specimen extraction (Figs. 7.7 and 7.8), the extraction site is sealed and peritoneal access regained. In this approach, maintenance of the pneumoperitoneum can be achieved in different ways: our general preference is to use the Alexis bundle wound protectors with "a cap" (Alexis laparoscopic system with Kii Fios First Entry, Applied Medical, Rancho Santa Margarita, CA) (Fig. 7.9). A 5–12 mm port is situated in the middle of the cap, which enables a laparoscopic approach before and after specimen retrieval. This approach thus converts the stoma site in cases where a diverting ileostomy is needed (Fig. 7.10), into an additional working port, with a 12 mm trocar. This port can be used as an access port for endoscopic staplers, as well as extraction site where specimens can be removed through a wound protector which is part of the trocar bundle (Fig. 7.9). Additionally, the operating surgeon can utilize this trocar by standing between the patient's legs and take down the splenic flexure when needed in hybrid cases when using laparoscopic approach.

Lim and associates compared laparoscopic and robotic anterior resections in sigmoid colon cancer patients and found that robotic approach was associated with significantly longer operative time [18]. Shin et al. [7] interestingly reported comparable operative time with robotic compared to laparoscopic resection of left-sided colon cancer. Similarly, comparable operating

Fig. 7.6 Robotic EndoWrist® stapler 45 (Copyright © 2014 of Intuitive Surgical, Inc. Used with permission)

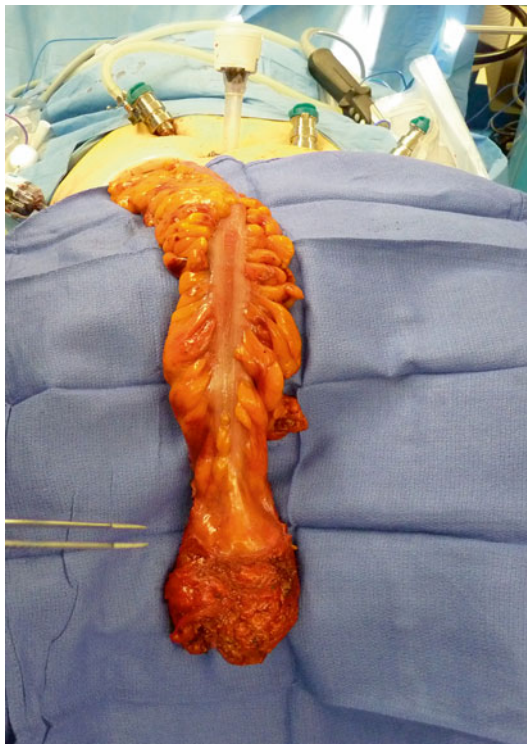

Fig. 7.7 Specimen extraction

times were detected in patients who underwent laparoscopic or robotic colectomy for colon cancer [19]. Additionally, Deutsch et al. compared laparoscopy and robotic approach for left colectomies in either benign or malignant diseases of colon and reported longer operating time for robotic technique [11]. In summary, current literature lacks a uniform study design in evaluating the operative time during robotic colectomy. However, it is obvious that operative time in robotic colectomy is generally increased and affected by many factors. The main important factor affecting operative time in robotic colorectal surgery is the presence of trained and experienced surgical team in the operating room, as well as experienced robotic surgeon. Cost analysis of operating room time includes multiple variables: room setup time, time for draping and docking the robot, skin-to-skin procedure time, undocking/storage time, and room turnover time. These factors are improved by effective team training, attention to efficient procedures, surgeon and team experience, and patient selection.

Reported blood loss and conversion rates in robotic left colectomy were similar to laparoscopic approach. Additionally, either comparable or even shorter length of hospital stay was reported for robotic left colectomy in colon cancer patients [7, 18]. Similarly, comparable outcomes in terms of blood loss and length of hospital stay were reported after robotic and laparoscopic left colectomy for benign and malignant disease of the colon [11].

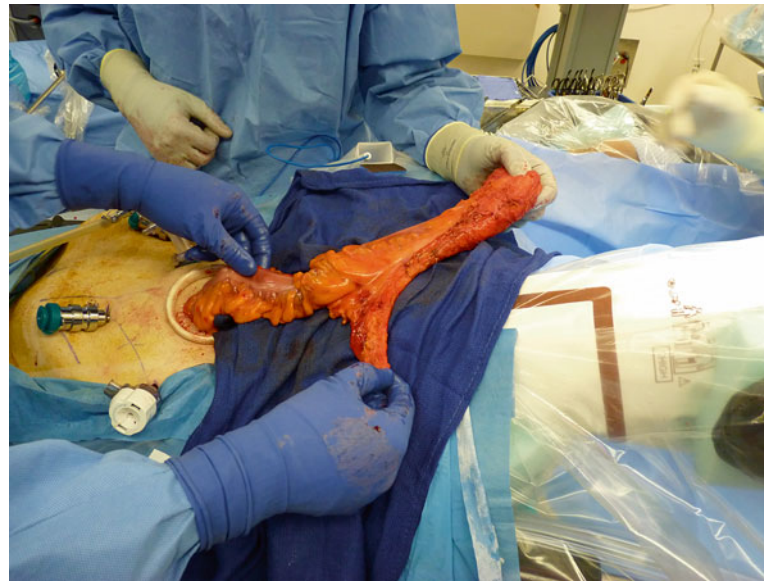

Fig. 7.8 Specimen extraction

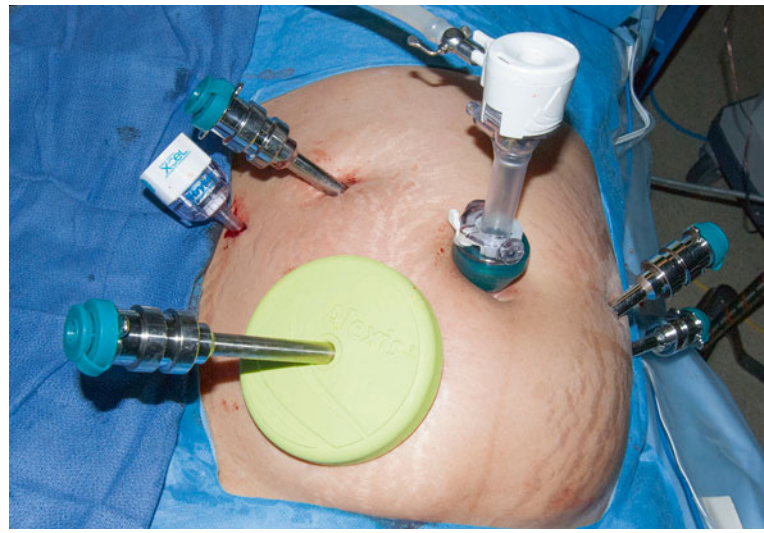

Fig. 7.9 Extraction site is sealed and peritoneal access regained

No severe complications and mortalities were reported after robotic anterior resection for sigmoid colon cancer, and postoperative morbidity and mortality rates were similar compared to laparoscopy group. Similarly, 92 % overall and 89 % disease-free 3-year survival rates were detected after robotic sigmoid colectomy and were comparable to laparoscopy and open procedures [18]. Intraoperative, pathological, and short-term postoperative outcomes for robotic left colectomy reviewed from the previous studies are shown in Table 7.2.

Cost of Robotic Colectomy

The cost of a robotic system including its yearly maintenance fees and disposables can represent a significant cost to hospitals and health systems. This is compounded by the lack of reimbursements

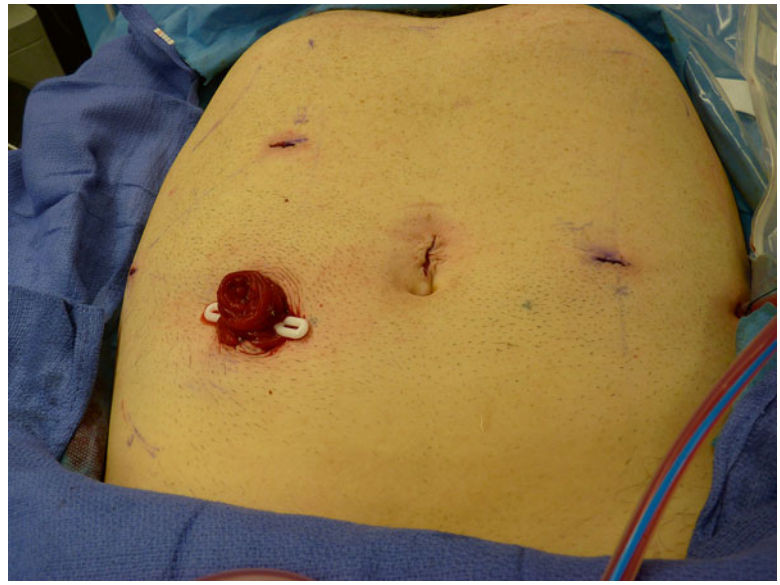

Fig. 7.10 Postoperative view of the abdomen

Table 7.2 Outcomes of robotic left and sigmoid colectomy for cancer

	No. of patients	Operative time (minutes)	Blood loss (ml)	Conversion	No. of harvested lymph nodes	Anastomosis leakage	Length of stay (days)
Lim DR et al. 2013	34	252.5	60.3	0	12	0	5.5
Helvind NM et al. 2013	101[a]	243	N/A[b]	5	23.4	5[c]	6.4
Shin JY, 2012	7	337.1	105.7	0	16.9	0	9.1
Luca F et al. 2009	55[d]	290	68	0	18.5	7[e]	7.5

[a]Cohort includes 44 left colectomies
[b]No data for blood loss
[c]Anastomotic leak for all colectomies
[d]Cohort includes 27 left colectomies
[e]2 out of 7 anastomotic leaks were after colectomy

by payers. Currently, robotic prostatectomy is the only procedure with an associated CPT code; however, the reimbursements remain the same for laparoscopic and robotic cases. Initial studies reported that robotic colorectal surgery is associated with an additional $350 direct equipment cost per case [20]. Despite the increasing clinical implementation of robotic colectomy, it is still expensive compared to conventional laparoscopic procedures [4, 21] as well as open surgery [22]. Up to date, there are no published reports that have established the cost-effectiveness of robotic colorectal surgery. Expected improvements in technology and potential competitions may reduce the cost of robotic surgery in the future.

Learning Curve

There are few studies in the literature investigating the learning curve for robotic colorectal surgery [23–28]. However, all the published studies in colorectal surgery evaluated the learning curve, focused specifically in robotic proctectomy rather than colon surgery. Nevertheless according to the results of the several studies, a high level of proficiency in overall robotic colorectal surgery can be achieved after 15 to 35 cases assuming the trainee is experienced with laparoscopic colorectal surgery. Several reports have also suggested that robotic technology shortens the learning curve of complex tasks when compared to conventional

laparoscopy. However, further studies are warranted in order to determine the learning curve specifically for robotic colon resections.

Advantages of Robotic Colectomy

- Three-dimensional high-definition video imaging
- Image magnification function
- Filtration of physiological tremor
- Better ergonomics
- Articulating robotic instruments
- Intracorporeal anastomosis
- Opportunity of performing remote surgery regardless of distance

Disadvantages of Robotic Colectomy

- Prolonged operating time
- Increased cost
- Potential need for double-docking in left colectomy requiring splenic flexure mobilization
- Steep learning curve and need for specialized surgical team

Future Directions

In the last two decades , surgical techniques have moved toward a less invasive approach from open to laparoscopic surgery and to single-incision laparoscopic surgery (SILS). The new emerging techniques and devices have reduced the number of ports and improved cosmesis while decreasing abdominal wall and body trauma. Robotic single-port colon surgery has been introduced for right colectomy procedures [29–31] and studied. The most frequently reported SILS in colorectal surgery has been the right hemicolectomy through umbilical access. Single-incision robotic colectomy can offer cosmetic advantage, reduce the number of required port sites and abdominal wall trauma, and facilitate specimen extraction using the port placement location. Current literature has demonstrated that SILS application in colonic surgery is safe and feasible. The challenges are related to triangulation, internal and external instrument collision, and operative exposition. In the future, prospective, randomized trials will be needed to further evaluate the benefits, potential complications, and oncological outcomes compared to single-incision laparoscopic right hemicolectomy.

Another technological advancement in the robotic colorectal surgery is the addition of image-guidance and tissue perfusion analysis. The anastomotic leakage is one of the most dreaded complications in colorectal surgery. One of the main causes of anastomotic leakages is considered to be the perfusion of the intestinal stump. The evaluation of the perfusion of the stumps is usually subjective based on the active bleeding edge of the section, the pulsatility of the mesentery vessels, and the lack of discoloration of bowel segments. In minimally invasive surgery, the loss of tactile feedback can make this assessment even more challenging. Near-infrared camera of the robotic platform allows visualizing the vascular structure of the colon after indocyanine green (ICG) injection. It was reported that fluorescence imaging reduced anastomotic leak rate after low anterior resection and may also help to identify sentinel lymph node [32]. It seems this technology might be very impactful for the reduction of anastomotic leaks in colorectal surgery.

Summary

Utilization of laparoscopy increased over the years after the first laparoscopic cholecystectomy. Studies did show that laparoscopy has many advantages over open surgery including reduced blood loss, smaller incision, decreased postoperative pain, and shorter recovery time after surgery. Shorter postoperative hospital stay after laparoscopic surgery was translated to reduced costs. Additionally, laparoscopic colectomy has comparable outcomes with the open colectomy in the management of colon cancer.

Despite many advantages of laparoscopic surgery, some limitations continue to exist including

two-dimensional visualization, fulcrum effect, restricted degrees of motion of the laparoscopic instruments, and amplification of physiological tremors. The introduction of the da Vinci® robotic surgical system (Intuitive Surgical, Inc., Sunnyvale, CA) has revolutionized the field of minimally invasive surgery. Robotic system provides high-definition three-dimensional vision, surgeon motion filtration, articulating movements of the instruments, stable camera control and retraction, and better ergonomics. The fatigue that is associated with unnatural positions during laparoscopy was eliminated by the use of robotic technology.

Its advantages may overcome the limitations of laparoscopic surgery and may shorten the steep learning curve in minimally invasive colorectal surgery. Despite its advantages over conventional laparoscopy procedures, robotic surgery has some limitations. Up to date, no long-term oncological outcomes data exist for robotic colorectal surgery. Additionally, increased cost of the robotic technique is a major drawback that limits its extensive implementation.

Robotic colectomy has been proven to be feasible and safe and can be expected to have additional advantages from the improved visualization and articulation of instruments and precision in dissection over laparoscopic surgery especially in complicated procedures. Robotic colectomy for cancer seems to offer comparable short-term outcomes to conventional laparoscopy in terms of length of hospital stay, morbidity, and mortality. Additionally, robotic colectomy can be performed without compromising oncological principles in the short term. However, prolonged operating time, increased costs, and steep learning curve are its major drawbacks. Further studies and prospective randomized studies are warranted to determine whether these advantages will translate into improved clinical outcomes.

As with most new surgical innovations, it is important that industry, national regulators, and surgeons work in collaboration to optimize the technology, its functionality, and cost-effectiveness while facilitating safe adoption into clinical practice.

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Essentials and Future Directions of Robotic Rectal Surgery

8

Raul Martin Bosio and Alessio Pigazzi

Introduction

Laparoscopic colorectal surgery was first described in 1991. Despite obvious benefits such as decreased pain and morbidity, improved cosmesis, shorter length of hospital stay, faster recovery times, and return to work, its progress was slowed down due to concerns of worse oncological outcomes and to potential increase in health-care cost [1–3]. In 2001, during all this controversy, the first cases of colorectal surgery performed with the robot appeared in the literature [4, 5]. A decade later laparoscopic colon and rectal surgerix is now considered both from an oncologic and all patient care standpoints (including costs), comparable or even superior to open procedures [1, 3, 6, 7]. Higher rate of positive circumferential resection margin found in the laparoscopic arm of the United Kingdom Medical Research Council Conventional versus Laparoscopic-Assisted Surgery in Colorectal Cancer (CLASICC) had initially raised concern, but the 5-year follow-up results have shown no negative effects on overall survival (OS). On the contrary, the 5-year OS of rectal cancer patients on the CLASICC trial was 52.9 % for those in the open arm versus 60.3 % for the laparoscopic group. Local recurrence was similar between arms (8.7 % for the open vs. 10.8 % for the laparoscopic arm). Results from the COLOR II trial, which randomly assigned 1,103 patients to either laparoscopic ($n=739$) or open rectal surgery, showed that positive circumferential resection margin was 10 % with both techniques. Surprisingly, morbidity was higher in the laparoscopic arm (40 % vs. 37 %; $p=0\cdot424$); however, mortality doubles in the open group (1 % vs. 2 %; $p=0\cdot409$) [8]. Revised practice parameters published by the American Society of Colon and Rectal Surgeons indicate that laparoscopic rectal resection can be performed "with equivalent oncological outcomes in comparison with open TME when performed by experienced laparoscopic surgeons" [9].

The focus of the controversy has now shifted, trying to determine the role of robotic surgery in colorectal surgery [4, 5, 10, 11]. The da Vinci® robotic system (Intuitive Surgical) can be described as an alternative platform for performing "laparoscopic" minimally invasive surgery, since it adopts most of the principles of laparoscopic surgery. Improved optics and wrist-function instruments have allowed it to emerge as an alternative to standard laparoscopy when operating in a confined space such as the pelvis, making it an attractive option for rectal resection

This chapter contains video segments that can be found on the following URL:

Electronic supplementary material Supplementary material is available in the online version of this chapter at 10.1007/978-3-319-09564-6_8. Videos can also be accessed at http://www.springerimages.com/videos/978-3-319-09563-9.

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and pelvic dissection [4, 5]. However, the increased costs associated with robotic surgery and a lack of randomized data regarding long-term oncological outcomes are areas still open for debate, casting a shadow over its long-term role in colorectal surgery [10]. Numerous published articles worldwide have described comparable oncological outcomes of robotic rectal resections to open and laparoscopic procedures [12–16]. However, as mentioned, large-scale randomized controlled trails confirming these results are not yet available [17].

This chapter will focus on the role of robotics in rectal surgery. Technical steps of common procedures, such as low anterior resection, abdominoperineal resection, and rectopexy, will be described [5, 13, 18–21]. Transanal specimen extraction and hand-sewn coloanal anastomosis techniques will also be reviewed during the course of this chapter.

Understanding Basic Technical Principles of Rectal Surgery

- The operating surgeon mind-set should be such that mobilization of the left colon including takedown of the splenic flexure should be considered routine steps in rectal surgery. Failure to obtain a complete mobilization increases the risk of tension on the anastomosis and places the patient at risk for an anastomotic leak.
- High ligation of the inferior mesenteric artery (IMA) before it branches is the standard approach. In highly selected cases, arterial division could be performed above the bifurcation of the IMA. Preserving flow to the left colic while dividing the superior hemorrhoidal artery could be performed when treating benign disease (i.e., rectal prolapsed), and the colon is redundant enough that will still allow for a tension-free anastomosis to be performed.
- Although a medial-to-lateral approach is preferred, the surgeon should be able to modify its approach to a lateral-to-medial technique depending on each case's characteristics.
- IMA first versus inferior mesenteric vein (IMV) first: Depending on patient's characteristics, starting the dissection at the level of the IMV offers an excellent alternative starting point for a medial-to-lateral technique.
- There are four anatomic areas that should be kept in mind during dissection, as autonomic nerve is most likely to get injured in these locations: (a) the superior hypogastric plexus during dissection of the IMA, (b) the hypogastric nerves during posterior rectal mobilization, (c) the pelvic plexus during lateral mobilization of the rectum, and (d) the anterior nervi erigentes during anterior pelvic dissection.
- Rectal resection with adequate partial or total mesorectal excision (TME) should be performed following the same principles described for open TME. Intraoperatory rectal examination or flexible sigmoidoscopy with CO_2 should be employed as needed to verify location of the tumor and level of dissection.
- Division of the specimen and extraction site may vary depending on the disease that is being treated, patient characteristics, and surgeon experience. Our preferred extraction site is through a Pfannenstiel's incision. However, a transanal approach is feasible in selected patients, leaving the abdomen only with trocar-site-size incisions. The selected ileostomy site is also a possible extraction site in well-selected patients.
- Anastomoses are usually performed with a standard double stapled technique. When removing very distal tumors, after transphincteric resections, a hand-sewn coloanal anastomosis may allow for reconstruction of the gastrointestinal tract and avoid an abdominoperineal resection. Although not technically complex, surgeon experience is key to perform an adequate hand-sewn coloanal anastomosis. Opportunities to learn this technique are limited outside specialty training and may contribute to a number of patients undergoing abdominoperineal resections instead [22, 23].
- Transanal specimen extraction followed by construction of a double pursue string stapled colorectal anastomosis should also be consid-

ered in selected cases, such as when treating rectal prolapse. Pursue string constructions are facilitated by the hand-wrist capabilities of the robotic instruments compared to standard laparoscopic ones. Experience is of paramount importance for safe specimen extraction and anastomosis creation.

Robotic Surgery for Rectal Pathologies

In our practice, it is our preference to perform those cases that will require a mid and low rectal dissection (i.e., rectal cancer, rectal prolapse, ulcerative colitis, etc.) using a hybrid laparoscopic-robotic approach. Although a single-dock strategy to address both the left colon and rectum is feasible [24, 25], we feel it is faster to perform the division of the IMA and IMV, as well as the mobilization of the left colon including taking down the splenic flexure with standard laparoscopic equipment. We subsequently proceed to use the robot specifically for the rectal portion of the procedure.

The next part of this chapter will describe in detail the technical steps commonly performed during a laparoscopic-robotic rectal procedure. Technical aspects have been broken down into a "step-by-step" approach to enable surgeons with varied degrees of training in colon and rectal surgery to better understand these procedures. The initial part of the chapter will describe common technical steps performed during the course of most rectal surgeries, while the later part will focus on technical steps performed for specific pathologies.

Step-by-Step Technical Approach to Rectal Surgery

Common Initial Steps in Rectal Surgery

Room Setup and Positioning

The patient is placed on the operating room table in a modified lithotomy position. The patient's buttocks should be located just before the edge of the table with the hips slightly flexed and abducted. Loosely aligning the knee to the patient's opposite shoulder should contribute to decrease pressure on the lateral compartment of the lower extremities and avoid nerve injury. As we ensure that feet and legs are ergonomically positioned and padded, it is important to ensure that the plantar aspect of the feet rests completely on the footrest and that position changes do not lift them. Changes in operating room table position and patient sliding can lead to the superior edge of the Allen stirrup applying pressure to the posterior aspect of the lower extremities and risk patient injury.

Once in lithotomy, positioning should be in such a way that the patient can be placed in steep Trendelenburg and extreme lateral positions without sliding. Various methods have been described to prevent patient sliding, such us using beam bags and various styles of straps with varied degrees of success and associated risks such as brachial plexus injury. It is our preference to position the patient directly on a large foam mat that is secured to the operating table through Velcro straps. This mat has been described to provide a "friction hold" and decreased in-line sliding. A second strap, in this case a Velcro belt, is also required over the chest and secured to the operating table at this level. It prevents the patient from sliding while the bed is tilted toward the right (usual position during the pelvic portion of the procedure). It is our preference to position both arms parallel to the patient, tucked to the operating table.

Preoperative antibiotics are administered per NSQIP guidelines. Rectal irrigation with water is performed routinely in rectal cancer cases or when a transanal extraction is planned. A Foley catheter is placed in all cases. Ureteral stents are not routinely used; their role is reserved for cases where a large inflammatory process is expected. Reassessment of the pathology via digital rectal exam is usually performed prior to initiation of the procedure and as necessary during the case and prior to stapling. Intraoperative flexible sigmoidoscopy with CO_2 has been used more and more in our practice for both tumor location and anastomosis evaluation.

Pneumoperitoneum and Port Placement

A six-port technique is standard in our practice. It includes one 12-millimeter (mm) regular laparoscopic port for the camera, two 8-mm left lower quadrant robotic ports, a 12–15-mm right lower quadrant port (RLQ) (an eight-mm robotic port is inserted in a "trocar-in-trocar" configuration in this location), as well as two 5-mm regular laparoscopic ports located in right upper quadrant (RUQ) and epigastric locations.

Pneumoperitoneum can be achieved in a number of ways. Access to the abdominal cavity through an open technique at the level of the umbilicus or placement of a Veress needle in this area is a valid entry option. It is our preference, however, to create pneumoperitoneum by placing a Veress needle at Palmer's point, 1–2 cm below the left costal margin at the left midclavicular line (MCL).

Port location is decided *after* pneumoperitoneum has been created. Routinely, our approach to port placement is as follows:

(a) A 12-mm camera port (C) is placed at the halfway point between the xiphoid process and the pubis symphysis. In tall or large patients, it is important that this trocar is placed no further than to 20 cm from the pubic symphysis. Visualization may be limited when this port is too high in the abdomen, as the sacral promontory may prevent the instrument from achieving the necessary angle for adequate visualization of structures located deep in the pelvis.

(b) The following description is a very practical and "easy-to-remember" approach for trocar placement. Once the C port is in place, a line is drawn connecting this port to the right and left anterior superior iliac spine. Three robotic ports (R) are then inserted under direct visualization using this line as guidance. Each port is four fingerbreadths apart from each other:
   - R1 is a 12-mm trocar inserted in the right lower quadrant, four fingerbreadths away from C on the projection of the previously mentioned line. Using the halfway point between C and the right anterior superior iliac spine (ASIS) is also a valid way to determine trocar positioning but may lead to a trocar being placed to lateral, especially in obese or above-average-size patients. This may affect the ability of standard length graspers and coagulation devices to reach the splenic flexure (instrument being introduced from R1) or the deep pelvis (instruments introduced through the L1 port). A 12-mm port is required to allow passage to endostaplers. An 8-mm robotic port is introduced ("trocar-in-trocar" technique) through this trocar during the dissection part of the procedure. If a robotic stapler is planned to be used, the trocar placed in this location is a 15-mm robotic trocar instead.
   - R2 is an 8-mm trocar placed in a mirror image of R1 on the left side.
   - R3 is an 8-mm trocar inserted four fingerbreadths apart (8–10 cm), lateral to R2, usually on the same transversal plane, directly above the left ASIS.

   It is important to emphasize that instruments should be introduced into the abdominal cavity *always* under direct visualization. Port placement is key in robotic surgery in order to minimize collision between arms that could determine a limited range of motion for a particular instrument and subsequently inability to reach the targeted structured.

(c) Two additional 5-mm laparoscopic ports (L) are also inserted:
   - L1 is located along the right MCL, four fingerbreadths lateral to C and about four fingerbreadths (about 12 cm) superior to R1.
   - L2 is usually inserted in the epigastrium, just lateral to the midline, four fingerbreadths from L1.

R2 and R3 can be placed at the beginning of the case or once the laparoscopic portion of the procedure has been completed.

Initial Operative Steps

Both surgeon and assistant stand on the right side of the patient. The procedure starts by inspecting the abdominal cavity to rule out metastatic

disease when treating rectal cancer. The peritoneum is first examined for any evidence of metastatic disease. Subsequently, the patient is placed in Trendelenburg position and rotated to the right (partial right lateral decubitus) to facilitate displacement of the small bowel and even the cecum out of the pelvis. If adhesions are encountered, it is of paramount importance to divide them to allow for the bowel to move outside the pelvis prior to start the robotic pelvic dissection. This is in order to prevent bowel injury due to the lack of haptic feedback from the da Vinci® system.

Atraumatic bowel graspers are used to avoid bowel injury during the laparoscopic portion of the procedure.

Laparoscopic Medial-to-Lateral Dissection of the Left Colon and Vessel Ligation

The R1 and L1 ports are the operative port during this portion of the operation (Video 8.1). The C and L2 ports are controlled by the assistant surgeon. A medial-to-lateral mobilization of the left colon is our preferred approach. However, dissection may begin either at the level of the IMA (classic approach) or at the level of the IMV. Starting the dissection at the level of the IMV requires excellent exposure of the fourth portion of the duodenum and the ligament of Treitz, where the IMV can be easily identified, traveling in the mesocolon just superiorly (2–3 cm) to the ligament of Treitz (Fig. 8.1). This approach requires the small bowel to be displaced away from the LUQ, while the transverse colon should be positioned high in the LUQ over the stomach. These maneuvers may be difficult in obese patients as the small bowel falls back in this area or when adhesions from epiploic appendages or the omentum from the transverse colon to the descending colon are present. Once adequate exposure has been obtained and the inferior mesenteric vein (IMV) is identified, we proceed to grasp the mesocolon and gently retract it anteriorly. Dissection starts by opening the peritoneum just below and following the course of the IMV, usually above the ligament of Treitz (Fig. 8.2). Monopolar cautery or scissors are usually employed, and access to an avascular plane is easily gained. As we progress, blunt dissection is used to elevate the IMV and mesocolon off of the retroperitoneum (Fig. 8.3). As dissection advances laterally and toward the splenic flexure, Gerota's fascia is encountered and dissected away from the mesocolon. At this point, the IMV can be divided with an advanced bipolar device or using a vascu-

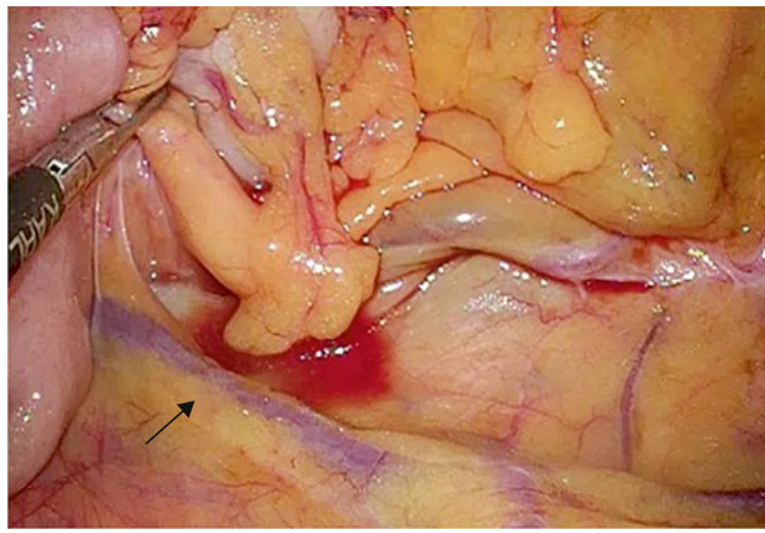

Fig. 8.1 Inferior mesenteric vein identified (*arrow*) just lateral to the ligament of Treitz

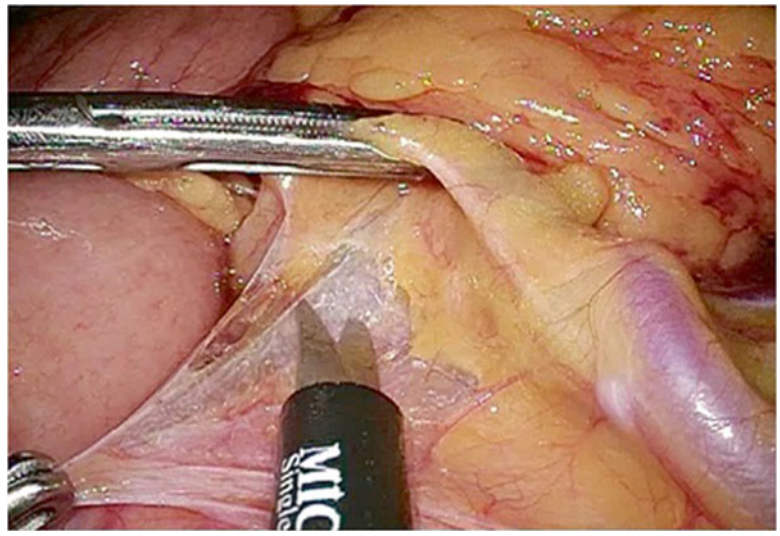

Fig. 8.2 Dividing the peritoneum below the inferior mesenteric vein just lateral to the ligament of Treitz. Dissection starts in the avascular plane as shown in this picture

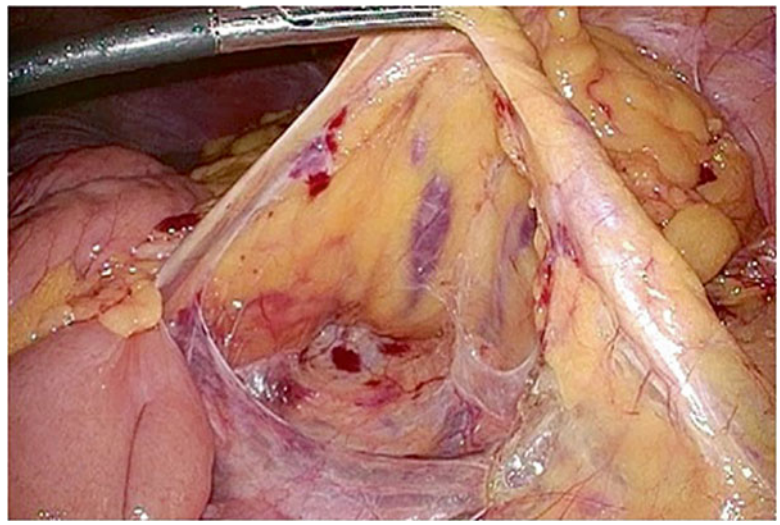

Fig. 8.3 Plane of dissection under the inferior mesenteric vein and mesocolon. In this case, the inferior mesenteric vein is held up by an atraumatic grasper

lar stapler. Our preference is to clip it and then divide it using a vessel sealer, preferably an advanced bipolar device.

Progressing with the dissection toward the splenic flexure as well as entering the lesser sac can be accomplished as dissection is carried on in this plane. However, the inferior edge of the pancreas is in this location and can be difficult to identify in the robust patient. Unless clearly visualized, continuing dissecting toward the LUQ could place surgeons not familiar with this approach at risk of actually lifting the tail of the pancreas along with the mesocolon. Our recommendation is not to continue toward the LUQ, rather to extend the dissection in a distal manner toward the IMA. Access to the lesser sac should

be accomplished while taking down the splenic flexure in a more traditional lateral-to-medial approach as we will describe later on.

Once the IMA has been identified, we usually gently lift the pedicle toward the anterior abdominal wall. The parietal peritoneum distal to the IMA and below the superior hemorrhoidal artery is then opened toward the sacral promontory, and blunt dissection allows entry into an avascular plane (think of this area as a "square" where the roof is the superior hemorrhoidal artery and the floor is the retroperitoneum containing nerves and the iliac vessels. The proximal "wall" of this square is the IMA, and the distal one is the rectum). As dissection advances from medial to lateral, the gonadal vessels and the ureter are encountered and dissected downward toward the retroperitoneum. Visualization of the psoas muscle usually indicates that the dissection is being carried out too deep; in these cases, the gonadal vessels and ureter are usually being lifted with the mesocolon.

A common mistake that makes structure identification difficult is starting the dissection through a small peritoneal opening. Whenever structures are not clear, it is helpful to extend the peritoneal incision distally toward the rectum; this would allow for a larger area of blunt dissection and facilitate the identification of anatomical landmarks. Care should be taken during development of this plane not to injure the left ureter, as well as the hypogastric nerve plexus. Division of IMA or its branches should be avoided prior to identification of these structures.

As the dissection is completed, a very characteristic "T"-shaped configuration is easily visualized as the mesocolon is lifted toward the anterior abdominal wall. This "T" shape is the result of the IMA and its two branches (left colic and superior hemorrhoidal artery) having being dissected off the retroperitoneum (Fig. 8.4). The left ureter travels lateral to the IMA and can be lifted with the pedicle if the dissection is not complete; hence the importance of identifying this structure prior to division of the IMA. The IMA can then be divided at its origin with a vessel-sealing device or vascular stapler. We routinely clip the IMA prior to using an advanced bipolar device. However, this reflects a personal preference, and it is not a necessary step.

Splenic Flexure Takedown

Having completed the medial-to-lateral dissection and divided both the IMA and IMV, we then proceed to complete the mobilization of left colon by taking down the line of Toldt. Dissection usually

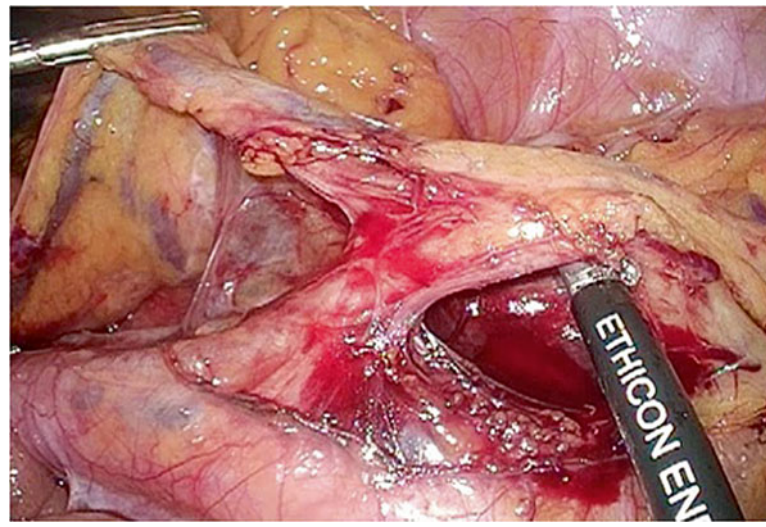

Fig. 8.4 Classic "T" image of the inferior mesenteric artery, as the mesocolon is being lifted off the retroperitoneum. The left colic artery (to the *left*) and the superior hemorrhoidal artery form the horizontal part of the "T"

begins at the LLQ. As the assistant surgeon retracts the colon medially, the line of Toldt is divided, and the plane already developed from the medial approach, between the colonic mesentery and the retroperitoneum, is easily encountered. As we continue toward the LUQ, attachments from the omentum to the descending colon are usually encountered and divided. The dissection progresses then proximally, dividing the attachments from the omentum to the transverse colon. This part of the procedure can be technically challenging in the obese patient with very high lying splenic flexures. A simple maneuver to complete the splenic flexure takedown is to approach it from the transverse colon side. An area in the distal transverse colon is selected, and the omentum is then dissected of the transverse colon with an advanced sealing device. The division of the phrenocolic and splenocolic ligaments, as well as entering the lesser sac, allows the dissection to be carried out to the base of the mesentery and complete the mobilization of the splenic flexure.

Robotic Total Mesorectal Excision (rTME)

It is standard in our practice to perform a robotic total mesorectal excision technique using a four-arm da Vinci® robot docked at the patient's left hip. It is important to emphasize that the patient is in relatively steep Trendelenburg and rotated to the right at the time of docking (Video 8.2). Even though rectal procedures can be performed also by docking in between the legs, we prefer a left hip approach to allow access to the anus to perform intraoperative digital or endoscopic examinations as needed. With this approach, the central column of the da Vinci® cart, the patient's left ASIS, and the patient's right shoulder are all aligned.

A 0-degree robotic camera is placed in C; rarely a 30-degree camera is used. Arm 1 is docked in R1. R1 would be the entry point later in the procedure of the stapler devices. Robotic stapler devices required the use of a 15-mm robotic trocar, while standard laparoscopic endostapler requires a 12-mm port. Arm 1 then will be docked to either a 15-mm robotic trocar or, using a "trocar-in-trocar" technique, to an 8-mm robotic trocar that has been introduced into a regular 12-mm laparoscopic port. R1 usually carries a robotic hook or monopolar scissors. A bipolar fenestrated grasper is placed in Arm 2 and docked in R2. Arm 3 is docked in R3 with a ProGrasp™ (Intuitive Surgical). The assistant surgeon continues standing on the right side of the patient and will use L1 and L2 to assist. An extended-length suction irrigator is usually in L1 and will be used for suction-irrigation but also to generate contra-traction as necessary. L2 holds the upper rectum out of the pelvis and toward the right or left as required.

The rTME begins at the sacral promontory below the plane of the superior hemorrhoidal artery, in the areolar/avascular plane that exists between the mesorectal envelope (endopelvic visceral fascia—EVF) and the endopelvic parietal fascia (EPF). Arm 2 (left hand of the surgeon) provides retraction, while Arm 1 (right hand of the surgeon), with a combination of electrocautery and blunt maneuvers, develops this plane of dissection within this avascular space toward the pelvic floor (Fig. 8.5). We usually try to avoid grasping the mesorectum with Arm 2, as the robotic arm may easily tear the tissues. Placing the instrument in an "L" or "I" configuration increases the area of contact between the instrument and the mesorectum, improving retraction and facilitating exposure of the areolar tissue. The hypogastric nerves should be identified during this part of the dissection. It is important to understand that the dissection should be carried out in the space located behind the mesorectal fascia (or EVF) and anterior to the endopelvic parietal fascia (EPF). Violating the endopelvic parietal fascia leads to the presacral space and increases the risk of injuring the hypogastric nerves and presacral veins. As dissection progresses distally, it is important to understand that the posterior mesorectum curves upward and anteriorly toward the anorectal junction. As the endopelvic parietal fascia fuses with the mesorectal fascia to constitute "Waldeyer's fascia" (just above the levator ani muscle), dissection past this point reaches the inferior edge of the mesorectum and a bare rectum. Further dissection may allow the surgeon to gain access to the intersphincteric plane from the abdominal side.

Posterior dissection up to this level may be achieved prior to dividing the lateral stalks. However, a combination of posterior and lateral dissection is

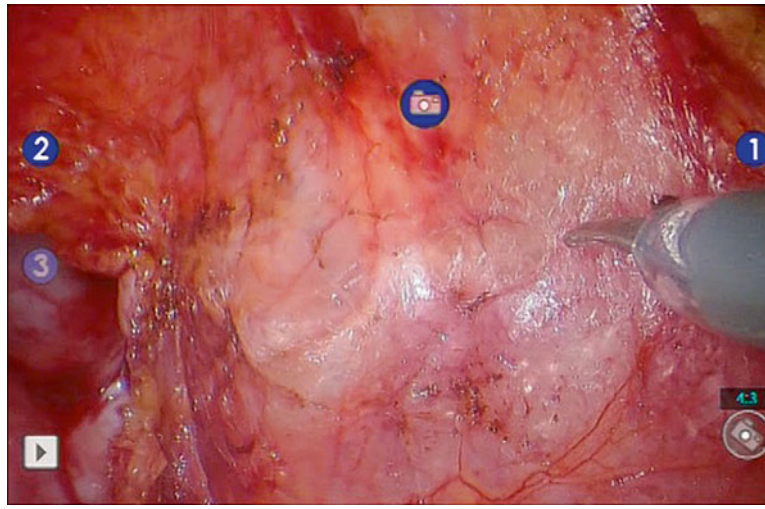

Fig. 8.5 Retrorectal space: As tension is created by the robotic Arm 2 retracting the rectum toward the pubis, areolar retrorectal tissue is clearly visualized

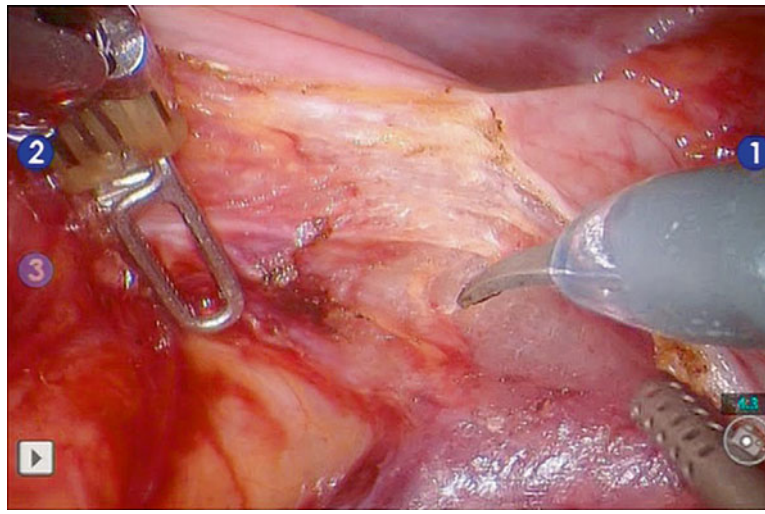

Fig. 8.6 As the retrorectal dissection progresses, the rectum is retracted anteriorly and to the left exposing the right lateral stalk

usually required to reach the pelvic floor and anorectal junction. Extending the dissection in the posterior plane as much as possible greatly facilitates the following anterolateral dissection and the identification of the lateral stalks (Fig. 8.6).

Dissection of the right and left lateral stalks can be approached both from posterior to anterior (Fig. 8.7) or from anterior to posterior once the peritoneum between the rectum and seminal vesicles or upper vagina has been opened (Fig. 8.8). Arm 3, again in an "L" configuration, provides significant retraction anteriorly and superiorly, while Arm 2 retracts the rectum down into the pelvis, exposing the plane between the vagina and rectum (Fig. 8.9). As dissection progresses anteriorly and moves toward the lateral stalks,

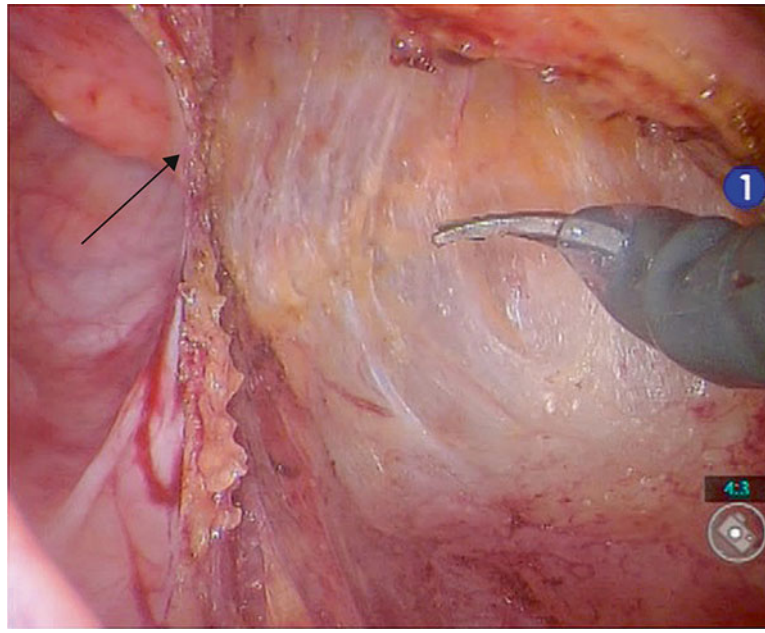

Fig. 8.7 Retrorectal space: As the retrorectal dissection progresses, the rectum is retracted anteriorly and to the right exposing the left lateral stalk (*arrow*)

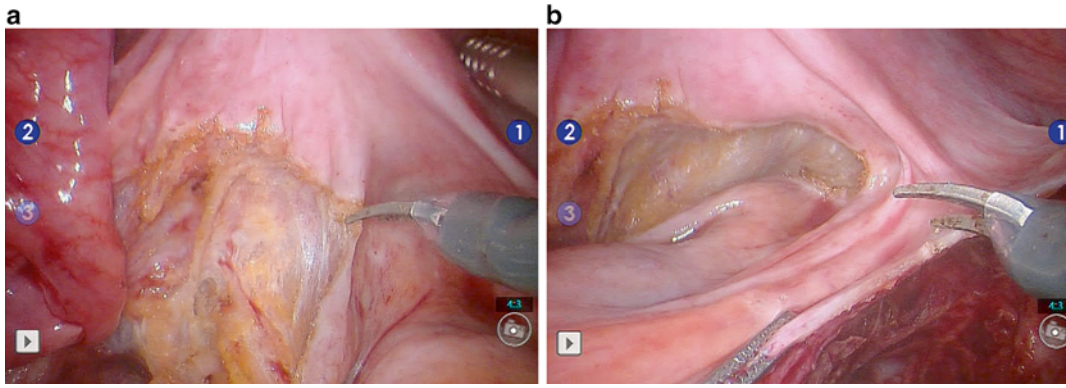

Fig. 8.8 (**a**) As the stalks are being divided, the peritoneum anteriorly, between the rectum and the vagina, is opened. Dissection is progressing from *left* to *right* in this picture. (**b**) This picture shows the peritoneum between the vagina and the rectum divided on the *left side*. The peritoneum on the *right side* as well as the right lateral stalk is clearly visualized

terminal branches of the middle hemorrhoidal vessels crossing through the mesorectum are usually encountered. They can be divided with either monopolar (Arm 1) or bipolar cautery (Arm 2) as needed. The hypogastric nerves, located now laterally in the mid-pelvis sidewall, remain behind the endopelvic parietal fascia beyond our plane of dissection, allowing for a complete autonomic nerve preservation.

Anteriorly, Denonvilliers' (rectovesical) fascia can be resected en bloc with the rectum when dealing with large anterior tumors. Once

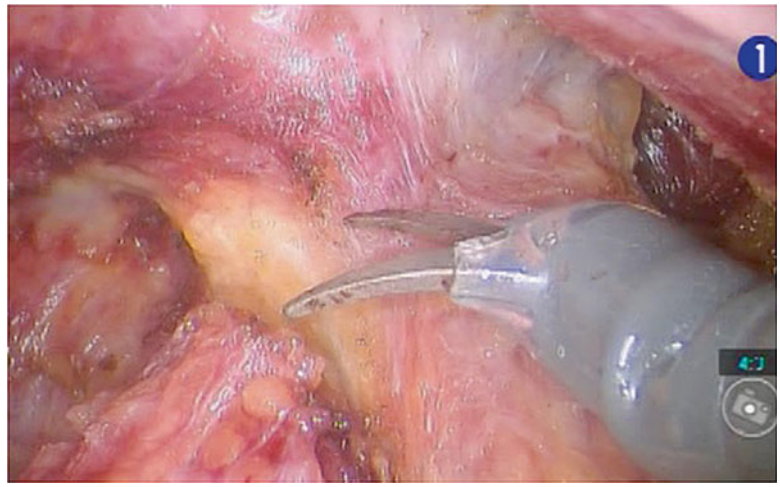

Fig. 8.9 Developing the plane between the rectum (below the robotic scissors) and the vagina (above)

the rectum has been completely mobilized, a digital rectal exam or flexible sigmoidoscopy is usually performed to ensure that the selected level for rectal division is clear. The rectum is then divided using an articulating laparoscopic or robotic linear stapler. The R1 robotic arm is removed, and the articulating stapler, usually a 45-mm green or black cartridge load or the purple Tri-Staple cartridge, is introduced. The stapler can be placed engaging the rectum from right to left or in an anterior to posterior fashion, especially in a narrow pelvis. External pressure in the perineum can help apply the stapler even more distal in the rectum. Rectal transection requires an average of 2.5 staple loads. After the distal specimen has been divided, the robot is undocked.

Our practice is to bring the specimen out through a suprapubic Pfannenstiel's incision. The fascia is divided in a transverse fashion, while the muscle is split (not divided) in a vertical manner. A wound protector is routinely placed prior to specimen extraction. Transection of the colon is then completed with electrocautery, and the anvil of a circular stapler is secured in place with a purse string. If a colonic J pouch is to be created, the colon is divided with a linear 75-mm stapler with a blue cartridge. An enterotomy is then created in the antimesenteric border to allow passage of a linear stapler with a blue load to create a pouch measuring about 5 cm. The anvil of the circular stapler is then introduced through this enterotomy and secured in place with a purse string. Subsequently, a circular end-to-end stapled anastomosis is constructed under laparoscopic vision (Fig. 8.10). A flexible sigmoidoscopy is routinely performed to assess the quality of the anastomotic ring. As the assistant fills the pelvis with water, an air seal test is performed as well (Fig. 8.11). If the donuts are not intact or if the integrity appears compromised, the decision must be made to reinforce versus reconstruct the anastomosis. It is our preference to place a drain in the pelvis. A loop ileostomy is usually constructed in high-risk patients or with low anastomosis (<7 cm).

Disease-Specific Steps

Robotic Transabdominal Transanal Intersphincteric Dissection

A robotic transabdominal transsphincteric resection is our preferred approach for rectal cancers located at the dentate line or within 2–4 cm [21, 22]. Patient selection is of great importance, as preexisting incontinence will worsen after this

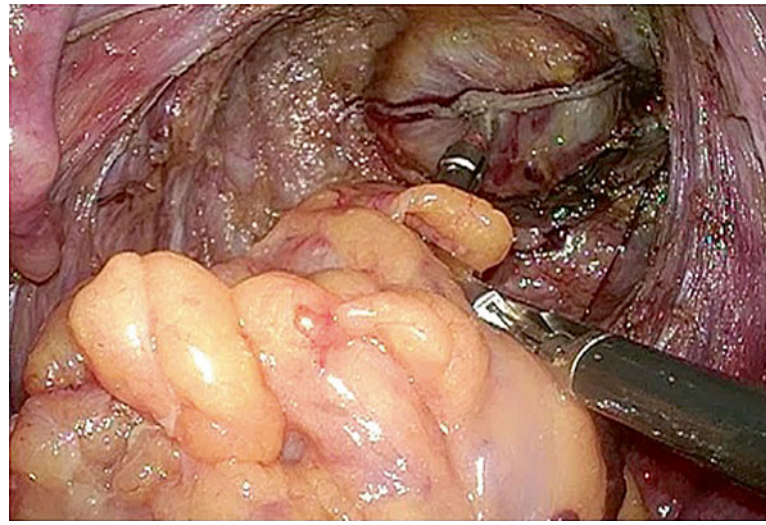

Fig. 8.10 Construction of an end-to-end colorectal anastomosis, using a double-stapler technique

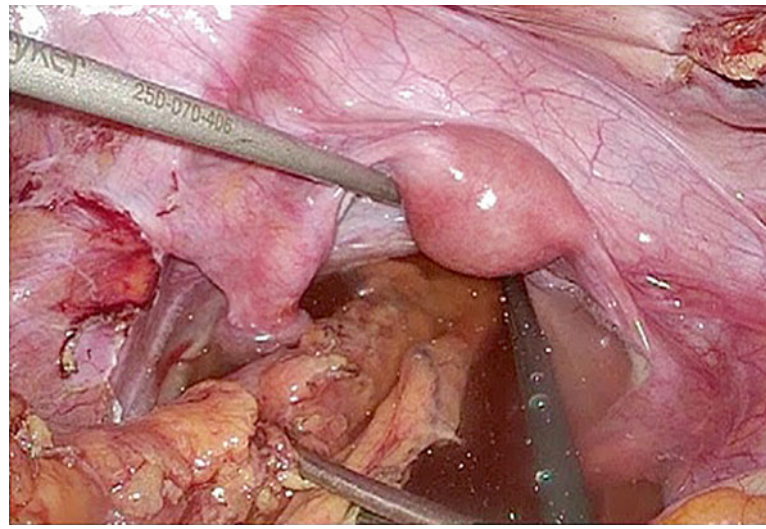

Fig. 8.11 Air leak test. It is our practice to perform it using a flexible sigmoidoscope. It allows direct visualization of the anastomosis as well as insufflation to perform an air leak test

procedure. In such patients, an abdominoperineal resection would be a better surgical option. Endorectal ultrasound complements preoperative evaluation, since involvement of the external sphincter is usually a contraindication to this procedure [21, 23].

It is our preference to perform the transanal dissection first, followed by a laparoscopic-robotic transabdominal approach [18].

The transanal part of the procedure is usually performed with the patient prone, in jackknife position. With the aid of a Lonestar retractor, the inferior edge of the tumor is identified. Various degrees of internal sphincter resection have been described (partial, subtotal, and total internal sphincter resection with or without associated segmental external sphincter resection), and the resection is tailored to each specific case. In gen-

eral, a circumferential incision is made in the mucosa, and the plane of dissection is the extended through the internal anal sphincter. Usually, we tend to dissect posteriorly as far proximal as possible, keeping the tip of the coccyx as a landmark. A sponge is usually placed in the deepest part of the dissection and is encountered later on during the rTME part of the procedure.

Subsequently, the patient is placed in lithotomy position, and the surgery proceeds as described before. As the rTME progresses deep into the pelvis, the sponge placed in the retrorectal space is encountered. At this point, the abdominal dissection continues circumferentially along the intersphincteric groove until both the transanal and transabdominal dissection planes meet. The rectum is then removed transanally or transabdominally, depending on the bulk of the specimen. If a transanal extraction is feasible, an Alexis wound protector is placed through the anus, and the specimen is subsequently delivered.

Hand-Sewn Coloanal Anastomosis

During this part of the procedure, the robot is undocked, and the patient is placed in a high lithotomy position. The colon is then divided making sure it reaches the anus without tension. While maintaining the colon grasped, the Alexis wound retractor is removed, and a Lonestar retractor is then placed in usual fashion. A head light is required during this part of the procedure. Four-corner full-thickness sutures (anterior midline, posterior midline, left lateral, and right lateral) are placed and tighten. Subsequently, interrupted sutures are placed in each quadrant creating an airtight tension-free coloanal anastomosis. The abdomen is then irrigated laparoscopically, and a drain is placed in the pelvis. It is our practice to protect this suture with a diverting loop ileostomy.

Laparoscopic-Robotic Abdominoperineal Resection

Very low rectal tumors invading the external sphincter complex or in patients with significant fecal incontinence are best treated with an abdominoperineal resection (APR) [21]. Depending on the size of the tumor and patient characteristics, a conventional versus an extralevator APR (E-APR) should be performed.

In a standard APR, the rTME proceeds as described above. However, if an E-APR is planned, the rTME stops as the levator muscles are reached. In an E-APR, the rectum is resected en bloc with the muscle, rather than dissected off it. This wide resection is performed using robotic scissors in Arm 1, transecting the levators at their origin both posteriorly and anteriorly until the ischiorectal fat is visualized. Limits of an E-APR dissection are as follows: (1) anteriorly, Denovillier's fascia in men and the posterior vaginal wall in women; (2) laterally, the medial edge of the obturator fascia; and, (3) posteriorly, a plane just anterior to the tip of the coccyx.

After the rectal portion is completed, the robot is undocked, and a circumferential incision around the anus extending from the perineal body to the coccyx is created. As the dissection progresses posteriorly, the precoccygeal space is entered. At this point, with the aid of a finger inside the pelvis, the remaining attachments are divided circumferentially. Special care should be taken not to injure the prostatic urethra, especially when treating bulky anterior tumors. In females, an en bloc posterior vaginectomy is the indicated step in those situations. The specimen is then delivered through the perineum, and the wound is copiously irrigated. Standard three-layer skin closure may not be possible after an E-APR. Preoperative planning for skin closure with a pedicle flap is recommended; however, a final decision should be determined intraoperatively once the specimen is removed. Among several flaps available, a vertical rectus abdominis myocutaneous (VRAM) flap is a popular option, providing well-vascularized, non-irradiated skin, subcutaneous fat, and muscle coverage to the defect.

As the operation concludes, a laparoscopic end colostomy is brought out through a premarked stoma site (usually R2 port site).

Rectal Prolapse: Ventral and Posterior Rectopexy

Many procedures, via abdominal or perineal approaches, have been described for the treatment

of rectal prolapse [26]. Classically, two main factors need to be considered when selecting a procedure: (1) patient's performance status, as this pathology is often seen in elderly debilitated patients, and (2) its association with constipation. In the era of open procedures, debilitated patients were usually offered transanal procedures such as perineal resection or a Delorme procedure, whether healthy patients would undergo a transabdominal rectopexy. Patients with constipation were and still are offered a resection rectopexy, albeit laparoscopically or robotic nowadays [27–29]. Even though this classic view still holds, improved overall patient care and minimally invasive approaches allow elderly patients to undergo abdominal procedures safely. Incontinence associated with rectal prolapse is in many cases secondary to chronic inflammation from the exposed mucosa and improves after reduction of the prolapsed rectum. However, sphincter tone and function can remain impaired due to chronic stretch and associated pudendal neuropathy [30]. However, the prolapse needs to be taken care of first, and treatment for incontinence offered at a later stage depending on persistence of symptoms.

This chapter will describe a transabdominal rectopexy. A transabdominal approach allows for either an anterior (ventral) or posterior rectopexy to be performed; both could be combined with a sigmoid resection if indicated. Fixation of the rectum to the area of the sacral promontory can be achieved with sutures or using either a biological or non-biological mesh. Although posterior rectopexy is currently the most common technique in the United States, anterior rectopexies are gaining popularity [31]. The choice of procedure, however, is based mainly on surgeon's experience and preference. Minimally invasive or robotic techniques for abdominal rectopexy result in decreased postoperative pain, shortened length of hospital stay, and early recovery when compared to open procedures [32]. Enhanced suture capabilities due to EndoWrist instruments tend to facilitate this procedure, especially when a ventral rectopexy is planned.

Rectal prolapse surgery includes three general steps: sigmoid resection, if indicated, rectal mobilization, and fixation of the rectum to the sacrum with or without mesh placement. Constipation usually supports the decision to perform a sigmoid resection.

For the purpose of this chapter, three procedures will be described: (1) a laparoscopic-robotic resection and posterior rectopexy without mesh, (2) a posterior suture rectopexy with mesh, and (3) a robotic ventral rectopexy with mesh.

Laparoscopic-Robotic Resection and Posterior Rectopexy Without Mesh: Technical Aspects

- Pneumoperitoneum creation, port placement, initial steps, and laparoscopic medial-to-lateral dissection of left colon and ligation of vessel technique have already been described earlier in this chapter. When treating rectal prolapse, steps are modified as follow:
- Vessel ligation: The IMV is preserved, and if possible, the superior hemorrhoidal artery is divided while keeping flow to the left colic artery.
- Lateral dissection is kept to a minimum, and the splenic flexure is usually not taking down.
- Posterior mobilization of the rectum is carried out robotically from the sacral promontory to the level of the coccyx. Again, Arm 2 acts as a retractor in an "L"-shaped configuration, while Arm 1 with monopolar scissors is the main operative arm. Dissection can be challenging, due to chronic distortion of planes secondary to bowel redundancy and elongation of the mesorectum and peritoneal attachments.
- Subsequently, the peritoneum is opened over the lateral mesorectum and extended anteriorly onto the peritoneal reflection. However, lateral stalks should not be divided, as this may increase pelvic floor dysfunction and constipation. Anteriorly, the dissection is carried out as distal as possible in the plane between the prostate or vagina and the rectum.
- Once the dissection is completed, division of the bowel at the level of the upper rectum is performed. The resected sigmoid is removed through a Pfannenstiel's incision; an anvil is then secured in place with a purse string with

usual technique. A tension-free end-to-end circular colorectal anastomosis is then created just above the level of the promontory and tested as described earlier in this chapter.

- A suture rectopexy without mesh is then performed. It is our personal preference to avoid mesh used whenever bowel is resected. In these cases, the suture rectopexy is performed using a robotic needle driver through R1. Two to three non-reabsorbable sutures are then placed through the mesorectum and the presacral fascia just below the sacral promontory. Care is taken to avoid injury to the ureters, presacral veins, or hypogastric nerves.

Posterior Suture Rectopexy with Mesh

If the sigmoid is not resected, a posterior mesh rectopexy may be performed. Mesh selection is surgeon dependent and includes the use of biologic and non-biological mesh. Dissection starts at the sacral promontory and proceeds as described above. Once completed, the selected mesh is sutured to the presacral fascia posteriorly. Subsequently, as the sigmoid and rectum pull out of the pelvis, the mesh is sutured to the lateral mesorectum either on one or both sides of the rectum.

Anterior Rectopexy with Mesh

This technique has been extensively used in Europe, and their results have been validated in multiple articles. With this technique, dissection starts by opening the peritoneum on the right side of the rectum and extending it across from right to left ("hockey stick" shape) in the plane between the vagina and the rectum. Dissection is carried out posteriorly to the level of the levators and anteriorly as far as possible as described for a posterior rectopexy. Again, lateral stalks should be preserved. Once the dissection has been completed, an approximately 18-cm-long by 4–6-cm-wide mesh is introduced into the abdomen. Its distal edge is placed deep in the rectovaginal space and sutured in place to the anterior aspect of the rectum. The proximal edge is then sutured to the presacral fascia just below the sacral promontory. The peritoneum is then sutured closed covering the mesh.

Special Situations: How We Do It

Transanal Specimen Extraction and Double-Purse-String Anastomosis Technique

Transanal specimen extraction followed by a double-purse-string circular end-to-end anastomosis can be performed after segmental colonic resection. When treating rectal prolapse, due to the rectum and anal sphincter complex being chronically dilated, transanal specimen extraction is usually feasible. In this situation, after dividing the mesocolon with a vessel sealer, the sigmoid colon is divided proximally with a robotic or laparoscopic linear stapler introduced through Arm 1. Subsequently, the upper rectum is divided using robotic monopolar scissors. At this point, a long ring forceps or a Babcock clamp is then introduced through the anus and advanced into the abdomen through the rectal lumen. The sigmoid colon is then grasped by the clamp and slowly pulled out through the rectum and anus.

The stapled sutured line from the descending colon is then sharply removed, and the anvil of a circular stapler is then introduced and secured in place by a robotically constructed purse string.

A second purse string is then placed at the cut edge of the rectum and tightened around the pin of a circular stapler introduced through the anus. At this point, an end-to-end circular anastomosis is constructed. The anastomosis is then tested as previously described.

Future Directions

As of 2009–2010, only 42 % of colorectal cases in the United States were performed laparoscopically. During that same period, the percentage of minimally invasive colorectal cases performed robotically was 2.78 % [11]. Even though increased cost remains a problem for widespread adoption of this technology, published data as well as national database reviews suggest that robotic surgery is associated to a lower conversion to open cases in rectal pathology [33–35]. Further studies are needed to asses if lower conversion rates and shorter postoperative recovery

times could help offset overall procedural costs. In such a case, widespread use of this technology could potentially be justified. However, whether low conversion rates are due to the procedure being facilitated by the robotic platform or a consequence of only highly trained surgeons performing robotic rectal resections is still not clear. The answer to this question may hopefully be provided as more and more surgeons with different levels of skills and training adopt this technology. However, as technology evolves, it is difficult to foresee a future without robotic surgery, especially for rectal pathology.

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Essentials and Future Directions of Robotic Hepatobiliary Surgery, Including Cholecystectomy

9

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Introduction and History

Advances with robotic technology have taken great strides such that robotic techniques are able to surpass limitations of traditional laparoscopic surgery, thereby theoretically improving the minimally invasive approach [1, 2]. For example, robotic technology includes instruments with flexibility comparable to the human wrist, whereas the instruments of traditional laparoscopy are restricted to only 4 degrees of freedom; the optics used for robotic surgery are three-dimensional, not two; surgeon tremor is eliminated; and robotic surgery allows the surgeon to operate in a more optimal and comfortable position [1, 2]. These advantages enable the surgeon to finely dissect, reconstruct, and maintain vascular control even in more challenging locations [3] such as the porta hepatis and the retrohepatic inferior vena cava. It is thought that these characteristics make robotic assistance during liver resection and biliary surgery a safer and more efficient minimally invasive approach when compared to pure laparoscopy.

Cholecystectomy

Open cholecystectomy was first described by Carl Langenbuch in 1882 [4]; just over 100 years later in 1985, Erich Muhe performed the first laparoscopic cholecystectomy [4]. Benefits of the laparoscopic approach that were observed over time included faster patient recovery time, shorter hospital stays, and decreased pain [5–7]. Cholecystectomy has since evolved to become one of the most commonly performed surgical procedures in the United States. With the emergence of robotic-assisted surgery as a potentially improved form of minimally invasive surgery, surgeons interested in the technology are beginning to perform robotic-assisted cholecystectomy.

This chapter contains video segments that can be found on the following URL:

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Robotic-assisted cholecystectomy has served as a prototype procedure for surgeons who are first using robotic technology. The first robotic cholecystectomy was performed in Belgium in 1997 [8]. Since then, multiple groups throughout the world began to perform similar procedures using robotic systems available, including the Zeus Robotic Surgical System (Computer Motion, Santa Barbara, CA, USA) with the Automated Endoscopic System for Optimal Positioning (AESOP®; Computer Motion, Inc., Goleta, CA, USA) as well as the da Vinci® Robotic Surgical System (Intuitive Surgical, Inc, Sunnyvale, CA, USA) [9–14]. Early reports concluded that cholecystectomy was feasible using robotic assistance, although longer operative times and increased costs of surgery were initial concerns. Regarding operative times, as surgeons gained more surgical experience and with more extensive evaluation, surgeons began to demonstrate similar intraoperative times when comparing robotic-assisted surgery to laparoscopic surgery [12, 15, 16]. Kornprat and colleagues suggested a longer total intraoperative time in their prospective, comparative study, but dissection time between cohorts was similar [12]. In a 1:1 case-matched study, Breitenstein and colleagues demonstrated no difference in time from skin to skin [15], although they did suggest an increased setup time. Increased cost compared to laparoscopy has also been a concern [15]. Without a clear benefit compared to laparoscopy and with increased costs, the value of robotic assistance for cholecystectomy has been questioned outside its use as "practice" [17]. More recently, a role for robotic assistance during cases of complex, benign gallbladder disease such as Mirizzi's Syndrome—a disease process that is still considered a relative contraindication to laparoscopic cholecystectomy—and choledocholithiasis has been suggested [16, 18–22]. Also, in our own experience, we have found that the precision and excellent visualization of robotic technology are very valuable during cholecystectomy in cirrhotic patients. Thus, robotic-assisted cholecystectomy may be beneficial over pure laparoscopy by enabling successful and efficient minimally invasive treatment of the more complex/technically demanding gallbladder cases.

With the emergence of single-incision laparoscopic surgery (SILS) cholecystectomy as an alternative to standard laparoscopic cholecystectomy, interest in single-site robotic cholecystectomy (SSRC) has emerged and grown. The anticipated benefits of standard SILS cholecystectomy are less pain, quicker recovery, and improved cosmesis when compared to the standard 4-port laparoscopic cholecystectomy, although the true benefit is still uncertain [23]. However, the standard SILS technique has several technical challenges, including inverted instrument positioning, instrument clashing, image instability, and decreased range of motion. First reported in 2011, SSRC aims to eliminate or lessen the significance of these challenges [24–26]. For SSRC, curved robotic instruments are used, and the perceived position of these instruments is inverted by the robot for more intuitive maneuvering by the surgeon. Of note, the instruments used during SSRC are different from standard robotic instruments in that EndoWrist technology is not used, and the camera used is 8.5 mm instead of 12 mm. Early studies suggest that SSRC is a feasible procedure [24–30]. Its role in general surgery is yet to be determined.

Bile Duct Resection

Cases of extrahepatic bile duct surgery have been reported—these cases have been reported as solely bile duct cases or in the setting of cases involving the liver, gallbladder, or pancreas [16, 19–22, 31–33]. The main conclusion to be drawn is that application of robotic-assisted technology is feasible for these cases. The sole study of robotic assistance during choledochal surgery is necessary to better define its role.

Liver Resection

Elective hepatic resection was first described by Langenbuch in 1888 [34]; the practice of liver resection has since transformed as knowledge and technology have grown. Improved definition of hepatic anatomy [35–38], advances in surgical technique and anesthesia care [39–44], more

Table 9.1 World review: demographics

Authors	Year	Country	Study type	# Pts	Age (years)	Male:Female
Choi	2008	Korea	Case series	3	63 (59–70)	1/2
Tomulescu	2009	Romania	Case series	7	NA	NA
Berber	2010	USA	Comparative	9	66.6+/−6.4	7/2
Chan	2011	China	Case series	27	61 (37–85)	16/11
Giulianotti	2011	USA/Italy	Case series	70	60 (21–84)	30/40
Ji	2011	China	Comparative	13	53	9/4
Wakabayashi	2011	Japan	Case series	4	NA	NA
Lai	2012	China	Case series	10	65.1+/−13.8	5/5
Troisi	2013	Italy/Belgium	Comparative	40	64.6+/−12.1	27/13
Tsung	2013	USA	Comparative	57	58.4 +/− 14.6	24/33

frequent and more extensive use of intraoperative ultrasound [45, 46], better quality of preoperative imaging obtained, and eventually the incorporation of vascular stapling devices [47] as well as energy-induced hemostasis [48–50] have all contributed to improved outcomes after liver surgery [51–53]. As a result, indications for hepatic resection have broadened to include patients with certain benign diseases as well as select patients with abnormal liver function. Additionally, as laparoscopic experience and technology have improved, minimally invasive techniques have been incorporated into the practice of liver surgery with the intent to take advantage of the benefit they can bring. Multiple studies have demonstrated less postoperative pain, shorter time of ileus, decreased length of stay, fewer postoperative complications, and improved cosmesis [54–56] with minimally invasive hepatectomy.

Most recently, robotic technology has been used for liver resection. The first reported robot-assisted liver resection took place in Japan and was reported in 2004 [14]. Multiple centers across the world have since used robot assistance for hepatectomy. Successful procedures have been reported, and outcomes have been comparable to the laparoscopic approach, including short-term oncologic outcomes [57].

Review of the world literature reveals 10 studies evaluating 240 cases of robotic liver resection [14, 58–65] (Table 9.1). These studies include descriptive and/or outcomes data for original cases of multiport, robotic-assisted hepatectomy. Case reports and cases of donor hepatectomy are not included. Three studies included liver resection combined with other procedures such as colon resection [58, 59, 65]. Of these 240 cases, 169 patients (70 %) had malignant disease. The most common malignancies reported were metastatic colorectal cancer in 80 patients (49 %) and hepatocellular cancer in 51 patients (31 %) (Table 9.2). Other malignant pathologies described include cholangiocarcinoma, gallbladder cancer, hepatoblastoma, and other metastases. The most common benign pathologies seen were hemangioma in 20 (37 %), focal nodular hyperplasia in 8 (15 %), cystic disease in 8 (15 %), and hepatic adenoma in 7 (13 %). Other pathologies described include stone disease, inflammation/stricture, and infection. Regarding oncologic outcomes, of 6 studies reporting pathologic margins, all but one study demonstrated R0 resection was achieved >90 % of the time using this technology. Long-term outcomes are not yet available given the recent application of this technology. Both major and minor hepatectomies were performed—major hepatectomies were reported in 68 of 240 patients (28 %) (Table 9.3). Of these 68 major hepatectomies, 47 procedures were described. Right hepatectomy was performed in 28/47 patients (60 %), left hepatectomy in 17 (36 %), and extended right hepatectomy in 2 (4 %). Conversion to minimally invasive hand-assisted hepatectomy occurred in 1/240 (0.4 %) for bleeding. Conversion to open hepatectomy occurred in 17/240 patients (7 %) for bleeding, safe assurance of margins, difficulty in liver mobilization, and inability to safely access hilar structures. No perioperative mortality was

Table 9.2 World review: pathologic results

Authors	# Pts	Malignant	Benign	Tumor type—malignant	Tumor type—benign	R0
Choi	3	2 (67 %)	1 (33 %)	1 CRM; 1 HCC	1 Hepatolithiasis	100 %
Tomulescu	7	7 (100 %)	0 (0 %)	NA	NA	NA
Berber	9	9 (100 %)	0 (0 %)	4 CRM; 3 HCC; 2 OM	0	NA
Chan	27	21 (78 %)	6 (22 %)	7 CRM; 13 HCC; 1 GBC	1 Hem; 1 HA; 4 pyogenic cholangitis	NA
Giulianotti	70	42 (60 %)	28 (40 %)	16 CRM; 13 HCC; 2 CC; 3 GBC; 7 OM; 1 HB	9 Hem; 7 FNH; 6 HA; 4 Cystic; 1 stenosis; 1 Inflam	100 %
Ji	13	8 (62 %)	5 (38 %)	6 HCC; 2 CC	3 Hem; 1 FNH; 1 hepatolithiasis	100 %
Wakabayashi	4	3 (75 %)	1 (25 %)	3 HCC	1 Hem	NA
Lai	10	9 (90 %)	1 (10 %)	7 CRM; 2 HCC	1 Biliary papillomatosis	67 %
Troisi	40	28 (70 %)	12 (30 %)	24 CRM; 3 HCC; 1 CC	6 Hem; 4 Cystic; 2 other	93 %
Tsung	57	40 (70 %)	17 (30 %)	21 CRM; 7 HCC; 12 other	NA	95 %

CRM colorectal metastases, *HCC* hepatocellular carcinoma, *CC* cholangiocarcinoma, *GBC* gallbladder carcinoma, *OM* other metastases, *Hem* hemangioma, *FNH* focal nodular hyperplasia, *HA* hepatic adenoma, *Inflam* inflammatory lesion, *HEM* hemangioma, *FNH* focal nodular hyperplasia, *HA* lesion, *HB* hepatoblastoma, *NA* not available

reported, and postoperative complications were seen in 37 of 240 cases (15 %). This seems comparable to the 10.5 % morbidity (between 0 % and 50 %) reported in the laparoscopic literature [56]. Reported liver-related morbidity for the robotic group included bile leak/biloma in 9 cases (4 %), transient liver failure in 2 (0.8 %), and ascites in 1 (0.4 %).

It is difficult to derive conclusions for outcomes such as operative time, estimated blood loss (EBL), and length of stay (LOS). It is suspected that case complexity as well as the learning curve of the surgeon/robotic surgery team are relevant to this, as demonstrated for other types of surgical procedures and techniques [59, 66–69]. In addition, metrics such as length of stay are heavily influenced by cultural differences. In our case-matched study of robotic vs. laparoscopic liver resections, we evaluated the impact of our learning curve on these outcomes. We noted that after the first 13 cases, operative time, EBL, and LOS all significantly improved [62].

Current experience with robotic-assisted liver resection suggests that this form of surgery is safe and effective in appropriate hands; the pending question is its benefit. It is possible that surgical robots are an "enabling technology" in the spectrum of minimally invasive surgery, allowing surgeons to complete more complex and geographically challenging cases in a purely minimally invasive manner [59, 70]. In a world review of minimally invasive liver resections, 75 % of cases were noted to be completed using purely minimally invasive technique [56]—nearly 20 % were completed using hand-assisted laparoscopic methods or the laparoscopic hybrid technique. The Louisville Consensus Statement on Laparoscopic Liver Surgery also supports that not all liver cases are suitable for laparoscopy as it does not recommend laparoscopy for lesions in a posterosuperior location. It further suggests that hand assistance and hybrid procedures are ways to make laparoscopy safer and more efficient operations [71]. In our own case-matched study of robotic liver resection, we found a significant difference in the proportion of cases that could be completed in a completely minimally invasive manner (without the use of the hand port or the hybrid procedure)—of the 57 cases of robotic-assisted hepatectomy performed during the time of study, 93 % of robotic cases were completed with the minimally invasive technique compared to 49.1 % of laparoscopic cases ($p<0.001$) [62]. Reports of successful parenchymal-sparing tumor resection for lesions in the posterosuperior segments using robotic technology have been described. Perhaps robotic assistance broadens our minimally invasive ability. Additional study and comparison of this technique to open and laparoscopic surgery should be pursued.

Table 9.3 World review: procedures and operative outcomes

Authors	Major Resection	Major Resection: Procedure	Time (mins)	EBL (mL)	LOS (days)	Conversion (%)	Complications (%)	Liver Failure	Bile Leak	Bleeding	Mortality
Choi[a]	0		380 (360–650)	300 (100–700)	6 (6–13)	0	0	0	0	0	0
Tomulescu	0		137 (120–180)	NA	11(4–19)	0 %	0 %	0	0	0	NA
Berber	0		258.5 +/– 27.9	136 +/–61	NA	1 (11.1 %)	0 %	0	0	0	NA
Chan	1 (3.7 %)	1 LH	200 (90–307)	50 (5–1000)	5.5(3–11)	1 (3.7 %) – hand port	2 (7 %)	0	1	0	0
Giulianotti[b]	27 (38.6 %)	20 RH; 5 LH; 2 RTS	270 (90–660)	262 (20–2,000)	7 (2–26)	4 (5.7 %)	15(21 %)	2	2	0	0
Ji	9 (69.2 %)	2 RH, 6 LH; 1 LH + caudate	338(150–720)	280	6.7	0 %	1(8 %)	0	1	0	NA
Wakabayashi	0		NA	Minimal	NA	0	0 %	0	0	0	0
Lai	10(100 %)	6 RH; 4 LH	347.4+/–85.9	407+/–286.8	6.2 +/– 3.6	0 %	3(30 %)	0	2	0	0
Troisi[c]	0		271+/–100	330+/–303	6.1+/–2.6	8 (20 %)	5 (12.5 %)	0	2	1	0
Tsung	21 (36.8 %)	NA	253 (180–355)	200 (50–337.5)	4 (3–5.5)	4 (7 %)	11(19.3 %)	0	1	0	0

RH right hepatectomy, *LH* left hepatectomy, *RTS* right trisegmentectomy

[a]Cases include combined liver/colon resections. Time (mins) indicates only hepatectomy portion of procedure

[b]Cases include combined procedures

[c]Cases include combined liver/colon resections which were subtracted by Troisi et al. for calculation of Time, EBL, and LOS.

This chapter describes our methods for gallbladder surgery and liver resection—cholecystectomy, right hepatectomy, left hepatectomy, left lateral sectionectomy, and nonanatomic resection—using robotic assistance.

Indications for Robotic-Assisted Hepatobiliary Surgery

The indications for robotic-assisted hepatic resection are evolving as the technology is only recently being applied. Currently, we recommend using the Louisville Consensus Statement [71] as an initial guide to patient selection. Members of this consensus conference for the application of laparoscopic liver surgery concluded that minimally invasive technique could be used for patients with a single lesion of 5 cm or less located in segments 2–6. They also concluded that major liver resection should be performed with minimally invasive technique only by those experienced with liver surgery as well as with minimally invasive liver resection. Lastly and importantly, they suggested that the surgeon should be facile with minimally invasive technique, including the skill of intracorporeal suturing should bleeding become an issue.

Technique of Robotic-Assisted Hepatobiliary Surgery

The techniques of robotic-assisted hepatobiliary surgery remain similar as to what has been described for open surgery. In addition, two experienced surgeons familiar with liver and gallbladder anatomy are recommended to ensure smooth teamwork; this optimizes proper exposure, identification, and control of important structures as they are encountered during the case. One surgeon sits at the robotic console, and one assists at the operating room (OR) table.

Patient Positioning, Room Setup

The patient is positioned supine on the OR table. The arms are tucked, and the legs are split. The undocked robot is positioned at the patient's head. For our cases, anesthesiologist usually works at the patient's left shoulder, and the scrub nurse works at the patient's right side—this can vary depending on what the room will allow. One surgeon stands at the patient's right, and one stands between the legs. For the more complex cases, an additional surgeon or assistant is present at the patient's left (Fig. 9.1). The patient will be positioned in 30° reverse Trendelenburg for the duration of the case after ports are placed.

Cholecystectomy

Access is gained to the abdominal cavity by a 5 mm optical trocar in the left upper quadrant (LUQ), and pneumoperitoneum of 12 mm Hg is created. Additional ports are placed using a 5 mm, 30 degree scope for visualization. Additional port sites include (1) a 12 mm port at the umbilicus for the robotic camera, (2) a subcostal, robotic port in the right midclavicular line, (3) a robotic port between the right lowest rib and anterior superior iliac spine near the anterior axillary line, and (4) a 5 mm assistant port in the right lower quadrant (Fig. 9.2). The initial port in the LUQ is changed for a robotic port. Ports should maintain a distance of at least 8–10 cm. The steps for this procedure are as follows (Video 9.1):

Step 1: The robot is docked with the camera placed at the umbilical port site. Robotic Arm 1 sits in the LUQ port, Arm 2 at the right midclavicular line, and Arm 3 at the right anterior axillary line.

Step 2: Robotic graspers are placed in robotic Arms 2 and 3, and a robotic hook or coagulating dissector is placed in robotic Arm 1.

Step 3: The gallbladder fundus is retracted superiorly using the grasper in robotic Arm 3, and the infundibulum is retracted laterally using the grasper in robotic Arm 2 (Fig. 9.3).

Step 4: Using the instrument in robotic Arm 1, the peritoneum surrounding the gallbladder neck is dissected to identify the junction of the gallbladder and cystic duct. Calot's triangle is exposed, and the critical view is defined (Fig. 9.3). The dissecting instrument in Arm 1 is switched for a robotic clip applier, and clips

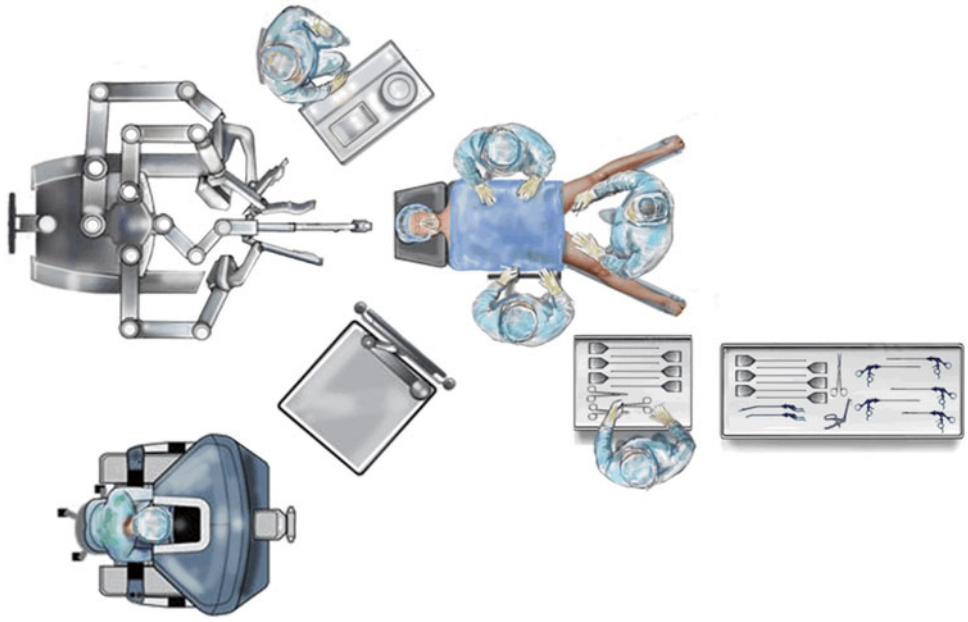

Fig. 9.1 Operating room setup (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

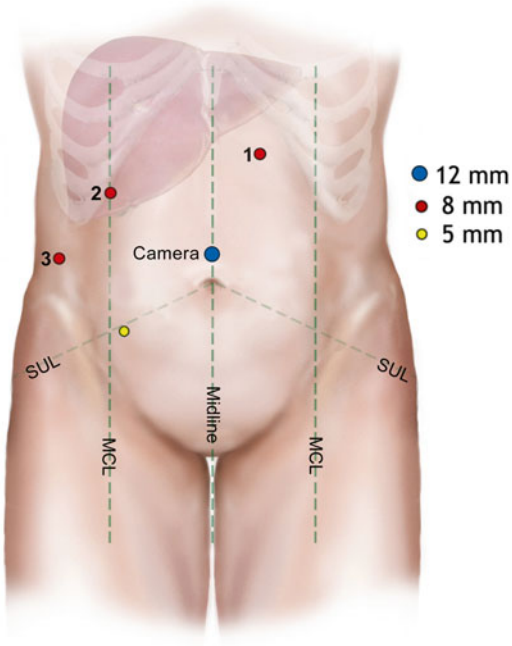

Figure 9.2 Ports, cholecystectomy (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

are placed on the cystic duct and cystic artery (two distal and one proximal). These structures are divided.

Step 5: A hook or coagulating dissector is placed back in robotic Arm 1, and the gallbladder is dissected from its fossa. Exposure is adjusted via Arms 2 and 3 as necessary.

Step 6: Just before and after the gallbladder is completely dissected from the liver, hemostasis to the gallbladder fossa is ensured. Clips on the cystic duct and artery are identified to ensure secure placement as in laparoscopic cholecystectomy.

Step 7: The robot is undocked, and an 8 mm camera is placed in the left upper quadrant port. The gallbladder is collected in a specimen bag introduced through the umbilical port. The gallbladder fossa and anterior surface of the liver are irrigated with sterile saline or water. The specimen is removed. Fascia is closed at the umbilical site in standard manner, and the skin of additional port sites is closed in standard manner.

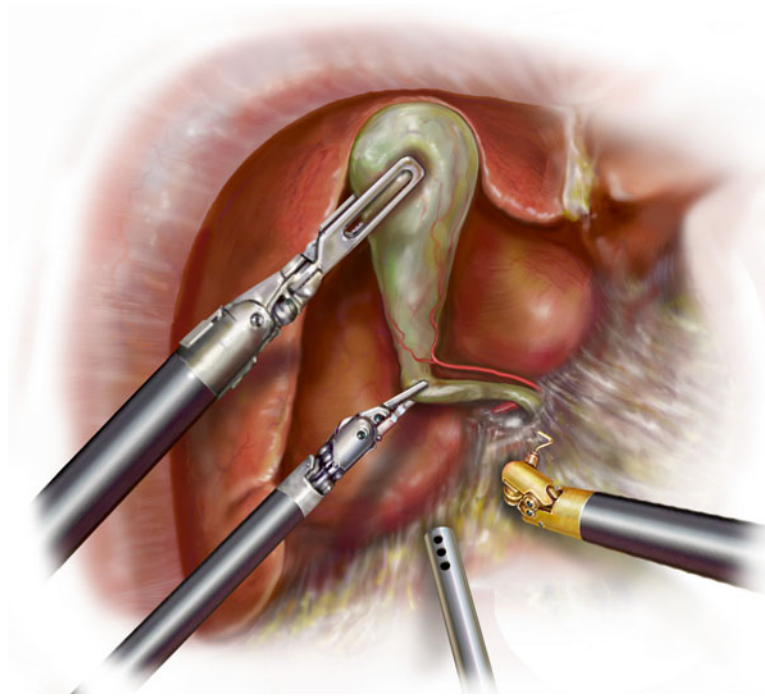

Fig. 9.3 Cholecystectomy, critical view (Used with kind permission from Randal S. McKenzie/ McKenzie Illustrations)

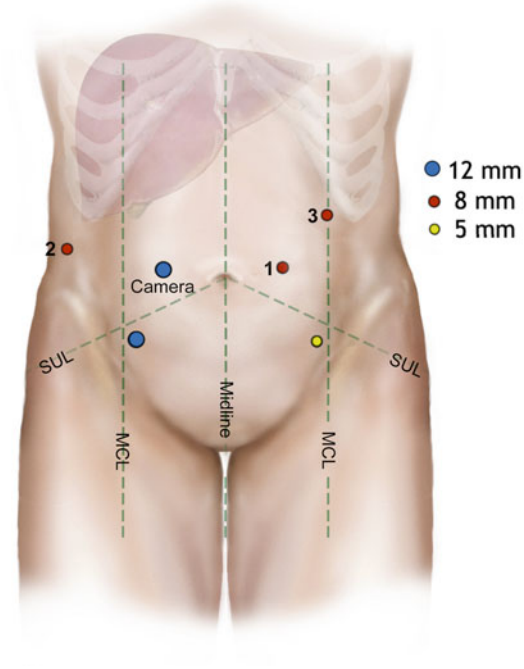

Fig. 9.4 Port placement, right hepatectomy (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

Right Hepatectomy

Access is gained in the left upper quadrant (LUQ) using a 5 mm optical port, and pneumoperitoneum of 12 mm Hg is created. A 5 mm, 30 degree scope is introduced, and additional ports are placed using direct visualization (Fig. 9.4). Additional port sites include a 12 mm port to the right of the umbilicus designated for the camera, a robotic port on the anterior axillary line at the right mid-abdomen, and a robotic port to the left of the umbilicus. A 12 mm assist port (for larger instruments such as the ultrasound and stapler, when necessary) is placed 8–10 cm inferolaterally to the camera port. A 5 mm assist port is placed 8–10 cm inferolaterally to the left abdominal robotic port. The scope is changed to a 10 mm, 30 degree scope and placed in the camera port. The LUQ port is finally changed to a robotic port. The steps for this procedure are as follows (Video 9.2):

Step 1: The round, falciform, and coronary ligaments are divided using a combination of a vessel sealing device and hook cautery (Fig. 9.5),

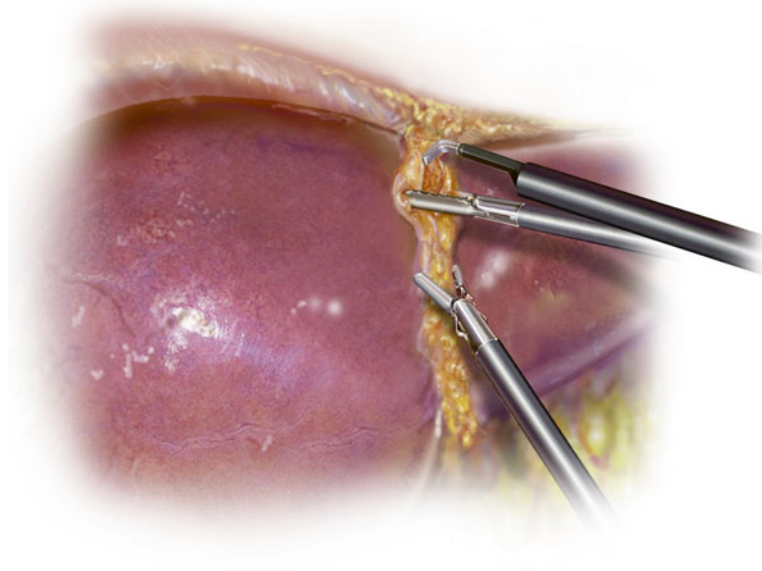

Fig. 9.5 Laparoscopic dissection of falciform ligament (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

exposing the anterior surface of the hepatic veins.

Step 2: The attachments of the right liver are dissected. With the patient's right side up, the gallbladder fundus is retracted superiorly using a grasper through the LUQ port. The right liver is retracted anteriorly using a closed grasper in the right mid-abdominal port. The hepatic flexure is dissected, and the colon is reflected inferiorly. Attachments to the duodenum are dissected from the liver as needed. Using a closed grasper, Gerota's fascia is pushed posteriorly using another closed grasper. A cautery device (vessel sealing device vs. hook) is used to divide the right triangular and coronary ligaments up to the right hepatic vein/inferior vena cava (IVC) (Fig. 9.6).

Step 3: Laparoscopic ultrasound of the liver is performed using the 12 mm assist port to confirm liver anatomy as well as lesion location and resectability.

Step 4: The robot is docked. The camera arm should be aligned with the patient's head. The camera is positioned in the camera port (Fig. 9.4). Arm 1 is positioned in the port to the left of the umbilicus, Arm 2 in the right robotic port, and Arm 3 in the LUQ port.

Step 5: Cholecystectomy and portal dissection. With a grasper in the robotic Arm 3 retracting the fundus of the gallbladder toward the patient's right shoulder, a bipolar grasper in robotic Arm 2 holds lateral retraction on the infundibulum, while a robotic hook in Arm 1 dissects around the cystic artery and duct. After identifying the critical view, the cystic artery and duct are clipped and transected using the 12 mm assist port. The gallbladder is not dissected from the gallbladder fossa until after the portal dissection is complete—the gallbladder helps in retracting the liver during portal dissection. "*It should be noted that this is different from the open technique during which the gallbladder is separated from the gallbladder fossa*". While maintaining anterosuperior retraction of the gallbladder, the porta is exposed. Tissue of the hepatoduodenal ligament is retracted laterally using the bipolar grasper in robotic Arm 2, and the hepatoduodenal ligament is dissected using hook cautery in robotic Arm 1. The right hepatic artery (HA) is next identified and defined (Fig. 9.7). This is stapled using a vascular load, roticulating stapler through the 12 mm assist port if ample space is present. This can alternatively be tied robotically or clipped with the robotic clip

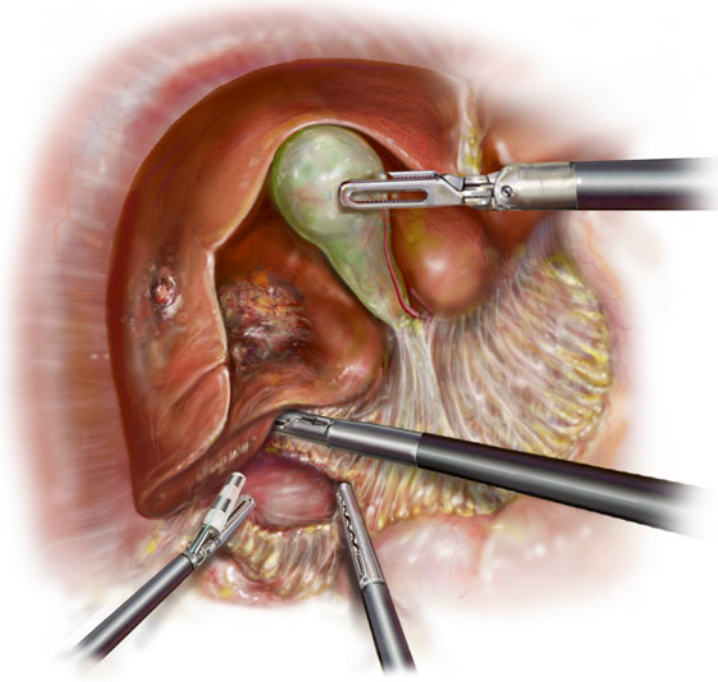

Fig. 9.6 Laparoscopic dissection of the right triangular ligament. The gallbladder is retracted superiorly. A grasper lifts the right liver up while another instrument pushes Gerota's fascia posteriorly, exposing the right triangular ligament (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

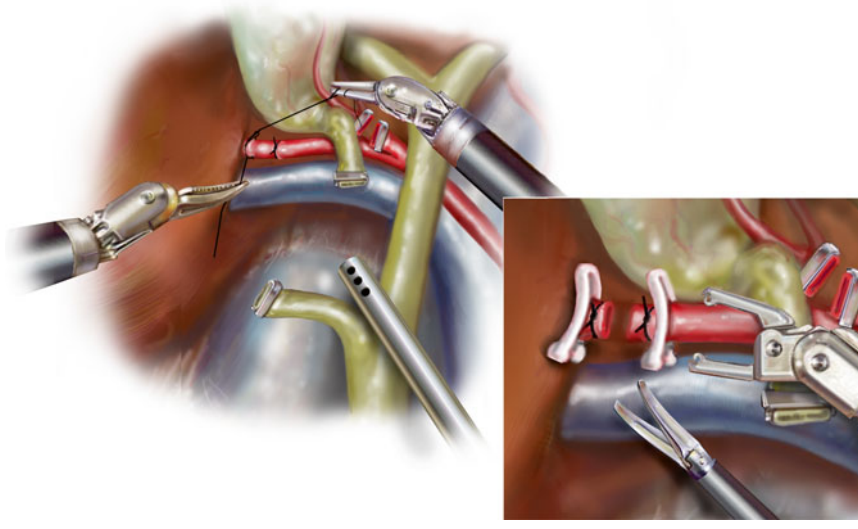

Fig. 9.7 Right hepatic artery dissection and ligation. The artery is tied, clipped, and ligated. Alternatively, a stapler via the 12 mm assist port can be used. Note that exposure is achieved by using a grasper in robotic Arm 3 to grasp the gallbladder fundus and retract it superiorly (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

applier through robotic Arm 1 prior to transection. The right portal vein (PV) is next identified and defined. A silk tie is placed around it but not tied. Robotic Arm 2 retracts this tie superolaterally to expose the length of the vein (Fig. 9.8). A vascular load, roticulating stapler is used to ligate and transect the right PV. The right hepatic duct (HD) is next identified and defined. A robotic dissecting forceps may be more beneficial than the hook if the duct is deep

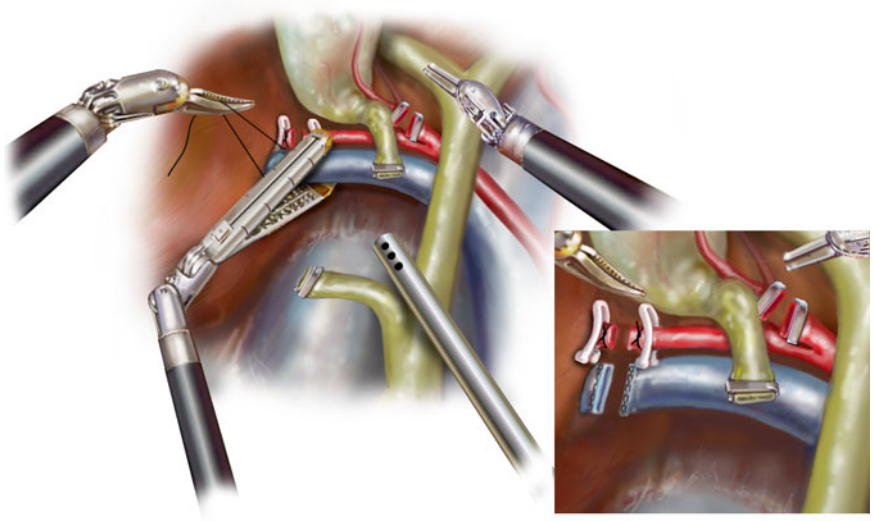

Fig. 9.8 Right portal vein ligation. A silk tie retracts the vein and exposes its full length, allowing room for the stapler (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

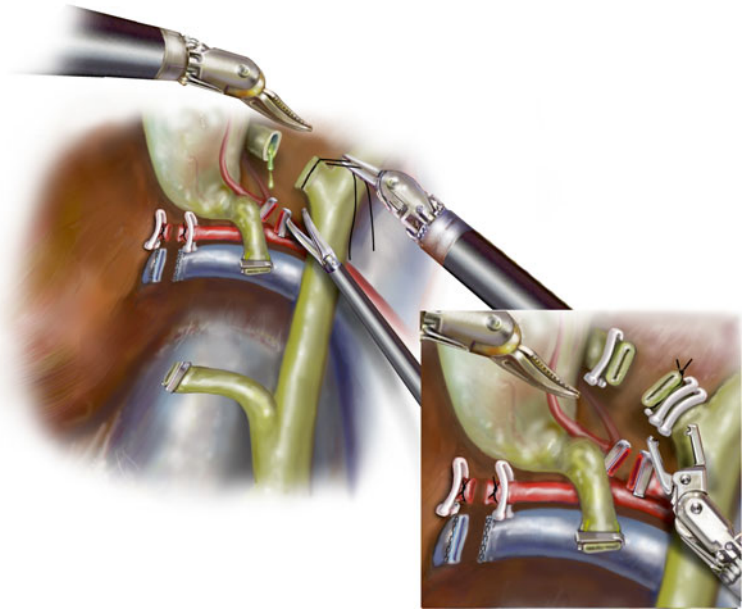

Fig. 9.9 Right hepatic duct division. Bile is identified from the proximal duct after transection. Both ends of the duct are ligated with robotic clips (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

within adjacent tissue. The right HD is tied distally and transected proximally (Fig. 9.9) with the intent to identify bile from the proximal duct. After bile is identified, the proximal duct is clipped to maintain a clean field. The free, distal end of the right HD is doubly clipped to prevent leak. During all of this, instruments through the two assist ports are used to help expose as necessary. After the portal dissection is completed, the gallbladder is dissected from the gallbladder fossa, placed in a laparoscopic bag, and removed from the abdominal cavity.

Step 6: The IVC is dissected. To first expose the IVC, robotic Arm 3 uses a sponge within a

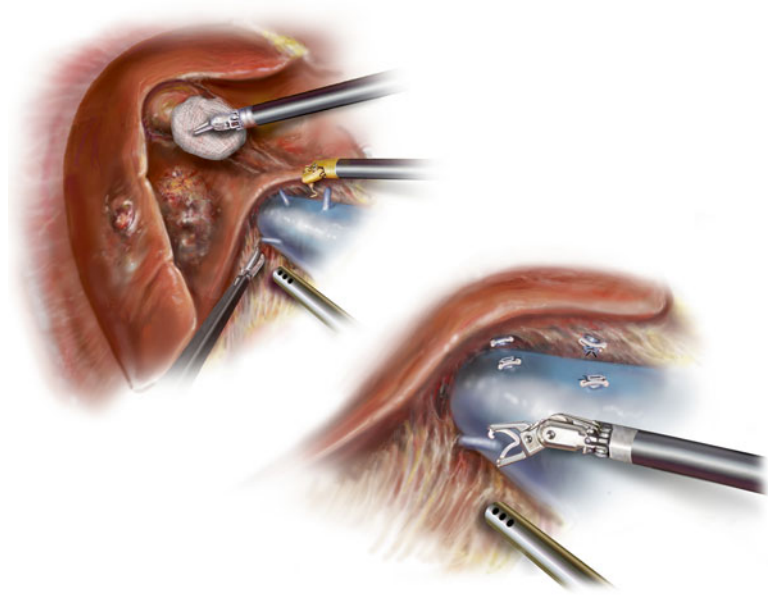

Fig. 9.10 IVC dissection. The gallbladder fossa is gently pushed superiorly using a sponge within a grasper via robotic Arm 3. This exposes the IVC. Suction is used in the 12 mm assist port to push the right kidney posteriorly (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

grasper to push the gallbladder fossa superiorly (Fig. 9.10), and the kidney is pushed posteriorly with a blunt instrument via12 mm assist port. The liver is next mobilized from the IVC. Short hepatic veins are identified and ligated—using a dissector in robotic Arm 2 and cautery in robotic Arm 1, the short hepatic veins are ligated with clips and silk ties, as appropriate. To clip, a robotic clip applier is passed through robotic Arm 1. To tie, a needle driver in robotic Arm 1 is used with a robotic dissector in Arm 2. This is done up to the right hepatic vein (RHV).

Step 7: Liver parenchyma is transected. Following the line of demarcation on the liver's surface, the line of transection is defined using hook cautery. Ultrasonography is repeated to be certain that the pathology will be included within the boundaries of transection. Figure of eight stitches using size 0 absorbable stitches are placed on either side of the line of transection, and these are retracted to either side using robotic ports (Fig. 9.11). The parenchyma is coagulated along the line of transection. Laparoscopic clips are placed on small vessels and ducts when needed. Progress is made until the RHV is encountered. The RHV is stapled intraparenchymally with a vascular load, roticulating stapler through the 12 mm assist port. Any remaining parenchyma is divided.

Step 8: The specimen is collected in a laparoscopic bag. Hemostasis on the liver's resection bed is ensured. The falciform is stitched to the diaphragm. The robot is undocked. The specimen is removed from the abdominal cavity—if necessary, the fascial incision is lengthened.

Step 9: The abdomen is closed. Ports are removed under direct visualization using laparoscopic equipment. Fascia and skin are closed in standard manner.

Left Hepatectomy

Access is gained in the left upper quadrant (LUQ) using a 5 mm optical port, and pneumoperitoneum of 12 mm Hg is created. A 5 mm, 30 degree scope is introduced, and additional ports are placed (Fig. 9.12). Port sites include a supraumbilical, 12 mm camera port; a robotic port to the right subcostal region at the midclavicular line; a left robotic port at the left subcostal region at the anterior axillary line; a 12 mm, right-sided assist port 8–10 cm inferolateral to the camera port; and a 5 mm, left-sided assist port 8–10 cm inferolateral to the camera. The scope is changed to a 10 mm, 30 degree scope and introduced into the camera

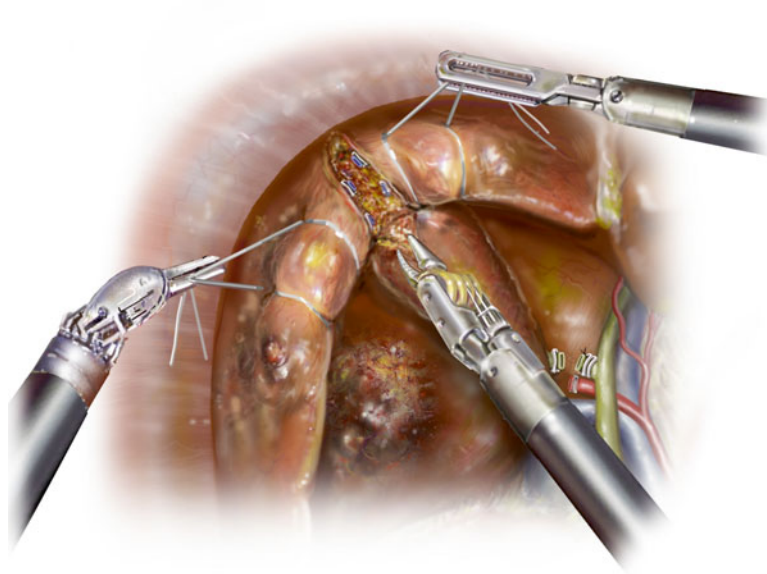

Fig. 9.11 Figure of eight stitches are placed on either side of the line of transection to retract the liver. Liver parenchyma is coagulated along the line of transection, placing clips when appropriate. Progress is made until the right hepatic vein is encountered, and this is stapled intrahepatically (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

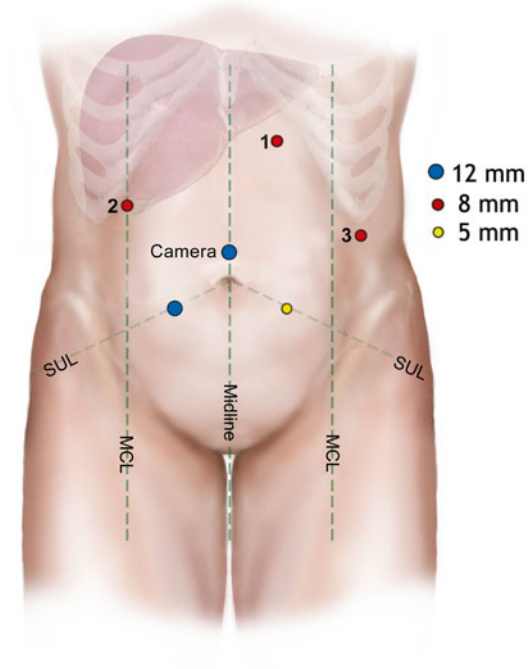

Fig. 9.12 Port placement, left hepatectomy and left lateral sectionectomy (Used with kind permission from Randal S. McKenzie/McKenzie Illustrations)

port. The LUQ port is changed to a robotic port. The steps for this procedure are as follows:

Step 1: The round, falciform, and coronary ligaments are divided using hook cautery. The anterior surface of the hepatic veins is exposed.

Step 2: With the patient's left side up, the ligamentous attachments of the left liver (triangular and coronary ligaments) are dissected up to the left hepatic vein with a cautery device. The left liver is next pushed anteriorly with a closed grasper in the right subcostal port, and the undersurface of the left liver is exposed. The gastrohepatic ligament is divided close to the left lateral segments and caudate lobe using cautery via one of the left-sided ports, while a grasper from the 12 mm assist port performs lateral retraction. If present, a replaced left hepatic artery is isolated and divided at this time.

Step 3: Laparoscopic ultrasound of the liver is performed using the 12 mm assist port to confirm liver anatomy as well as lesion location and resectability.

Step 4: The robot is docked. The camera arm is aligned with the patient's head, and the camera is docked first. Robotic Arm 1 is docked in the left subcostal port, robotic Arm 2 is docked in the right robotic port, and robotic Arm 3 is docked in the left port at the anterior axillary line.

Step 5: Portal dissection. The left liver is retracted anteriorly by a closed grasper in robotic Arm 2. A hook cautery device is used in robotic Arm 1 to dissect and define the left portal structures, and a suction tip or grasper is used in the 12 mm assist port to retract. The left HA is identified and dissected, tied robotically or

clipped with the robotic clip applier via robotic Arm 1, and transected. Next, the left PV is identified. To expose, the liver is retracted anteriorly by grasping and retracting the ligamentum teres via a grasper in robotic Arm 3. This allows a grasping instrument in Arm 2 to retract portal tissue. After defining the left PV, a silk tie is placed around it (this is not tied), and this is retracted superiorly and to the left using a grasper in robotic Arm 1 to expose the full length of the vein. A vascular load, roticulating stapler in the 12 mm assist port ligates and transects the left PV. The left HD is identified and defined with a dissecting forceps in robotic Arm 1, and a grasper is used in robotic Arm 2 for lateral retraction of adjacent portal tissue. The duct is tied distally and transected proximally. Once bile is identified from the proximal duct, the proximal duct can be clipped to maintain a clean field. The free, distal end of the left HD is doubly clipped.

Step 7: Hepatic parenchyma is transected, and the left hepatic vein is controlled intraparenchymally. Following the line of demarcation on the liver surface, the line of transection is defined using hook cautery. Ultrasound of the liver is repeated. Figure of eight stitches using size zero absorbable suture are placed on either side of the line of transection, and these are retracted to either side using robotic ports. Hepatic parenchyma is coagulated and divided, placing laparoscopic clips when appropriate. Progress is made up to the left HV, and this is ligated and transected using a vascular load, roticulating stapler through the 12 mm assist port.

Steps 8 and 9: Same as for right hepatectomy, although the falciform does not need to be stitched to the diaphragm.

Left Lateral Sectionectomy

Port placement and steps 1–4 are similar to left hepatectomy. Then, follow step 5:

Step 5: Parenchymal transection. The line of transection is defined just to the left of the falciform ligament. Ultrasound is repeated. Figure of eight stitches using size zero absorbable stitches are placed on either side of the line of transection, and these are retracted to either side using robotic ports. The parenchyma is coagulated and divided, placing clips when appropriate. A roticulating, vascular load stapler can be used via the 12 mm assist port as defined pedicles for segments II and III are encountered. Alternatively, segment II and III pedicles can be tied and transected as they are encountered. The specimen is collected, and the abdomen is closed as with right and left hepatectomies.

Nonanatomic Resection

Note that guidelines from the Louisville Statement are important to consider for this type of liver resection. Optimal port placement depends on lesion location. Ligamentous attachments are divided as necessary. Laparoscopic ultrasound is performed ensure that the specimen can be removed in its entirety by wedge resection and to help define the edges of resection. The robot is docked. The circumference of resection is defined with hook cautery with the help of the laparoscopic ultrasound. Figure of eight stitches using size zero absorbable suture are placed on at least one side of the line of transection, and these are retracted using a robotic grasper. The parenchyma is coagulated and divided, placing laparoscopic clips when appropriate. The lesion is delivered from the resection bed. The specimen is placed in a specimen bag, hemostasis is ensured, and the specimen is removed. The robot is undocked. Laparoscopic equipment is used to close fascia in standard manner, and ports are removed using direct visualization. Skin is closed.

Summary

Robotic assistance can safely be applied to gallbladder, bile duct, and liver surgery in the appropriate setting. The benefit of robotic surgery may be that it enables the surgeon to perform minimally invasive surgery for more complex procedures and in more challenging anatomic locations. Further investigation into its appropriate role is necessary.

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Essentials and Future Directions of Robotic Pancreatic Surgery

10

Melanie Ongchin, Melissa E. Hogg, Herbert J. Zeh III, and Amer H. Zureikat

Introduction

The past several decades have witnessed a substantial increase in pancreatic procedures. With a growing understanding of pancreatic diseases and the development of better diagnostic studies, pancreatic surgery can now be applied across a wide spectrum of conditions. For example, an increasing number of pancreaticoduodenectomies (PD) are being performed for premalignant pancreatic cysts or cystic neoplasms, pancreatitis or its complications, endocrine tumors, and cancers of the surrounding biliary ductal system or gastrointestinal tract [1]. Surgeries deemed "high risk" due to significant morbidity and mortality have greatly improved with developments in surgical technique, availability of ancillary services and intensive care, and improved diagnostic procedures.

With the increased number of pancreatic surgeries performed, new platforms for performing these procedures have been developed. Although the laparoscopic approach has become an accepted practice across many organ systems with good data supporting equal or superior outcomes to open surgery, laparoscopic pancreatic surgery has not been widely embraced by the majority of surgeons. The limitations experienced with the laparoscopic approach may be overcome with the use of robotic systems. The ability to articulate instruments with 3-D visualization and stability have made robotic surgery an ideal platform for operating on such an unforgiving organ. As with any new technology, its utility and benefits are the subject of rigorous assessment. This chapter focuses on the history, evolution, and outcomes of robotic pancreatic surgery.

This chapter contains video segments that can be found on the following URL:

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History of Robotic Surgery

The word robot was introduced in 1921 by the Czech writer Karel Čapek in his play R.U.R (Rossum's Universal Robots). The plot of this darkly apocalyptic satire concerns a race of factory-produced mechanical workers that look exactly like people, gradually develop human personalities, and, at the end, destroy the human race. At the suggestion of his brother Josef, the playwright called his androids *roboti*, from the Czech *robota* meaning "work, labor, serfdom, drudgery" [2]. Today, robots are used to perform specific, highly complicated, repetitive tasks, used primarily in the fields of industry and engineering. Over time, robots have entered the medical and surgical field and have become more sophisticated and complex with advances in technology. The term "robotic surgery" often has the misconception of a machine performing complex surgery with varying degrees of artificial intelligence. The term robotic surgery is thus a misnomer; "computer assisted surgery" is a better description.

The earliest known surgical robot was the Arthrobot, developed in 1983 in Vancouver to improve surface conformity and accuracy of orientation in total hip arthroplasty. This was followed by the introduction of the Puma 560, a robot used in 1985 by Kwoh to perform neurosurgical biopsies with greater precision [3]. Three years later, Davies et al performed a transurethral resection of the prostate using the Puma 560. This system eventually led to the development of PROBOT, a robot designed specifically for transurethral resection of the prostate. While PROBOT was being developed, Integrated Surgical Supplies Ltd. of Sacramento, CA, was developing ROBODOC®, a robotic system designed to machine the femur with greater precision in hip replacement surgeries [4]. In October 1993, after successful completion of the ten-patient feasibility study, the FDA authorized an expanded program of up to 300 operations (150 with ROBODOC® and 150 in a manual control group). ROBODOC® was installed in two US hospitals, New England Baptist in Boston, MA, and Shadyside in Pittsburgh, PA, in addition to the first at Sutter General [5].

During this time, a group of researchers at the National Air and Space Administration (NASA) Ames Research Center interested in virtual reality used this concept to develop telepresence surgery—a concept that was a driving force behind the development of surgical robots. Computer Motion, Inc. of Santa Barbara, CA, used funds provided by the Army to develop the Automated Endoscopic System for Optimal Positioning (AESOP®), a robotic arm controlled by the surgeon's voice commands to manipulate an endoscopic camera. Integrated Surgical Systems (now Intuitive Surgical, Sunnyvale, CA) licensed the SRI Green Telepresence Surgery system and, after much redesign, reintroduced it as the da Vinci surgical system in 1999. Within a year, Computer Motion put the Zeus system into production [4], and following a merger with Computer Motion Inc. (AESOP® and ZEUS systems) in 2003, Intuitive Surgical has become the sole producer of robotic surgical devices [4, 6].

After initially setting foot in the realm of cardiothoracic surgery with the first robotic-assisted heart bypass in Leipzig, Germany, the use of robotic-assisted surgery in the field of urology started becoming increasingly popular [6]. From the initial description of the first robotic-assisted radical prostatectomy in 2000, it had become widely accepted by urologists, so that by 2008, approximately 80 % of prostatectomies performed in the United States were done robotically [7]. With increasing experience and improvements in surgical technique, intricate aspects of the procedure such as urinary continence and modifications to minimize erectile dysfunction were addressed, resulting in improvements in patients' quality of life. Over time, the application of the robotic platform has extended beyond that in the field of urology, being used by general surgeons, gynecologist, cardiac surgeons, and surgical oncologists.

Evolution of Open and Minimally Invasive Pancreas Surgery

The evolution of pancreatic surgery spans nearly two millennia. Friedrich Wilhelm Wandesleben (1800–1868), a small-town German physician,

performed surgical drainage of a traumatic pancreatic pseudocyst in November 1841. This operation should be acknowledged as the world's first reported operation on the human pancreas [8]. Allen Oldfather Whipple has been deemed the father of North American pancreatic surgery with the first description of pancreaticoduodenectomies in 1935. His two-staged procedure, presented at the American Surgical Association, followed 5 years later by the one-staged procedure laid the foundation for the evolution of pancreatic surgery in America [9]. During the 1960s and 1970s, pancreatic resection, most commonly a PD for carcinoma, was associated with a perioperative mortality rate exceeding 20 % and a considerably higher morbidity rate [10]. However, improved preoperative planning with triphasic CT imaging that allows for a better understanding of the tumors relation to surrounding vasculature and improved nursing and ICU care have all contributed to decreasing the mortality to less than 2 % today at high-volume centers [9, 11, 12].

The evolution of pancreatic surgery over the years has coincided with the recent advances in minimally invasive techniques. With the advent of the first laparoscopic cholecystectomy performed in Böblingen, Germany, by Dr. Med Erich Mühe in 1985, the role of laparoscopy has permeated all fields of surgery [13]. Laparoscopy provides the patient with improved convalescence, decreased pain with smaller incisions, and decreased morbidity as compared to open surgeries. Despite the widespread use of laparoscopic surgery in other aspects of surgery, its acceptance in procedures requiring complex resections and reconstructions has been slow. For example, laparoscopic distal pancreatectomy (LDP) has been performed more frequently than laparoscopic PD (LPD), likely due to the lack of anastomoses and the ability to control major sources of bleeding, if encountered [14, 15]. Its application in PD has been limited to a few skilled surgeons at a small number of high-volume centers despite a nearly two-decade time period since its debut by Gagner and Pomp in 1994 [16–18]. A recent review of 27 LPD papers by Gumbs et al. in 2011 indicated an overall mortality of 2 % and morbidity of 48 % [16], similar to results of open PD, confirming the safety of laparoscopic pancreatic resections in the hands of talented specialized surgeons. However, only 285 cases were included over that time period, reflecting the lack of dissemination of this complex operation. Similarly, in patients with narcotic-dependent, life-limiting pain and failure to thrive, laparoscopic longitudinal pancreaticojejunostomy (Puestow procedure) has been described in two small series by Tantia and Pallanivelu, respectively [19, 20]. Both authors showed that a laparoscopic approach to this procedure is feasible and safe in comparison to the open technique; however, similar to LPD, this complex pancreatic reconstruction is not widely performed, likely due to the limitations of the laparoscopic approach and its difficult adoption.

Robotic Pancreatic Surgery

Since the advent of the robotic platform, the number of robotic procedures has risen exponentially. Its growing popularity has been mostly due to its ability to overcome some of the limitations of the laparoscopic technique. Robotic surgery has several benefits (Table 10.1) with respect to the laparoscopic approach such as the three-dimensional binocular vision and the high number of degrees of freedom, making it more feasible to execute the complex tasks of suturing and dissecting. These factors enable the pancreatic surgeon to adhere to principles of open pancreatic surgery which involves excellent hemostasis through control of

Table 10.1 Advantages of robotic surgery

Advantages of robotic surgery	Disadvantages of robotic surgery
Magnification of 20–30×	Lack of haptic feedback
Elimination of tremor	High start-up cost
Stereotactic binocular vision (3-D vision)	Cost of maintenance
Near 360° range of motion in instruments	Bulky
Improved dexterity	Inability to change patient positioning once docked
Improved ergonomics for the surgeon	Inability to operate in multiple quadrants of the abdomen
Ability to perform micro-anastomoses	Need for additional staff

delicate retroperitoneal vasculature and meticulous suturing technique [15]. We will describe here some of the key robotic procedures and their reported outcomes thus far.

Robotic Pancreaticoduodenectomy (RPD)

At our institution, robotic pancreaticoduodenectomy (RPD) is performed with principles that recapitulate the open approach in regard to technique and oncologic principles. As with any new technique, patient selection is crucial to the appropriate use of any operative platform. Most RPDs are performed by two skilled pancreatic surgeons experienced in open PD and venous reconstructions if needed. Patients with favorable tumors are offered RPD; currently, the only contraindication to performing a PD is vascular abutment (borderline resectable tumors). To this end, patients undergo triphasic CT scanning and EUS prior to any surgical planning since both modalities have been found to be highly useful in predicting which patients can undergo an R0 resection [21].

Our dissection is initially performed laparoscopically through six trocars (Fig. 10.1; Video 10.1). Once the abdomen is insufflated, the laparoscope is inserted to examine for evidence of metastatic disease. If none is evident, the right colon and duodenum are mobilized by the Kocher maneuver. Dissection is continued laparoscopically until the transection of the stomach and jejunum at which point, the robot is docked. The portal structures and retropancreatic tunnel

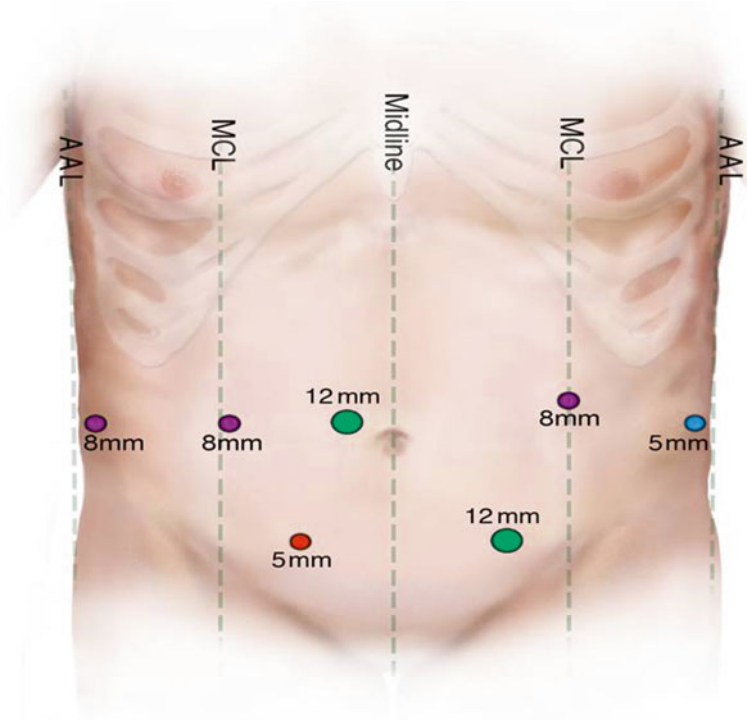

Fig. 10.1 Port site configuration for robotic pancreaticoduodenectomy, central pancreatectomy and total pancreatectomy. *Purple* 8 mm ports are robotic arms 1 (left MCL), 2 (right MCL), and 3 (right AAL). Camera port is 12 mm (*green*) above and to the right of umbilicus. *Blue* port (5 mm left AAL) is for self-retaining liver retractor. Lower ports (*red* 5 mm, *green* 12 mm) are laparoscopic assistant ports. Note that the left lower quadrant 12 mm (*green* port) is the specimen extraction site. For a robotic distal pancreatectomy, and Appleby resection, robotic arm 3 is placed in left AAL (instead of 5 mm blue port), while the right AAL port is used for the self-retaining liver retractor

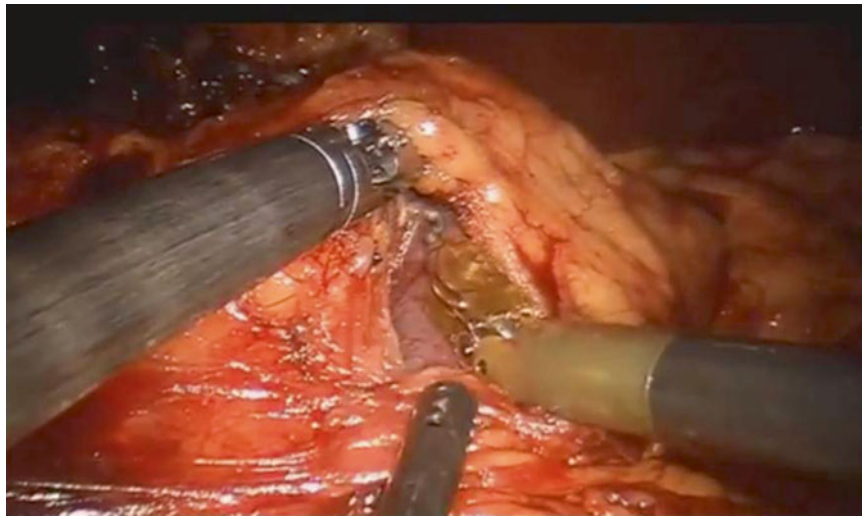

Fig. 10.2 Retropancreatic tunnel. Creation of the tunnel under the pancreatic neck: Careful dissection along the inferior and superior borders of the pancreas allows for the creation of the retropancreatic tunnel in order to carefully divide the pancreas without injury to the mesenteric vessels below

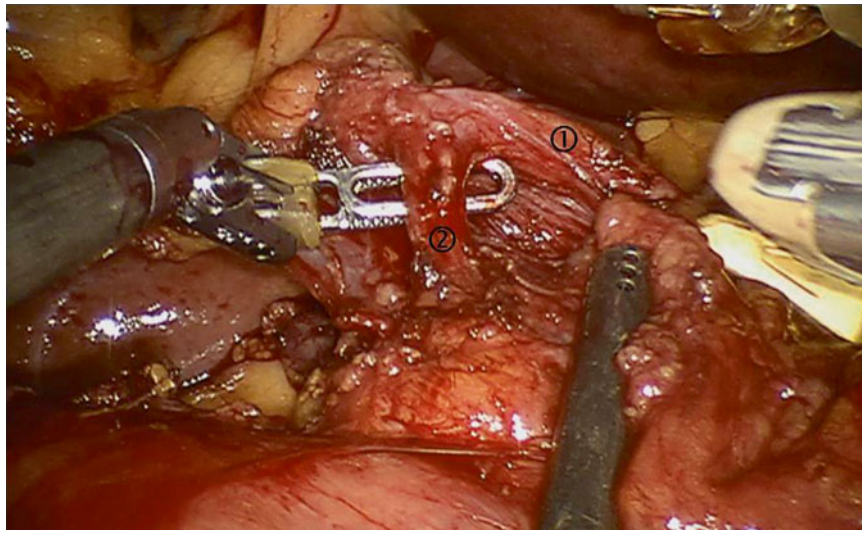

Fig. 10.3 Dividing the gastroduodenal artery: With the increased magnification that can be achieved with the robot, one can carefully dissect around major vasculature. Seen here is the (1) common hepatic artery and (2) gastroduodenal artery which is divided with a vascular stapler (coming in from the left), reinforced with a clip

are dissected and the pancreas transected with electrocautery with "cold" transection of the duct, allowing the surgeon to identify even the smallest duct in a soft/normal gland (Fig. 10.2). One of the benefits of the robotic platform is the high magnification and articulation of the instruments allowing for the thorough and meticulous dissection around major vessels such as the gastroduodenal artery (Fig. 10.3) and the superior and inferior pancreaticoduodenal vessels, which are usually a source of considerable morbidity and bleeding in most pancreaticoduodenectomy series [15]. Once the pancreas is divided, care is taken to dissect the retroperitoneal margin and

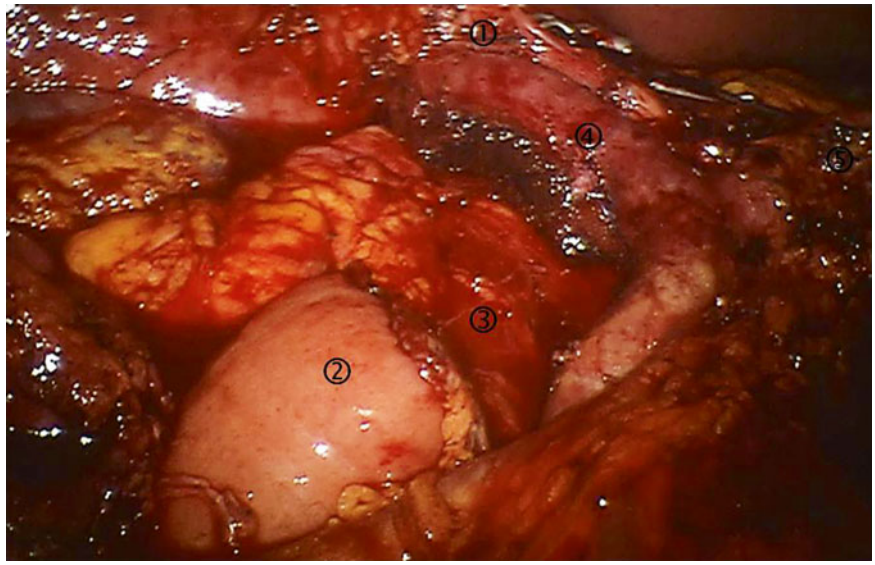

Fig. 10.4 Final resection. This is the final resection bed after the specimen has been removed. The common bile duct (1) and jejunum (2) have been divided with an endoscopic stapling device. One of the benefits of the robotic platform is the high magnification that can be achieved, thereby allowing for delicate dissection around major vasculature such as the inferior vena cava (3) and the portal vein (4)

uncinate process where vessels are divided between silk ties or a LigaSure™ (Covidien AG, Switzerland) or vascular stapler. This type of careful dissection is feasible with the increased magnification and precision of the instrument allowing for an excellent oncologic retroperitoneal margin resection with the removal of all peripancreatic and perivascular tissue on the plane of Leriche (Fig. 10.4). The reconstruction is performed first by a duct-to-mucosa pancreaticojejunostomy using a modified Blumgart technique (Fig. 10.5), followed by a hepaticojejunostomy completed with either an interrupted or running technique depending on the size of the hepatic duct (Fig. 10.6). Finally, the duodenojejunostomy or gastrojejunostomy is performed using a two-layered anastomosis (Fig. 10.7). Patients with unanticipated sidewall involvement of the SMV or portal vein can be resected safely with an R0 resection and fine suturing of the vessel wall (Fig. 10.8) with extreme precision, control, and dexterity.

To date, one of the largest series of open PD was reported by Winter et al from Johns Hopkins in 2006. Their impressive high-volume center published their review of 1432 cases for pancreatic cancer, demonstrating a reliable target for comparison when describing new technology. The authors reported a mean operative time of 380 min for the procedure, a mean blood loss of 800 mL, 58 % R0 resection, and a mean length of stay [22] of 9 days. They described a 5 % pancreatic fistula rate (pre-ISGPF criteria) and a 2 % mortality rate. Outcomes for the RPD have been comparable, with certain parameters even showing superiority to historic series (Table 10.2). Recently, the University of Pittsburgh reported the largest series of RPD. We reviewed our first 250 consecutive robotic pancreatic resections, of which 132 were RPD. This experience has shown that not only is RPD feasible but that it can be safe with a 30- and 90-day mortality of 1.5 % and 3.8 %, respectively. Morbidity remains a considerable factor with any new technology but showed comparable grade 3 and 4 complication rates of 10 % and 11 %, respectively, to the open approach. Interestingly, rates of Clavien-Dindo grades 3–5 complications decreased significantly from 30.7 % to 13.6 % ($p < 0.05$) with improved

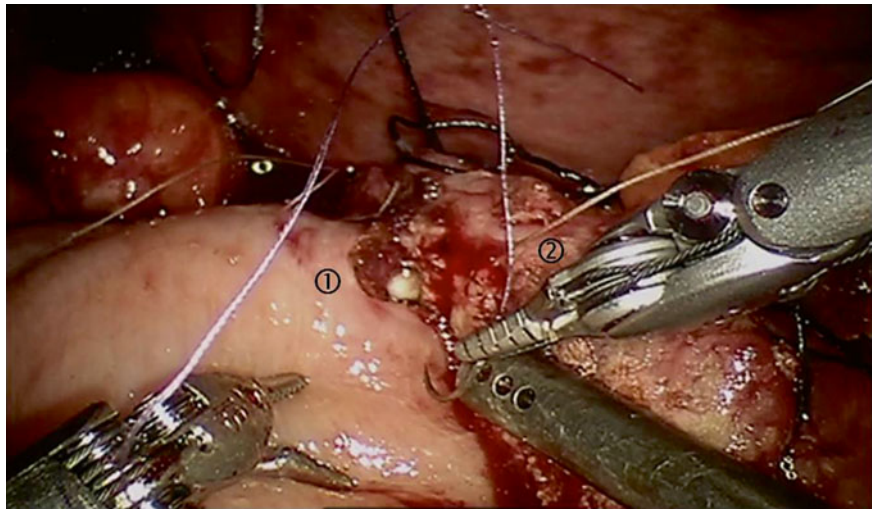

Fig. 10.5 Creating the pancreaticojejunostomy: The pancreaticojejunostomy is created according to the modified Blumgart technique. 2–0 silk horizontal mattress sutures are placed to approximate the seromuscular layer of the jejunum (1) to the pancreatic parenchyma (2). An enterotomy is created in the jejunum with electrocautery, and an interrupted duct-to-mucosa anastomosis is created between the pancreatic duct and the jejunal mucosa using 5–0 Vicryl sutures. A 5–7 French pancreatic stent is placed to ensure duct patency. The final layer is performed with the anterior 2–0 silk stitches

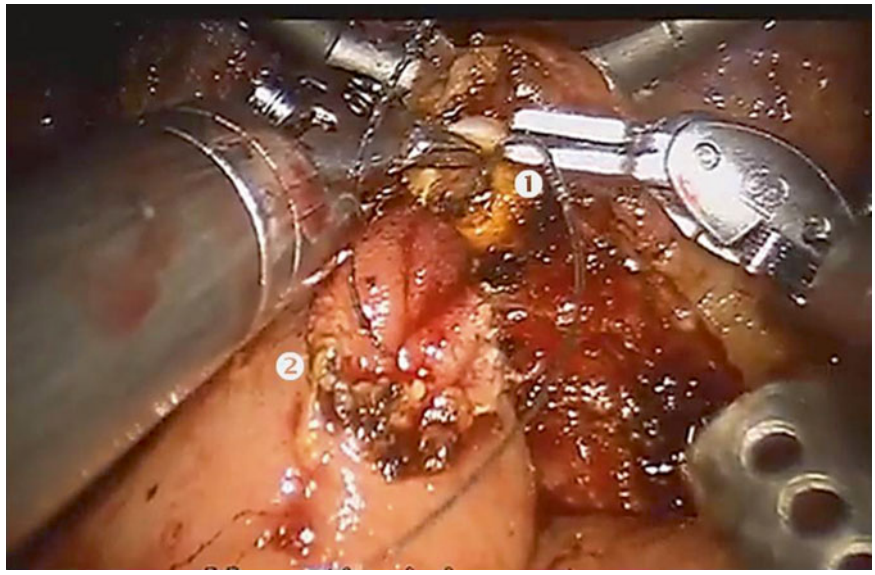

Fig. 10.6 Creating the hepaticojejunostomy: The hepaticojejunostomy is created between the common hepatic duct (1) and jejunum (2). This is performed using absorbable interrupted 5–0 sutures for small ducts or running 4–0 v-LOC for larger, thicker ducts. A stent may be used for small ducts

experience [23]. Median EBL was 300 ml, with a conversion rate of only 8 % (4.5 % in the last 112 cases). Clinically significant pancreatic leak (grade B and C) by ISGPF criteria was 7.4 %, and length of hospital stay was 10 days. The low conversion rate is superior to many early laparoscopic series, and the low EBL is superior to most open series. Because this technique remains in its early stages, no long-term results can be concluded.

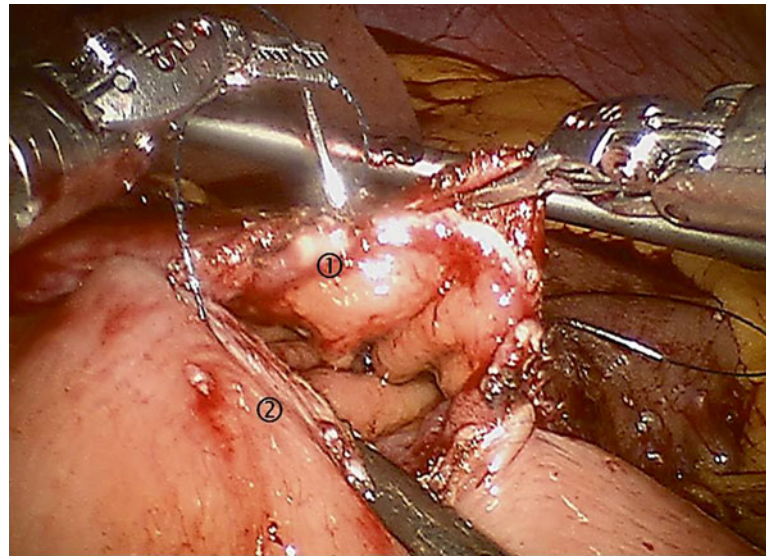

Fig. 10.7 Creating the gastrojejunostomy: The stomach (1) is sutured to the small bowel (2) starting with an outer row of 2–0 silk sutures followed by an inner layer of 3–0 absorbable v- LOC suture in a Connell fashion as seen here. Similar steps are used for creating the duodenojejunostomy in pylorus preserving robotic pancreaticoduodenectomies

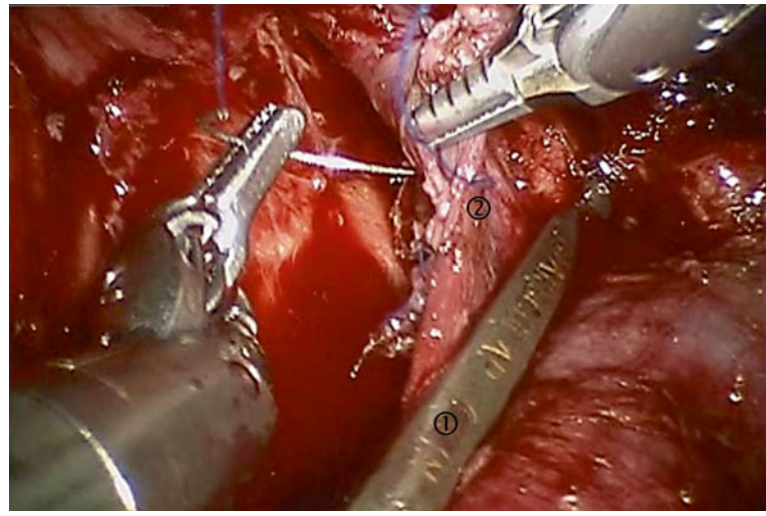

Fig. 10.8 Oversewing the portal vein after resecting an unexpected borderline resectable tumor that was abutting the side of the portal vein. Using the laparoscopic or robotic bulldogs (1), a site bite of the portal vein (2) can be performed safely in order to perform an R0 resection for pancreatic adenocarcinoma. The ability to articulate the instruments allows for suturing this defect in a running fashion using 6–0 Prolene as seen here

Robotic Distal Pancreatectomy (RDP)

Since the first laparoscopic distal pancreatectomy (LDP) was described by Cushieri for chronic pancreatitis disease in 1996 [24], there have been a number of series reporting on minimally invasive DP (Table 10.3). In 2008, a large multi-institution study was performed by Kooby et al evaluating laparoscopic distal pancreatectomy to the open approach in a 3:1 matched comparison [25]. They demonstrated that the laparoscopic approach was associated with a lower blood loss, shorter length of stay, increased splenic preservation, and less overall morbidity without an increase in pancreatic fistula rates. However, without any randomized trials, no definite conclusions can be made regarding the preferred method, though their study is suggestive of the superiority of the minimally invasive approach compared to open in select patients.

Table 10.2 Outcomes of laparoscopic (LPD) and robotic pancreaticoduodenectomy (RDP)

Series	Type	Patients (n)	Time (min)	Conversions (%)	EBL (ml)	Pancreatic fistula (%)	Length of stay (days)	30-day mortality (%)	R0 Resection (%)	Lymph nodes (n)
Dulucq [44]	LPD	25	287	12	107	4	16.2	4	100	18
Pugliese [45]	LPD	19	461	32	180	16	18	0	100	12
Palanivelu [46]	LPD	75	357	0	74	7	8.2	1.3	97.4	14
Kendrick [18]	LPD	65	368	5	240	18	7	1.5	89	15
Zureikat [47]	LPD	14	456	14	300	36	8	7	100	19
Asbun/Stauffer [48]	LPD	53	541	17	195	16.7	8	5.7	94.9	23
Corcione [49]	LPD	22	392	9.1	NR	27.2	NR	4.5	100	NA
Zureikat [23]	RPD	132	527	8	300	17	10	1.5	88	19
Chalikonda [50]	RPD[a]	30	476	10	485	7	9.8	3	100	13
Bao [51]	RPD	28	431	14	100	29	7.4	7	63	15
Buchs [52]	RPD	44	444	4.5	387	18	13	4.5	90.9	16.8
Giulianotti [33]	RPD	50	568	22	394	38	22	8	90	18
Lai [53]	RPD	20	492	5	247	35	13.7	0	73	10

[a]for PDA only

Table 10.3 Outcomes of laparoscopic (LDP) and robotic distal pancreatectomy (RDP)

Series	Type	Patients (n)[a]	Time (min)	Conversions (%)	EBL (ml)	Pancreatic fistula (%)	Length of stay (days)	30-day mortality (n)	R0 (%)	Lymph nodes (n)	Spleen preservation (%)
Fernandez Cruz (27) [54]	LDP	82 (13)	222	NR	370	7	6.5	0	77	14.5	63.4
Jayarman (31) [55]	LDP	107 (16)	193	32	150	16	5	NR	97	6	21
Kooby (34) [25]	LDP	142 (54)	230	20[c]	357	26	5.9	0	93	NR	3
Zureikat [23]	RDP	83 (60)	256	2	150	43	6	0	97	16	NR[b]
Waters (39) [56]	RDP	17	298	2	279	0	4	0	100	5	65
Kang (37, 38) [57]	RDP	20	348	NR	372	NR	7.1	0	NR	NR	95
Daouadi (36) [27]	RDP	30	293	0	212	13	6.1	0	100	18.6	7
Giulianotti (21) [33]	RDP	46	NR	3	NR	9	NR	0	NR	NR	50

ISGPF international study group on pancreatic fistula, *LDP* laparoscopic distal pancreatectomy, *NR* not reported, *RDP* robotic distal pancreatectomy

[a]Figures in brackets are cancer diagnoses

[b]No intent for splenic preservation

[c]20 Cases converted out of 159

These results were supported by the authors at the University of Pittsburgh in 2013 who found that minimally invasive distal pancreatectomy yielded equivalent outcomes compared to open distal pancreatectomies (Magge et al) [26]. This was a retrospective study which compared open distal pancreatectomy to the minimally invasive approach—either laparoscopic or robotic assisted [26]. Specifically, short-term oncologic outcomes—margin negative status and lymph node clearance—were equivalent regardless of surgical technique. Moreover, the minimally invasive group had the added benefit of having a statistically significant shorter hospital stay (6 versus 8 days) and reduced blood loss (290 versus 570 cc) with similarly frequency of postoperative complications. The resulting median overall survival for the entire cohort was 19 months and in an intention-to-treat analysis was not different for the minimally invasive versus open approach.

Our same group compared outcomes of laparoscopic and robotic distal pancreatectomy (RDP) in a retrospective matched comparison. They noted a statistically significant decrease in the conversion rate to open with RDP compared to LDP; 0 % versus 16 %. The authors minimized patient selection bias—in that the easier cases may have been chosen for the newer robotic technique—by relegating the LDP control cohort to a period when robotic surgery was not available. In this comparison, a 35 % margin-positive rate was observed in the LPD group compared to zero in the RDP group which was significantly significant ($p<0.05$), suggesting that the laparoscopic approach may be inferior to the robotic approach in this matched comparison [27]. Laparoscopic and robotic DPs were otherwise equivalent in nearly all other measures of outcome and safety, but the significantly reduced risk of conversion to open despite a statistically greater probability of malignancy in the robotic cohort may suggest superiority in techniques.

At our institution, we have developed a hybrid approach to the robotic-assisted distal pancreatectomy which mirrors that of our RPD technique. Again, we initially start our dissection laparoscopically in order to enter the lesser sac, transect the short gastric arteries, and clear the anterior surface of the pancreas. At this point, the robot is docked and the superior and inferior borders of the pancreas are carefully dissected. Once completed, attention is placed on vascular control by visualizing the splenic vessels early and carefully creating the retropancreatic tunnel in order to divide the neck of the gland. Once completed, the robotic platform enables a complete lymphadenectomy to be performed [15, 27].

Robotic Central Pancreatectomy (RCP)

Central pancreatectomy (CP) has not been as commonly described as compared to DPs or PDs. Central pancreatectomy, also referred to as medial pancreatectomy, is a technique for benign or low-grade malignant neoplasms located to the left of the gastroduodenal artery and close to the splenomesenteric confluence [28]. Open CPs remain high-risk procedures due to the careful dissection around the splenic vessels and the magnified risk of pancreatic fistulas with pancreatic transection at two sites [29]. In addition, indications for this procedure remain rare as lesions in the pancreatic neck that do not require a distal pancreatectomy or an extended pancreaticoduodenectomy are far and few between. However, the potential benefits of decreasing or avoiding the risk of surgically induced diabetes and exocrine insufficiency due to the loss of pancreatic parenchyma for low-grade or benign lesions make the procedure attractive. Nonetheless, despite its rarity, a few papers have been published describing the laparoscopic approach to central pancreatectomy (Table 10.4).

At our institution, the robotic central pancreatectomy (RCP) is carried out similarly to our RDP. The initial dissection is carried out laparoscopically where the lesser sac is entered and the anterior service of the gland is cleared from the head distal to the lesion. Once this is completed, the robot is docked and a tunnel created over the portal vein similar to the RPD. The lesion is resected with an endoscopic stapler on the proximal margin, where the duct is reinforced with a suture ligature (Fig. 10.9). Electrocautery is used

Table 10.4 Outcomes of laparoscopic (LCP) and robotic central pancreatectomy (RCP)

Series	Type	Patients (n)	Time (min)	Conversions (%)	EBL (ml)	Pancreatic Fistulas (%)	Length of stay (days)	30-day mortality (%)	RO Resection (%)	Lymph Nodes (n)	Reconstruction	Endocrine or exocrine insufficiency (%)
Dokmak [29]	LCP	13	190	8 %	100	30.8	24	0	NR	NR	PG	1 (8 %)
Rotellar [58]	LCP	9	435	11.1 %	100	22	13.5	0	NR	NR	PJ	NR
Zhang [59]	LCP	8	286	0	57	12.5	10	0	NR	NR	PJ	0
SaCunha [60]	LCP	6	225	16.7 %	125	33	18	0	NR	NR	PG	0
Zhan	RCP	10	219	0	158	70 (all Grade A)	26.3	0	NR	NR	PG	NR
Abood [30]	RCP	9	425	11.1 %	190	78 (22 % Grade B/C)	10	0	100 %	NR	7 PG, 2 PJ	0
Kang [61]	RCP	5	432	3 completely robotic, 2 hybrid	275	20	14.6	0	NR	NR	PG	NR
Giulianotti [62]	RCP	3	320	0	233	33.3	9–27	0	NR	NR	PG	0

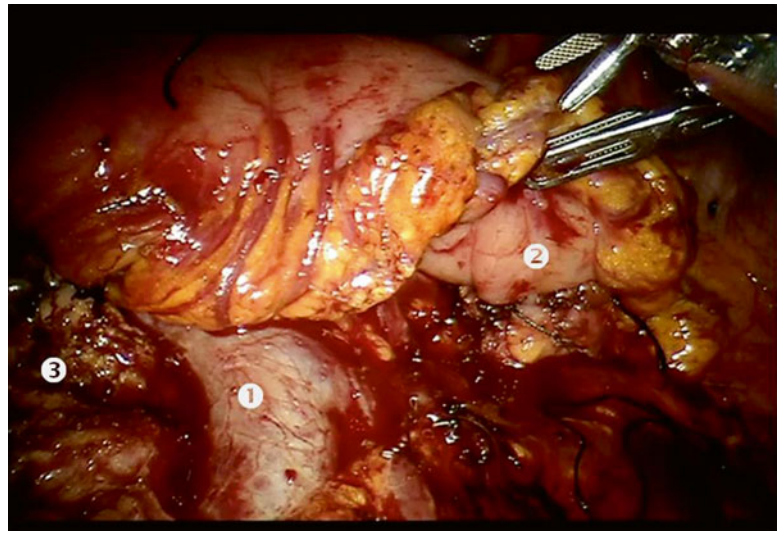

Fig. 10.9 Central pancreatectomy: Central or medial pancreatectomy is feasible with the robotic platform. You can easily see that the pancreas has been divided over the SMV/portal vein confluence (1) and the distal end of the pancreas has been anastomosed to the stomach via an end to side pancreaticogastrostomy (2). The proximal end of the pancreas is visualized (3)

on the distal margin with care to avoid thermal injury to the duct. Finally, the reconstruction is created via a pancreaticogastrostomy or pancreaticojejunostomy using a modified Blumgart technique [15, 30].

To date, Abood [30] and Zhan [31] provide the largest single institution series of RCP with 9 and 10 cases, respectively. They showed that RCP can be performed safely with similar oncologic outcomes to open procedures. In Abood's series, the median estimated blood loss was 190 mL, operative time was 425 min, and LOS was 10 days. Pancreatic fistula rate, according to strict ISGPF guidelines, was 78 % (seven of nine patients); however, only 22 % (two patients) were clinically significant with a grade B or C leak, both of which resolved nonoperatively. This mirrors pancreatic fistula rates published in other minimally invasive and open central pancreatectomy reports. For Zhan, the estimated blood loss was 158 mL, operative time was 219 min, and LOS was 26.3 days [31]. Their pancreatic fistula rate was 70 %, most of which were grade A fistulas that were managed conservatively. Overall, RCP did not show inferiority in regard to outcomes; however, it was noted that the operative time was longer than open approaches in patients whose reconstruction was via a Roux-en-Y pancreaticojejunostomy versus a pancreaticogastrostomy.

Ultimately, the rationale for central pancreatectomy is to preserve pancreatic parenchyma to decrease the risk of diabetes and exocrine insufficiency, which not only contributes to postoperative morbidity but affects patient quality of life. It has been shown in a recent study by Park that after excluding patients with preoperative diabetes, over half of the patients had endocrine insufficiency at 6 months after pancreatectomy, be it development of diabetes or impaired fasting glucose, with only modest improvement at 12 months postoperatively [32]. The rate of diabetes after distal pancreatectomy was 8 % in a series of 235 distal pancreatectomies with a 0 % rate of exocrine insufficiency [28]. In Abood's series, no euglycemic patients required insulin upon discharge or at the 30-day postoperative visit. None of the three preoperatively known noninsulin-dependent diabetics required escalation of their oral hyperglycemic medications at discharge or at the 30-day visit. Finally, none of the patients presented with clinical criteria for exocrine insufficiency, consistent with reports of exocrine insufficiency following central pancreatectomy ranging from 0 % to 8 % [28, 30]. From this study, central pancreatectomy can be safely performed robotically with similar outcomes to the open technique with the added long-term benefits of avoiding surgically induced diabetes and exocrine insufficiency though a minimally invasive approach.

Other Robotic Pancreatic Procedures

With increasing experience with the robotic platform, its use has been applied to other facets of pancreatic surgery. Both Zureikat [23] and Giulianotti [33] described the feasibility of performing lateral pancreaticojejunostomy for chronic pancreatitis with minimal complication, albeit with small numbers in each series (3 and 1, respectively). In regard to complications of pancreatitis leading to pancreatic necrosis, drainage procedures such as cystogastrostomy (Fig. 10.10) and cystjejunostomy are achievable with the robotic approach as well [33].

Robotic pancreatic enucleations have been reported for small NETs and premalignant lesions, such as IPMN. The authors reported one of the largest series of pancreatic enucleation on ten patients confirming its safety and feasibility [23]. The high resolution and dexterity afforded by the robotic platform enables the surgeon to carefully dissect around major vasculature to enucleate small pancreatic lesions, thus sparing pancreatic parenchyma and reducing morbidity. The added benefit of being able to identify the pancreatic duct by real-time ultrasound while performing the enucleation probably helps to reduce pancreatic duct leak. More complex pancreatic resections, such as the Appleby resection and total pancreatectomy with auto islet transplantation, have also been described in the literature, albeit with small numbers. This confirms the expansive array of complex pancreatic operations which can be performed using the robotic platform

Potential Benefits of Robotic-Assisted Pancreatic Surgery

Similar to laparoscopic surgery, one of the advantages of robotic-assisted surgery is the potential to reduce wound infection, a major source of morbidity after pancreatic operations. Since pancreatic cancer survival depends on the adjunct of chemotherapy [34], emerging data suggests that more robotic PD patients can receive chemotherapy compared to their open counterparts (abstract presented at SSO 2014). Similarly decreased blood loss has been shown as an important factor that

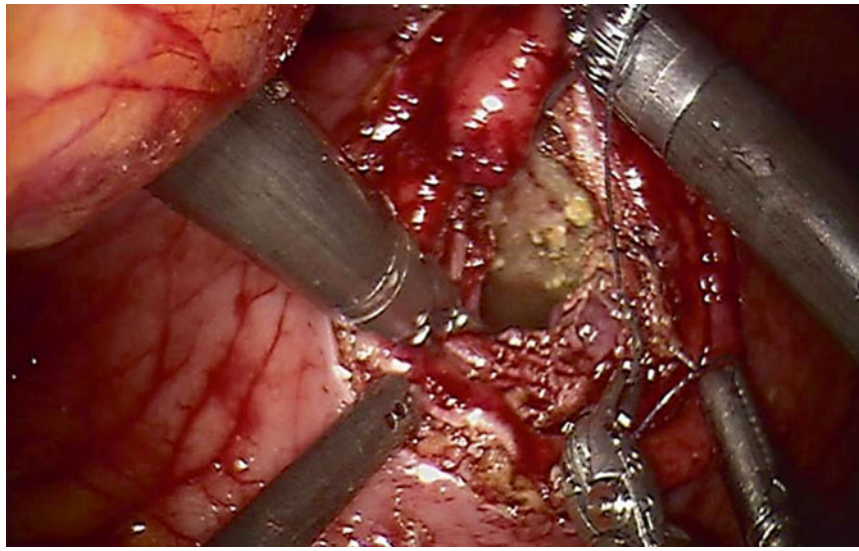

Fig. 10.10 Cystogastrostomy. Robotic surgery for benign pancreatic disease: Robotic surgery can be applied to both benign and malignant pancreatic disease processes. Here, a cystogastrostomy can be performed by suturing the wall of the pancreatic cyst to the posterior wall of the stomach. The anterior wall of the stomach is then closed in a running fashion followed by a layer of Lembert sutures

favorably influences survival after PDA resection [35]. It is likely that a combination of the above outcomes may ultimately yield a survival benefit for patients undergoing robotic pancreatic surgery in larger series with sufficient follow-up.

With advancements and increased use of cross-sectional imaging and EUS, coupled with the improved ability to identify dangerous mucinous precursors of pancreatic adenocarcinoma, robotic surgery may find a niche in the resections of premalignant pancreatic lesions. The availability of a minimally invasive approach with equivalent or superior recovery times might alter the risk/benefit ratio of pancreatectomy in favor of earlier intervention and improve patient acceptance of "prophylactic surgery" [36].

Lastly, surgeon ergonomics and comfort may well be an important decisive factor favoring robotics. Lee et al compared the postural and mental stresses of performing simulated surgical tasks with 13 novice medical students and residents using a Zeus surgical robotic system versus the laparoscopic surgical platform. They showed that while mental stress occurred at similar levels, physical stress worsened with laparoscopic surgery as laparoscopy caused more awkward upper body movements, thus increasing the potential risk of musculoskeletal injury compared with robotic surgery [37]. Further studies have shown a decrease in physical and cognitive ergonomics with the robotic platform as compared to laparoscopy due to the features of the robotic console [38]. For high-volume minimally invasive surgeons, the added benefit of comfort aids in decreasing surgeon fatigue and improving overall well-being.

Limitations and Criticisms of Robotic-Assisted Pancreatic Surgery

The most significant drawback to the robotic platform is the inability to operate in multiple quadrants of the abdomen (Table 10.1). The size and positioning of the robotic arms lead to frequent collisions between the them [36]. Because of this, careful planning is necessary before any incisions are made to ensure that the robotic ports are placed in a configuration that minimizes arm collision. This is compounded by the fact that once the robot is docked, the position of the table cannot be changed, thereby limiting the benefits of gravity in serving to retract organs. This is overcome by starting out most pancreatic resections laparoscopically for the early mobilization phases of any robotic operation.

One of the largest criticisms of the robotic platform remains the lack of haptic feedback. However, this is compensated for with improved magnification and the eventual reliance on visual cues for feedback. Though this does require experience, the learning curve for the robot is steep and allows the pancreatic surgeon to rapidly acquire the skills necessary to perform complex dissection and fine suturing [36].

Ultimately, one of the main criticisms of the robotic platform has been the cost of the console, equipment, and maintenance fees, as well as the increased operative time [39]. With increasing experience, operative times can be greatly decreased and are equivalent to, if not shorter than, laparoscopic equivalents [23]. Additionally, the overall cost of robotic surgery may eventually be balanced by a decrease in length of stay, morbidity, and readmissions costs. No studies have been conducted to determine the cost-effectiveness of the robotic platform over open or laparoscopic and further research will need to be conducted.

Future Directions

The robot platform has undergone numerous changes and configurations, addressing surgeon needs and surgical limitations met. Improved maneuverability and increased working space are two areas under investigation with the newer generation systems. As with laparoscopic surgery, the idea of "single incision" or "single access" minimally invasive surgery has permeated to the robotic realm and may enable large, complex surgery to be performed through one small incision [39]. Slimmer robotic arms will also help overall maneuverability and aid in avoiding collisions. Robotic stapling devices are now available,

which will be useful in obtaining control of large venous and arterial tributaries and will avoid the need to use the limited access from the assistant port [36].

In regard to the visual aids to the surgeon, the use of real-time integrated imaging in the robotic console will soon be possible so that the surgeon will be able to use virtual reality scenarios to superimpose the preoperative imaging with the real-time intraoperative views [36]. Additionally, Intuitive Surgical has developed a new tool named the Firefly® Fluorescence Imaging System [39]. By switching from conventional white light to fluorescence mode, critical anatomical structures such as bile ducts or vessels can be made visible by toggling light sources, thereby leading to safer surgery and avoiding inadvertent injury [36, 39].

Regarding surgical education and safe dissemination, simulation courses and training sessions are being developed to aid in robotic training to help decrease the learning curve needed to achieve competency. Various training forums have been developed, from dry labs to simulation to video-based tutorials. One recent study documented the face, content, construct, and concurrent validity of three dry lab exercises for robotic training. Expert surgeons found the featured dry lab exercises to be realistic and useful for training residents [40]. Virtual reality simulation programs, such as the da Vinci Skills Simulator, are sophisticated and efficacious adjuncts to surgical training residencies. Despite being in their infancy, studies have shown that they improve technical performance in urology and gynecology [41–43]. With increasing popularity in the surgical fields, alternative training methods are becoming more prevalent in residency and fellowship programs to aid trainees develop the skills necessary to perform complex robotic procedures.

Conclusion

The field of pancreatic surgery has undergone vast changes from the first surgery performed by Wandesleben in 1841 to the sophisticated minimally invasive pancreaticoduodenectomy today. A technology that remains in its infancy, robotic pancreatic surgery requires further research to look into the long-term benefits of the platform as compared to its open or laparoscopic equivalents. Despite this, many institutions have embraced the advantages of the robot, showing that it is a safe and effective platform for which to approach a wide range of pancreatic procedures.

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Essentials and Future Directions of Robotic Endocrine Surgery

11

Ryaz Chagpar and Eren Berber

Introduction

Since the first case series from Europe detailing the feasibility of robotic general surgery more than a decade ago, there has been a growing expansion in the number of indications for various general surgical procedures and increasing adoption of the robotic platform among surgeons from a variety of subspecialties, including endocrine surgery [1–3].

As value-based health care has now become a dominant feature in the practice of medicine, further development of robotic endocrine surgery may be limited unless improved quality in terms of clinical and patient based outcomes can be used to justify the generally higher costs of this technology.

This chapter aims to review the current indications and techniques for robotic adrenalectomy, thyroidectomy, and parathyroidectomy, with an emphasis on variation in clinical and patient-reported outcomes relative to traditional surgical approaches.

This chapter contains video segments that can be found on the following URL:

Electronic supplementary material Supplementary material is available in the online version of this chapter at 10.1007/978-3-319-09564-6_11. Videos can also be accessed at http://www.springerimages.com/videos/978-3-319-09563-9.

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Robotic Adrenalectomy

The first laparoscopic adrenalectomy was described by Gagner et al. in 1992 and has now become the standard technique for resection of benign functional and nonfunctional tumors [4]. Several non-randomized studies have demonstrated the superiority of both laparoscopic and retroperitoneoscopic approaches over traditional open surgery in terms of morbidity and costs with similar overall efficacy [5–7].

The potential benefits of the robotic platform over conventional laparoscopy for resection of a small deep-seated organ such as the adrenal gland, both in terms of visualization of the operative field with three-dimensional optics and more precise, less cumbersome dissection with tremor-minimizing wristed instruments, were recognized early with the first da Vinci® (Intuitive Surgical) robotic-assisted adrenalectomy being performed in 2001 by Horgan et al. using a lateral transabdominal approach [8].

Indications

The current indications for robotic adrenalectomy are identical to those for the laparoscopic approach and include all benign functional adrenal tumors, benign nonfunctional tumors ≥4 cm, or those demonstrating significant growth on follow-up CT scan, as well as adrenal metastases in selected patients with soft-tissue or solid-organ

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primary tumors, usually in the setting of mono- or oligometastatic disease [9–11]. Lesions that are highly suspicious for adrenocortical cancer based on preoperative clinical, biochemical, and imaging findings should likely be initially managed through an open technique. [12–14] If there is intraoperative evidence suggestive of gross extra-adrenal invasion during a robotic-assisted adrenalectomy, early conversion to an open approach prior to any significant dissection seems the most prudent course of action, so that an oncologically sound procedure consisting of en bloc resection of the tumor, regional lymphadenectomy, and removal of contiguously involved organs can be effectively performed.

Lateral Transperitoneal and Posterior Retroperitoneal Approaches: General Considerations

Currently, robotic adrenalectomy is commonly carried out through either a lateral transperitoneal or posterior retroperitoneal approach. Patient selection for a particular technique should involve consideration of the underlying endocrinopathy, body habitus, tumor bilaterality, and the type and extent of previous surgery.

The advantages of posterior retroperitoneal adrenalectomy (PRA) over the traditional lateral transperitoneal adrenalectomy (LTA) are being increasingly recognized for a select group of patients, particularly those with previous intra-abdominal surgery, as adhesiolysis and manipulation of other intraperitoneal viscera are minimized [15]. In addition, patients with limited central obesity secondary to Cushing's syndrome may also benefit, as abdominal fat tends to fall away from the operative site when the patient is positioned prone. Finally, robotic PRA can result in shorter operative times relative to LTA for patients requiring bilateral adrenalectomies, given the ability to surgically access both glands without repositioning the patient [16]. The posterior approach, however, may not be suitable for patients with larger tumors (e.g., >6 cm), given the relatively limited confines of the retroperitoneal space and heightened risk of malignancy. Similarly, patients in whom access to the retroperitoneum may be impaired, such as those with a small space between the 12th rib and iliac crest (>4 cm), or with a long distance between the skin and Gerota's fascia (>7 cm), should also be considered for an alternative approach [17, 18]. The larger working space and more familiar landmarks associated with the LTA make it ideal for larger, unilateral tumors, in which there is a small retroperitoneal space or previous retroperitoneal kidney surgery. It may also be less cumbersome in the event that conversion to an open transperitoneal approach is required.

Techniques

Lateral Transperitoneal Approach

The patient is placed in left or right lateral decubitus position dependent on the location of the mass (Video 11.1). Four trocars are commonly used, with placement essentially as for laparoscopic adrenalectomy (Fig. 11.1). A 12 mm optical trocar is introduced halfway between the umbilicus and the costal margin, and after achieving sufficient CO_2 pneumoperitoneum, an additional 12 mm trocar and two 8 mm trocars are placed along the costal margin. For left adrenalectomy, the splenocolic and splenorenal ligaments are divided. If needed, the remaining lateral attachments to the spleen are divided, and the spleen and tail of pancreas are reflected medially. For right adrenalectomy, the right triangular ligament is divided to elevate the right hepatic lobe. We prefer to carry out the splenic/hepatic mobilization laparoscopically, followed by intraoperative ultrasound to determine the location of the adrenal gland relative to major surrounding structures and as an additional assessment for any obvious extra-adrenal invasion. The robot is subsequently docked, approaching the patient from behind the ipsilateral shoulder, usually at a 45° angle with the table. If needed, the table can be moved clockwise so as to match the angle of dissection with the docking of the robot. Cadiere forceps are used from the left port and the robotic Harmonic scalpel from the right port (Fig. 11.2). Dissection proceeds initially along the superior

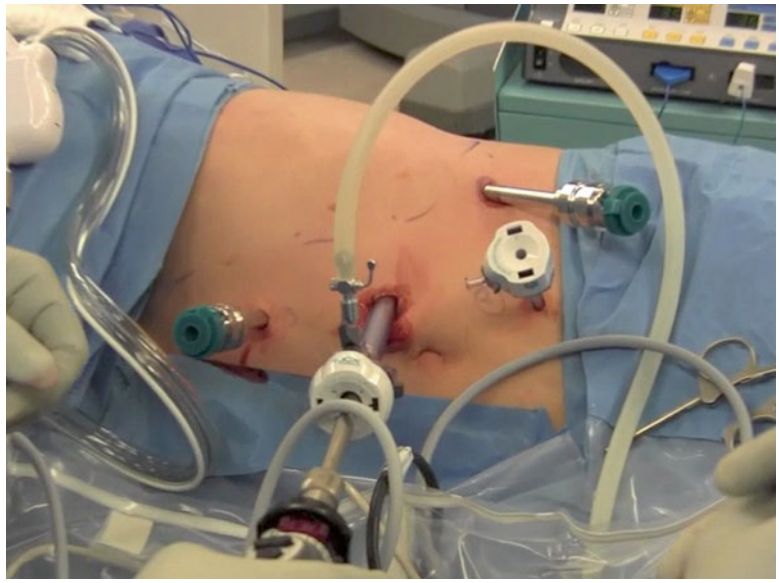

Fig. 11.1 Port placement for robotic lateral transabdominal adrenalectomy

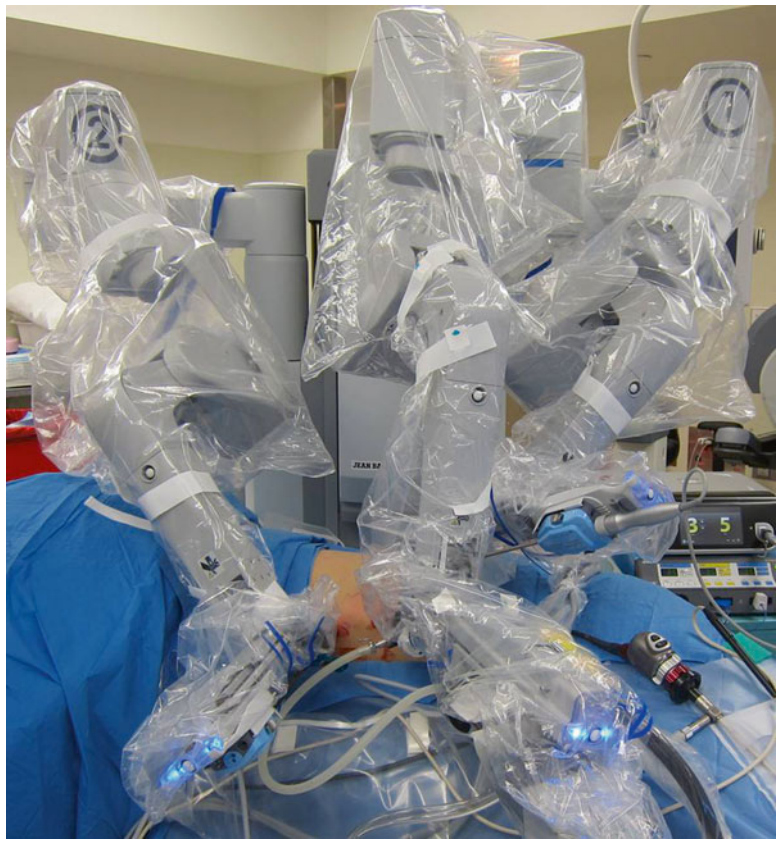

Fig. 11.2 Docking and instrumentation for lateral transabdominal adrenalectomy

and lateral borders of the adrenal gland, followed by the inferior and medial aspects. The adrenal vein is taken using the Harmonic scalpel if small (<4 mm) or divided between metallic clips placed by the first assistant if larger. After the adrenalectomy is complete, the robot is undocked, and the gland is removed using a specimen retrieval bag. Morcellation may be required if the specimen is large (e.g., >3 cm). Hemostasis is achieved laparoscopically and confirmed after desufflation and reinsufflation. Fascia is closed for both 12 mm port sites.

Posterior Retroperitoneal Approach

After establishment of general anesthesia, the patient is placed in a prone jackknife position using a Wilson frame, with both arms placed on boards situated at the head of the table and directed toward the anesthetist (Fig. 11.3) (Video 11.2). Transcutaneous ultrasound is then used to assess the position of the kidney, adrenal gland, and 12th rib to determine optimal port placement, which is an especially important component of successful PRA. An optical trocar is placed through a 1 cm incision made 2 cm inferior to the 12th rib in order to gain access to Gerota's space. The trocar is then replaced with a dissecting balloon to create a potential space under direct visualization. The dissecting balloon is then removed, and a 12 mm trocar is then introduced into this space with subsequent retroperitoneal insufflation to approximately 15 mmHg of CO_2. Two additional 5 mm ports are then inserted, one placed medially along the lateral border of the paraspinous muscles and the other laterally, inferior to the 11th rib. It is important to ensure that these 5 mm ports are as far as possible from the initial 12 mm port in order to avoid instrument collision (Fig. 11.4). Laparoscopic ultrasound is subsequently performed similar to the LTA technique, prior to docking of the robot (Fig. 11.5). Cadiere forceps are used via the lateral port and the Harmonic scalpel used from the medial port. Identifiable landmarks subsequent to the development of the retroperitoneal space and intraoperative ultrasound should include Gerota's fascia, the superior pole of the kidney, paraspinous muscles medially, peritoneum anterolaterally, diaphragm superolaterally, the inferior vena cava on the right, and the adrenal gland itself. Again, the superior and lateral aspects of the gland are initially dissected, with the inferior and medial borders being dissected last. Suction and irrigation as well as clipping of the adrenal vein when too large to be taken with the Harmonic scalpel can be performed by the first assistant through the medial port after temporary removal of the Harmonic scalpel. The robot is undocked after

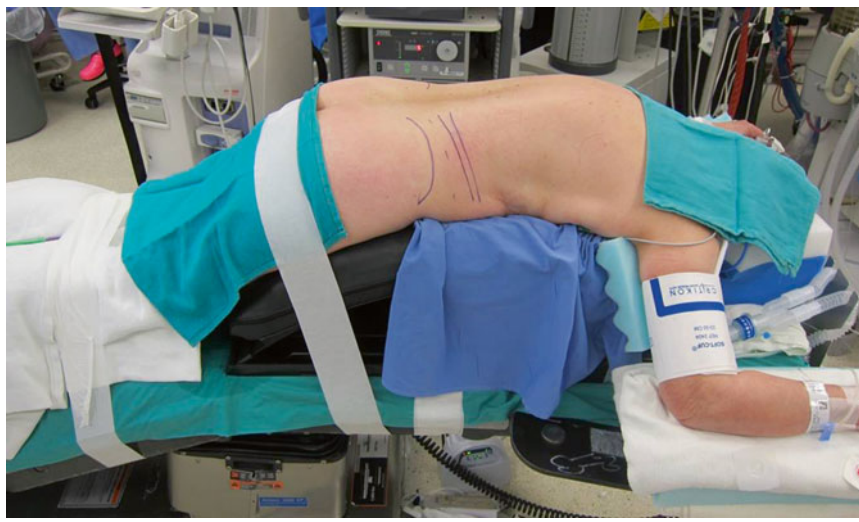

Fig. 11.3 Positioning for robotic posterior retroperitoneal adrenalectomy

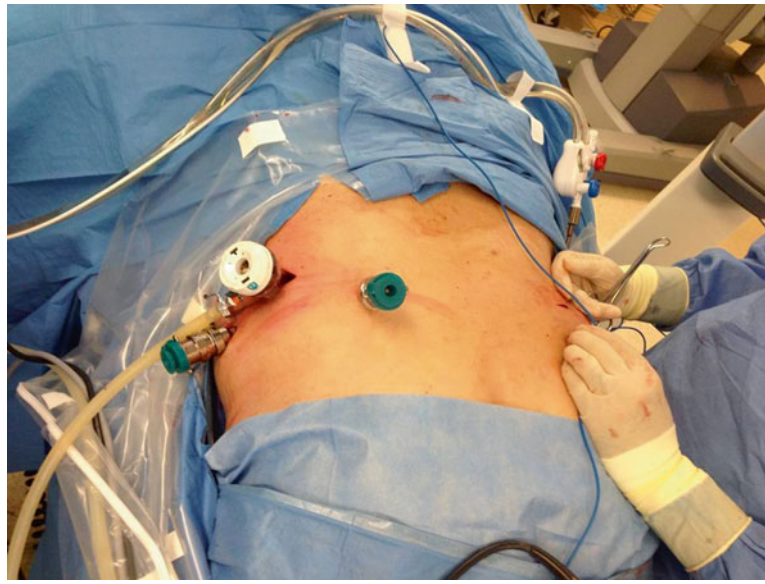

Fig. 11.4 Port placement for robotic posterior retroperitoneal adrenalectomy

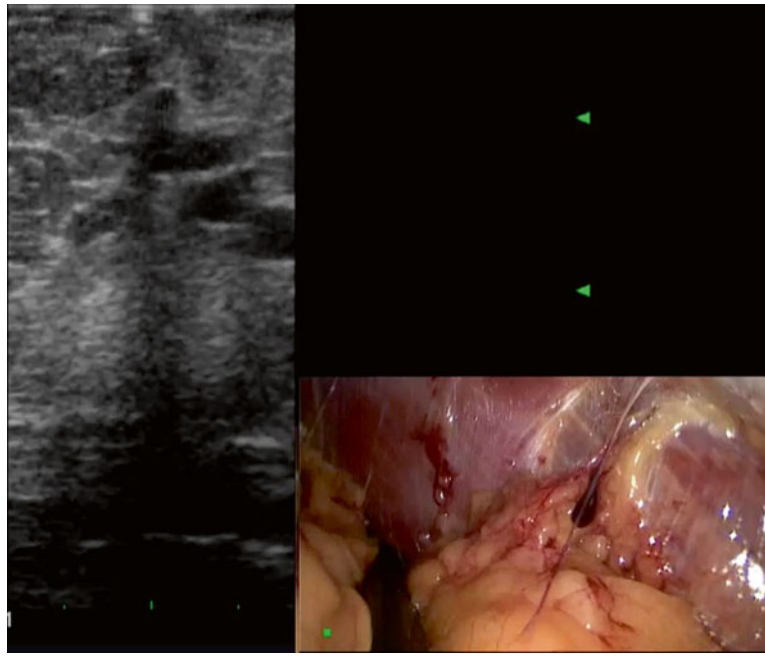

Fig. 11.5 Laparoscopic ultrasound is used to confirm adrenal location relative to surrounding structures

the dissection is complete, and the specimen removed with an endoscopic retrieval bag. Hemostasis is achieved at low insufflation pressures and confirmed after desufflation and reinsufflation. Fascia is closed for the 12 mm port site. It should be noted that the above technique differs slightly from that described by Ludwig et al., in which one of the arms is tucked, 8 mm ports are placed, and higher initial insufflation pressures are utilized [19]. Also, Ludwig's

approach involves initial dissection of the inferior and medial borders of the gland with early identification and division of the adrenal vein, leaving the anterior (peritoneal) and superolateral (diaphragmatic) attachments until the end.

Outcomes

The superiority of endoscopic over open approaches to adrenalectomy in terms of both morbidity and costs has been well established [5–7]. Although some retrospective studies suggest shorter operative times associated with the posterior retroperitoneoscopic over the lateral transperitoneoscopic approach, two small randomized controlled trials have demonstrated statistical equivalence between these two major endoscopic techniques for adrenalectomy in terms of operative time, complication rates, and hospital stay [20–24]. A cost analysis conducted at the Cleveland Clinic also suggests no significant difference in overall cost between the various endoscopic techniques. [6]

While robotic adrenalectomy offers potential advantages to the surgeon in terms of visualization, stability, and precision of dissection, it is also associated with additional initial costs, a learning curve, and potentially increased operating times which may detract from widespread adoption.

In 2004, Morino et al. published the first randomized trial comparing laparoscopic to robotic adrenalectomy using a lateral transperitoneal approach [25]. Twenty patients with benign adrenal lesions were randomized to each arm with exclusion criteria including bilateral lesions and tumors > 10 cm. From this early study, robotic adrenalectomy was associated with longer operative times (169 vs 115 min), increased perioperative morbidity (20 % vs 0 %), and higher total costs ($3,467 vs $2,737, excluding initial robot cost) relative to the laparoscopic approach.

In a subsequent retrospective analysis of patients who received either robotic ($n=50$) or laparoscopic ($n=59$) unilateral LTA, Brunaud et al. reported that the robotic approach was associated with less intraoperative blood loss although longer operative times overall compared with the laparoscopic approach [26]. This difference in operative time, however, was nullified after a learning curve of 20 cases on the robotic platform. A subset analysis, moreover, revealed that laparoscopic adrenalectomy was associated with longer operative times in patients with larger tumors (>5.5 cm) as well as in those with a BMI ≥ 30. We have also found that relative to conventional laparoscopy, use of the robotic platform can reduce operative times as well as conversion rates for patients with larger tumors (>5 cm), although we have not found any differences in perioperative outcomes or operative time for obese patients [27, 28]. In a related study of 100 consecutive patients who received robotic LTA, Brunaud et al. found that greater surgeon experience, higher first-assistant training level, and smaller tumor size were all independently associated with shorter robotic operative time [29].

Given the small working area of retroperitoneal space and rigidity of laparoscopic instruments, robotic PRA may hold even more promise than robotic LTA for improved outcomes relative to conventional laparoscopy. Our group recently reported our experience with 63 patients receiving either laparoscopic ($n=32$) or robotic PRA ($n=31$). Tumor size, blood loss, and hospital stay were similar between the two groups, as were overall skin to skin operative times. After an initial learning curve of 10 cases, however, operative times were significantly shorter in the robotic group (139 min vs 167 min), inclusive of robotic docking times, which ranged from 5 to 30 min. Pain scores on postoperative day 1 were lower in the robotic group than in the laparoscopic group, which was attributed to the potentially shorter operative time and less pressure on incisions as a result of fewer instrument changes and articulating instrumentation [30].

A recent meta-analysis of 600 patients from 8 retrospective studies and 1 RCT undergoing either robotic ($n=277$) or laparoscopic ($n=323$) adrenalectomy supports the continued use of the robotic platform as no significant difference in operative time, conversion rate, or postoperative complications was observed between the two groups, although there was a significantly shorter hospital stay (WMD −0.43 days) and estimated blood loss (WMD −18.2 mL) in the robotic group [31].

Conclusion

The feasibility and safety of robotic LTA and PRA have been demonstrated, although higher costs relative to laparoscopy, secondary in part to increased learning-curve associated operative times, are certainly initial shortcomings. The potential advantages of the robotic platform for patients with larger tumors, and to conduct finer dissections with less blood loss, should continue to be investigated.

Robotic Thyroidectomy

Open thyroidectomy for cancer has been the standard of care since the development of current surgical techniques over a century ago by Nobel Prize-winning surgeon, Theodor Kocher. Total thyroidectomy is a now a refined surgical procedure requiring minimal instrumentation and can be performed via a small cervical incision.

In an effort to further improve cosmesis, the development of remote access thyroid surgery came to the forefront in the 1990s, with the development of various endoscopic techniques involving incisions in the axilla and/or areola, obviating the need for a cervical scar.

The evolution of these endoscopic methods with the use of the robotic platform was the result of initial case reports from the United States in 2005 and subsequent large series that were published, predominantly from South Korea. [32, 33]

Indications and Patient Selection

The indications for robotic thyroidectomy are somewhat more restrictive than that for the conventional transcervical approach. The absence of previous neck surgery or a cervical scar coupled with an informed and highly motivated patient is an absolute requirement. To facilitate transaxillary access, patients should ideally have an axillary to sternal notch distance of less than 20 cm and have a BMI under 30. Relative contraindications include large goiters with a substernal component, as well as thyroid nodules greater than 4 cm, or those with potential for extrathyroidal extension. Uncontrolled thyrotoxicosis is currently an absolute contraindication of the robotic approach [34, 35].

Techniques

There are multiple remote access robotic techniques which have been employed to avoid the creation of a cervical scar, including most commonly those that involve an axillary incision, either unilateral or bilateral, with variations involving additional areolar incisions [34–37]. With the evolution of these transaxillary approaches, robotic total thyroidectomy can now be performed through a unilateral axillary incision using three robotic arms, as described below. The development of a robotic "facelift" thyroidectomy has also been reported by Terris et al., which obtains remote access through an incision in the posterior auricular crease extending to the occipital hairline [38].

Robotic Unilateral Transaxillary Thyroidectomy

We have recently reported a single-incision technique for performing total thyroidectomy from a unilateral axillary incision [35] (Video 11.3). This technique requires a medial to lateral dissection of the contralateral thyroid gland. When a 30° scope is used, the contralateral recurrent laryngeal nerve can be seen and preserved.

After establishment of general anesthesia, the patient is placed supine, with the neck extended. The ipsilateral arm is then extended to expose the axilla at the level of the shoulder, with 90° flexion at the elbow. The arm is padded and positioned on an armboard above the head. It is important to protect pressure points and avoid shoulder hyperextension so as to prevent brachial plexopathy [39]. The contralateral arm is placed at the patient's side. Prophylactic antibiotics are administered in all cases. A 5–6 cm vertical axillary incision is made and a subcutaneous skin flap created superficial to the pectoralis fascia, extending to the sternal notch inferiorly and clavicle superolaterally (Fig. 11.6).

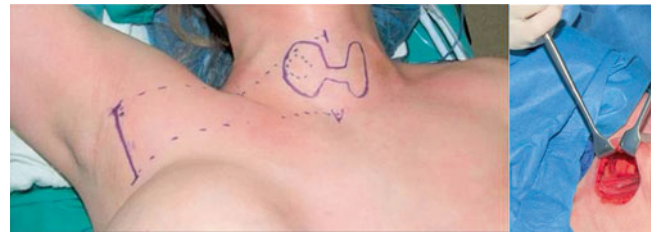

Fig. 11.6 Unilateral transaxillary approach to robotic thyroidectomy

Dissection is continued toward the anterior neck and a subplatysmal plane developed after crossing the clavicle until the two heads of the sternocleidomastoid muscle (SCM) are visualized. The sternal head of the SCM and strap muscles are retracted anteriorly with an elevating retractor in order to expose the thyroid (Fig. 11.7). The robot is then docked, approaching the patient from the contralateral arm. A 30° downward scope is placed through the center of the incision with Cadiere forceps used through a cephalad port and the Harmonic scalpel used through a caudal port (Fig. 11.8). We prefer this 3-arm approach with a laparoscopic suction irrigator being used by the first assistant for countertraction. Thyroidectomy then proceeds according to similar principles used in the transcervical approach. The inferior and superior poles are divided after defining the location of the isthmus. Identification of the recurrent laryngeal nerve and parathyroid glands is essential prior to completion of the ipsilateral lobectomy. The contralateral lobe is then dissected in a medial to lateral fashion, again tracing the recurrent laryngeal nerve and defining the location of the parathyroid glands. The lobe is removed through the axillary incision, which is then closed using subcuticular suture. We have found that drains are not usually required.

Outcomes

Although the conventional transcervical approach to thyroidectomy is still the current gold standard, there have been numerous non-randomized studies attempting to compare robotic, endoscopic, and conventional transcervical techniques with respect to oncologic equivalence, costs, and patient-reported outcomes, including cosmetic satisfaction [40–47].

In a recent meta-analysis of 2,375 patients from eleven studies, Lang et al. report longer operative time (mean difference = 56 min), hospital stay, and increased transient recurrent laryngeal nerve (RLN) injury rates in patients receiving robotic thyroidectomy compared to those who received conventional transcervical thyroidectomy [48]. While the mean difference in operative time was almost an hour, perhaps the most concerning of these outcomes was the difference in temporary RLN injury rates, which were three times higher in the robotic group when calculated based on number of nerves at risk (2.5 % vs 0.7 %). This nerve injury rate appeared to be independent of surgeon case volume, although could only be calculated from two of the eleven studies. Other perioperative outcomes, however, including blood loss, hypocalcemia, and overall morbidity were not statistically different between the two groups. In one robotic study, however, two brachial plexus injuries were reported (overall rate 0.2 %) likely due to shoulder hyperextension and other patient positioning effects that are specific to the transaxillary approach [39, 48]. Recognizing this risk early, we do not hyperextend the arm, but place it on an arm board, with less than 90° extension of the shoulder and elbow joints.

In a related meta-analysis of 2,881 patients from nine studies comparing open, endoscopic, and robotic thyroidectomy, Jackson et al. reported longer operative time but shorter hospital stay and increased cosmetic satisfaction for patients receiving robotic transaxillary relative to open transcer-

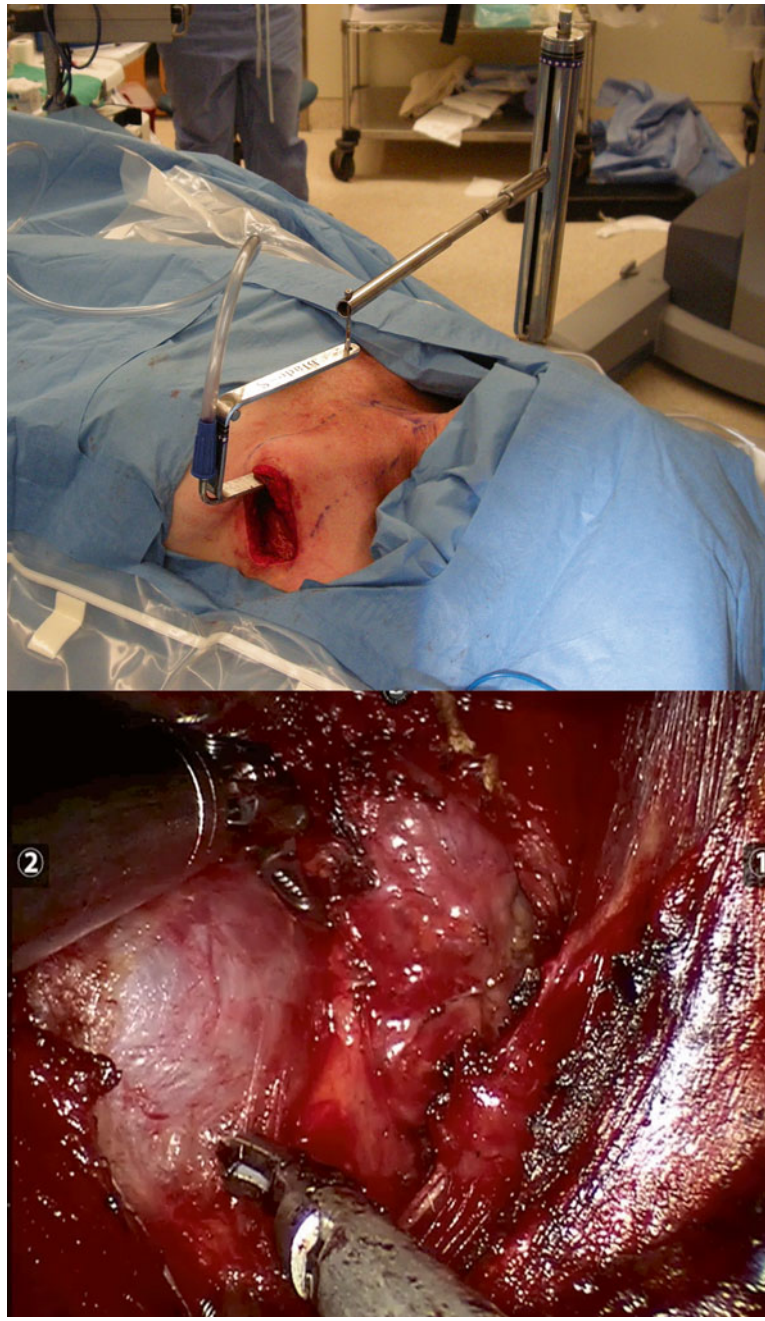

Fig. 11.7 Elevating retractor facilitates transaxillary access and improved visualization of operative site

vical thyroidectomy [49]. While individuals in the robotic group also had higher rates of transient hypocalcemia, the rate of temporary and permanent RLN injury was not statistically different between the robotic and open groups, inconsistent with the Lang analysis [48]. The Jackson analysis also demonstrated no significant difference in postoperative thyroglobulin (Tg) levels between the robotic and open groups, suggesting similar completeness of resection between these two

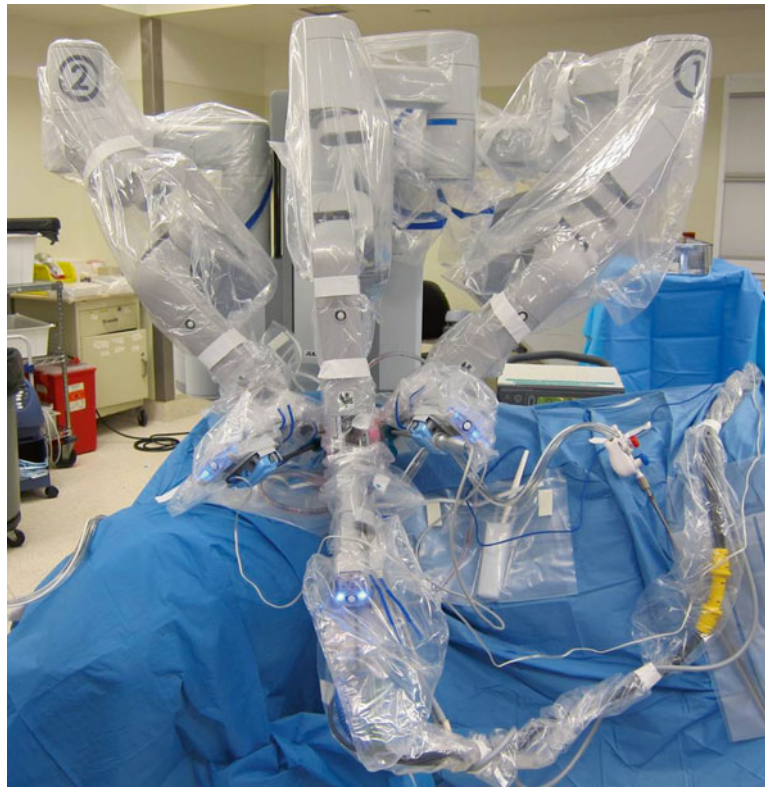

Fig. 11.8 Three-arm approach to unilateral transaxillary robotic thyroidectomy

techniques. Of note, three of the studies used in this meta-analysis ($n=590$) were also included in the study from Lang et al., all of which report both increased operative times and cosmetic satisfaction with the robotic approach, with no difference in complication rates. In addition, one study used in the Jackson et al. meta-analysis was excluded from that performed by Lang et al. based on overlapping data from two studies [42]. Despite these differences in study selection and analysis, it is seems consistent across most current studies that while the robotic approach may improve patient-reported cosmetic satisfaction, there is still some variability in perioperative outcomes when compared to the conventional open transcervical approach.

More recently, robotic transaxillary approaches have been used to perform central or lateral neck dissections. A study from Yi and colleagues reported on 521 female patients with papillary thyroid cancer who underwent either robotic ($n=98$) or open ($n=423$) thyroidectomy with concomitant central neck dissection [50]. While the rate of transient hypocalcemia was higher in the robotic group, there was no difference in serum Tg levels in both the immediate postoperative period and after remnant radioactive iodine (RAI) ablation performed at 6–12 months after the initial surgery.

Lateral neck dissections have also been attempted using a transaxillary approach with the robotic platform. Kang et al. initially reported their experience with 33 patients with lateral neck nodal metastases who underwent robotic total thyroidectomy with modified radical lymph node dissection (MRLND) [51]. Although most of the primary tumors were small, with 20 cases (61 %) having papillary microcarcinoma, lymph node retrieval appeared satisfactory, with a mean of 6.1 ± 4.4 nodes harvested in the central neck and 27.7 ± 11.0 nodes in the lateral neck. This group reported no major perioperative complications using this technique.

More recently, Lee et al. in a prospective analysis of 128 patients undergoing either robotic (n=62) or open (*n*=66) total thyroidectomy with MRLND reported longer operative time, but improved cosmetic satisfaction scores, as well as decreased postoperative swallowing difficulties and neck sensory changes in the robotic group [52]. Postoperative and post-RAI serum Tg levels, as well as the mean number of retrieved lymph nodes, were similar between open and robotic groups, as were length of hospital stay and perioperative complication rates, inclusive of hypoparathyroidism and nerve injury rates. This study, as most originating from South Korea, should be interpreted with caution, given patient and surgeon selection bias stemming from differences in the Korean and American health-care systems, patients' body habitus, culture-specific implications of a cervical scar, and, perhaps most importantly, surgical experience with this particular robotic technique.

Conclusion

The advantages of the robotic platform for thyroidectomy appear to lie mainly in patient-reported cosmetic satisfaction. Certainly, the increased cost associated with longer operative times is a perennial concern with this and other robotic endocrine surgical techniques. Moreover, given the potential for higher perioperative complications relative to traditional open techniques, including brachial plexopathies, as well as transient hypoparathyroidism and RLN injury, appropriate patient and surgeon selection is essential. At present, it would seem prudent to refer patients to high-volume centers of excellence in order to ensure optimal outcomes.

Robotic Parathyroidectomy

Transcervical parathyroidectomy, whether performed in a focused fashion, or with traditional four-gland exploration, is currently the standard of care, with success rates exceeding 97 %, when used in conjunction with intraoperative PTH measurement [53].

Robotic transaxillary approaches for parathyroidectomy, as those for thyroidectomy, have been pursued largely in an attempt to improve patient-reported cosmetic satisfaction for those individuals wishing to avoid a cervical incision, and as a potential improvement over endoscopic techniques with respect to both visualization of the operative field and precision of dissection.

Robotic transthoracic parathyroidectomy for ectopic glands located in the mediastinum has also been reported and is an evolving approach that potentially obviates the need for sternotomy or thoracotomy in select patients where surgical extirpation through a low transcervical incision is not feasible [54, 55].

Indications and Patient Selection

Given the evolving nature of this technique, and the fact that only a handful of cases have been reported in the peer-reviewed literature, it would seem prudent to initially restrict robotic transaxillary parathyroidectomy to patients with a biochemical diagnosis of primary hyperparathyroidism and positive preoperative localization with either ultrasound or sestamibi scan [47, 56]. As for robotic thyroidectomy, patients should be steadfast in their desire about avoiding a cervical scar and ideally have a BMI under 30, with an axillary to sternal notch distance of less than 17 cm, in order to facilitate transaxillary access. Exclusion criteria include previous neck surgery, significant thyroiditis, and bulky thyroid disease. For patients with ectopic mediastinal parathyroid glands, positive preoperative localization with ^{123}I-^{99}Tc-sestamibi subtraction SPECT/CT is also highly desirable prior to proceeding with robotic transthoracic parathyroidectomy [55].

Techniques

Robotic Transaxillary Parathyroidectomy

This approach is similar to that described above for robotic transaxillary thyroidectomy, with careful positioning to avoid iatrogenic neuropathy,

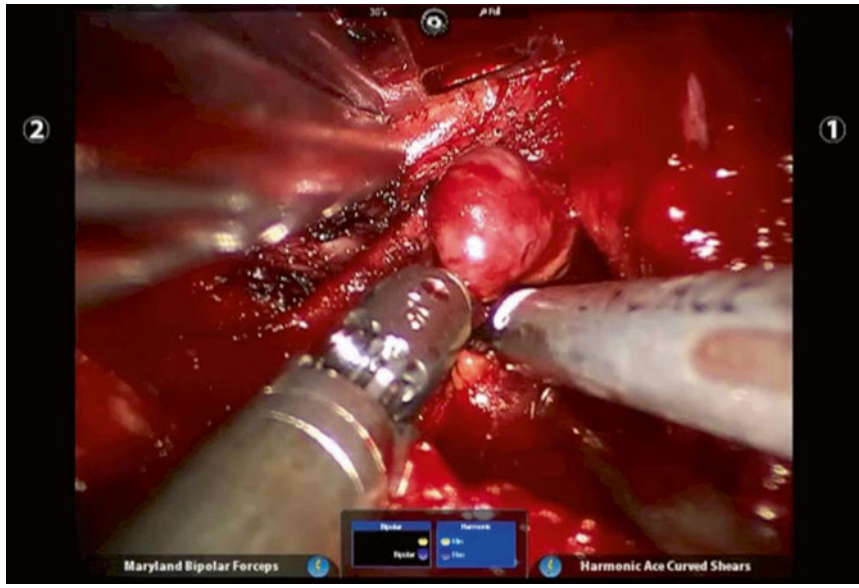

Fig. 11.9 Robotic transaxillary parathyroidectomy

and transaxillary access through creation of a subcutaneous flap and development of a subplatysmal plane until visualization of the two heads of the SCM [47] (Video 11.4). The robot is docked across the contralateral arm after retraction of sternal head of the SCM and strap muscles anteriorly with an elevating retractor. A 3-arm approach is used as for robotic thyroidectomy, with dissection targeted toward the parathyroid adenoma (Fig. 11.9). We routinely use intraoperative PTH measurements.

Robotic Transthoracic Parathyroidectomy

Under standard single lung ventilation, the patient is positioned supine on a vacuum mattress and tilted slightly toward the contralateral side. Robotic 8 mm ports are placed in the second and sixth intercostal spaces, along the anterior axillary line and midclavicular line, respectively. A middle 12 mm robotic port for the camera is placed at the fourth intercostal space medial to the anterior axillary line. We use CO_2 insufflation of 8–10 mmHg, although this is not universally adopted. Instrumentation is similar to the transaxillary approach. Dissection of pericardial fat and thymic tissue may be necessary depending on preoperative localization studies. Intraoperative PTH monitoring is routinely used. We have also found success by incorporating radio-guided techniques in this approach, using preoperative injection of ^{99}Tc-sestamibi along with gamma probe-directed measurement of in vivo and ex vivo counts to ensure that the resected tissue was parathyroid gland [55]. A chest tube is placed at the conclusion of the procedure.

Outcomes

Given the limited experience with robotic parathyroidectomy, there have been no studies to date directly comparing perioperative outcomes with the conventional open transcervical approach. There have, however, been several case series in the peer-reviewed literature.

Tolley and colleagues have reported their experience in 11 patients who underwent robotic transaxillary parathyroidectomy [57]. All patients were required to have positive preoperative localization studies on ultrasound and sestamibi SPECT/CT. Persistent disease was observed in

one patient who demonstrated an additional contralateral parathyroid adenoma on repeat ultrasound and sestamibi SPECT/CT which was not detected on initial localization studies. One patient underwent conversion to a conventional transcervical approach which was attributed to large patient body habitus. There were no other perioperative complications, including RLN paresis, hypocalcemia, hematoma, or wound infection. Docking, exposure, and closure times decreased and then plateaued with increased case load. Console time ranged from 25 to 105 min with longer times observed in patients with short necks, a BMI > 33, and a parathyroid adenoma in a retroclavicular location.

We have also reported our experience with four robotic transaxillary parathyroidectomies for primary hyperparathyroidism (two unilateral and two focal explorations) [47]. One patient developed a seroma that did not require operative intervention. We did not observe any other perioperative complications in terms of RLN injury, hypocalcemia, or hematoma, and all patients were free of disease at 6 months.

There have also been limited case reports of robotic transthoracic mediastinal parathyroidectomy. Approximately 2 % of ectopic mediastinal parathyroid adenomas are not amenable to resection via a transcervical approach. Historically, these have required a median sternotomy or thoracotomy for extirpation, which more recently has given way to the use of mediastinoscopic or thoracoscopic methods [58, 59]. In 2004 Bodner et al. reported the first successful case of robotic mediastinal parathyroidectomy for an adenoma located in the aortopulmonary window, which resulted in biochemical cure, although was complicated by transient RLN palsy. Of the 10 cases reported in the literature, 9 have resulted in biochemical cure with 2 transient RLN palsies [55]. The largest case series with robotic mediastinal parathyroidectomy has been reported by Ismail et al. with a total of five patients, three with primary hyperparathyroidism and two with recurrent secondary hyperparathyroidism [56]. Positive preoperative localization was obtained in all patients with fusion SPECT/CT. Median operating time was 58 min, and all patients had an appropriate drop in intraoperative PTH levels, with no reported perioperative morbidity or mortality.

Conclusion

The advantages of the robotic platform for transaxillary parathyroidectomy have not yet been adequately delineated given the limited case series reported in the literature. As in the case of robotic thyroidectomy, however, the potential remains for robotic parathyroidectomy to be associated with improved patient-related cosmetic outcomes relative to the conventional transcervical approach. The development of robotic mediastinal parathyroidectomy is also in early stages of development, although holds potential benefits over endoscopic techniques in terms of superior visualization and precision of dissection. For both of these techniques, however, the increased cost associated with longer operative times and instrumentation must be considered, along with the potential for increased morbidity, such as positioning-related neuropathy and RLN palsy. Careful patient and surgeon selection at experienced centers of excellence is therefore warranted for continued assessment.

Summary

The use of the robotic platform for endocrine surgical procedures holds significant potential for improvement of both clinical and patient-reported outcomes; however, these techniques must be wielded selectively, with careful patient and center selection. Volume-outcome relationships are already evident in current reports, with higher costs associated with learning-curve-associated operative times and perioperative complications. In the setting of our evolving value-based healthcare system, these limitations must be overcome quickly to merit continued development of these surgical techniques.

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Essentials and Future Directions of Robotic Major Pulmonary Resection

12

Bernard J. Park, Joanne Glanville, and Gregg Baranski

Introduction

Increasingly, minimally invasive video-assisted thoracic surgery (VATS) is being utilized for pulmonary resection because of patient benefits over traditional thoracotomy, such as decreased length of stay, decreased short-term postoperative pain, and fewer complications [1–3]. VATS lobectomy, initially described in multiple series in 1993, has proven to be feasible and oncologically acceptable for surgical eradication of non-small cell lung cancer (NSCLC) and other isolated tumors and conditions. However, despite multiple studies demonstrating these advantages, VATS for anatomic resection is still not the standard approach and is only slowly being implemented more widely. The explanation is likely multifactorial including (1) technical issues, such as two-dimensional imaging and limited maneuverability of instrumentation; (2) lack of adequate training; and (3) concerns about the consequences of major vascular injury with a closed chest approach.

In order to address the perceived technical limitations of conventional minimally invasive platforms, a master–slave robotic surgical system was developed (da Vinci® Surgical System, Intuitive Surgical, Sunnyvale, California). The major advances were the three-dimensional visual system that reestablished binocular vision and wristed instrumentation capable of seven degrees of freedom enabling more natural bimanual movement for precise dissection. The first indication for which the system was approved by the Food and Drug Administration was for cardiothoracic surgery because the original intent was to achieve true closed chest cardiac surgery. This, however, has not been fully realized. Instead, the most common applications that evolved were for pelvic procedures – prostatectomy and hysterectomy. Similarly, while use of robotics for general thoracic surgical procedures dates back to initial case reports in the early 2000s, it was not until 2004 and 2006 that actual series of robotic lobectomies were reported by Melfi and colleagues and Park and coauthors, respectively [4, 5]. These centers reported the initial technique and early perioperative experiences that demonstrated feasibility, safety, and concordance of outcomes with the largest series of VATS lobectomies. Subsequently, there has been a steadily increasing interest in robotic pulmonary

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resection with additional publications with greater numbers of patients and various modifications of the technique [6–8].

General Principles

The guiding principle that must be remembered when one is considering utilizing robotic surgical systems for any procedure is that it is a tool like any other in surgery. It is up to the surgeon to determine whether its use is appropriate and in the best interest of the patient. Robotic procedures are minimally invasive procedures, simply with different, perhaps more advanced, technology that has unique advantages and disadvantages. In the case of pulmonary resection, the robotic approaches that have been described all conform to the consensus criteria of a standard VATS lobectomy put forth in the Cancer and Leukemia Group B (CALGB) prospective, multi-institutional registry study (CALGB 39802) [9]. For early-stage NSCLC (node-negative, peripheral tumors ≤ 3 cm) this criteria include absence of rib-spreading, minimal incision size (no greater than a 4–8 cm access incision with 0.5 cm port incisions), videoscopic guidance at all times, and traditional hilar dissection with individual ligation and division of lobar structures. Adhering to these principles the authors were able to demonstrate that VATS lobectomy was associated with acceptable morbidity and mortality. Similarly, multiple independent centers have demonstrated feasibility and safety of robotic lobectomy [4–8] while adhering to these same universal aspects of minimally invasive thoracic surgery established for VATS lobectomy. Moreover, a recent multicenter study by Park and coauthors also demonstrated excellent long-term oncologic results of robotic lobectomy in the treatment of early NSCLC [10], as well as the feasibility of robotic segmentectomy [11].

For anatomic pulmonary resection the authors practice a VATS-based robotic approach with a small (3–4 cm), non-rib-spreading access incision, whereas others advocate a complete portal approach [7, 8]. While there are minor technical differences, the conduct of the procedure and utilization of the robotic technology for dissection are uniform.

Robotic Training and Accreditation

Currently, much like with VATS lobectomy neither the American Board of Thoracic Surgery nor any governing surgical society, such as the American College of Surgeons, Society of Thoracic Surgery, or American Association of Thoracic Surgery, has any published guidelines for the training and accreditation of surgeons and operating room teams for performance of robotic thoracic procedures. As a result, each hospital has developed its own policies. Most mandate that surgeons attend an intensive, two-day training course given by Intuitive Surgical® that is comprised of didactic instruction regarding the system components followed by simulation training for basic skills and cadaver-based training for specific procedures. It is critical for specialty-specific personnel – operating room nurses, surgical technicians, and bedside assistants – to be formally trained on the basics of system functioning, instrument changes, and position of the surgical cart. This is typically done by the robotic company representative. It is common, but not required for the prospective robotic surgeon to observe an established practitioner in order to become familiar with specific index procedures. This author cannot stress enough how critically important case observation is during the training and prior to implementation of robotics into treatment of patients.

Once the entire surgical team has received the appropriate training, institutions usually will allow implementation of the robotic system into procedures under the supervision and guidance of a case proctor, defined as a surgeon with documented clinical experience independently performing robotic procedures. The console surgeon is typically required to perform somewhere between three to as many as ten proctored cases before being granted independent robotic procedure privileges. Some hospitals require that eligible proctors themselves have performed minimum

number of cases, while the majority has no such requirement. In fact, most institutions do not mandate that the proctor be specialty-specific – thus, a robotic urologist may proctor a thoracic surgeon. While this may be in compliance with a specific institutional requirement, this type of implementation is ill-advised. The ideal situation is for the training surgeon to observe an experienced robotic surgeon in their respective field and then enlist that individual, if possible, to serve as the case proctor. This maximizes the continuity of training and, consequently, patient safety during clinical implementation.

Patient Selection and Preoperative Assessment

The theoretical benefit of utilizing robotic technology is to replicate what can be done through VATS or almost entirely what can be done through a thoracotomy. Patients eligible for robotic pulmonary resection include those with suspicious or biopsy-proven NSCLC or other pathologic tumors or disease processes confined to the lung and ipsilateral hemithorax. This should be evaluated through a dedicated, contrast-enhanced computed tomography (CT) of the chest. For NSCLC additional clinical staging should be performed with a whole body positron emission tomography (PET/CT). Suspicious mediastinal nodal or extrathoracic disease warrants further invasive staging to identify patients with advanced disease requiring multimodality or systemic therapy only. Patients should have adequate cardiopulmonary status and performance status to tolerate segmentectomy or lobectomy. Specifically, cardiac disease should be asymptomatic and stable on medication and preoperative pulmonary function tests should demonstrate a postoperative predicted forced expiratory volume in one second (FEV1) and diffusion capacity (DLCO) above 40 % of predicted. Borderline postoperative predicted lung function should be further investigated by quantitative lung scanning and/or exercise testing. Smoking cessation for active smokers should be aggressively advocated.

As with any new surgical technique or approach, careful selection of initial cases is critical to success and progression. While scenarios such as large tumors (>5 cm), extensive hilar or mediastinal disease, post-induction therapy, chest wall invasion, extensive adhesions, and need for bronchial or vascular sleeve resection do not absolutely preclude a robotic approach, it is wise to avoid these conditions until a sufficient experience with most straightforward cases has been developed. Conversely, given the cost and multidisciplinary (nursing, anesthesia, surgery) effort required, utilization of the robotic system for simple procedures such as wedge resection or pleural biopsies should be avoided. Informed consent for the use of robotic assistance should be obtained as a distinct portion of the procedure.

Operative Technique

Preparation of the Robot

The operating room technical staff sets up the robotic surgical system (surgical cart, surgeon's console, vision system) in the room (Fig. 12.1). In the beginning of the case, the nursing staff power up the system, run the appropriate diagnostics, and drape the robotic arms and camera. This requires two individuals and typically takes 5–10 min for staff who are trained and familiar with the process and occurs prior to or while the patient is undergoing induction of anesthesia and positioning.

Anesthesia Considerations

Standard methods of general anesthesia and single-lung ventilation are employed via either double-lumen endotracheal tube placement or bronchial blocker. The patient is placed in a maximally flexed, lateral decubitus position, and single-lung ventilation is initiated. Depending on the size of the operating room, it will often be necessary to move the table away from the anesthesia machine and angle the foot of the table

Fig. 12.1 Robotic surgical cart draped and prepared for docking

away from the surgical cart (Fig. 12.2). This establishes enough space to dock the robot. Care must be taken to ensure that sufficient length of the circuit tubing is available during this positioning, and the anesthesia team must be comfortable that there is adequate access to the patient's airway once docking of the robotic system has taken place.

Initial Exploration and Docking of the Robot

Initial thoracic exploration is conducted with the robotic thoracoscope through a 12 mm disposable port in the 8th intercostal space (ICS) just posterior to the anterior axillary line (Fig. 12.3) in order to verify tumor location, establish a tissue diagnosis if necessary, assess resectability and appropriateness of the robotic approach, and place the additional incisions prior to docking (Video 12.1). A 1 mm incision is placed posterior to the tip of the scapula in the 9th ICS just above the diaphragm. The 3–4 cm access incision is placed in the 4th or 5th ICS in the midaxillary line. A fourth incision may be employed posteriorly in the 5th

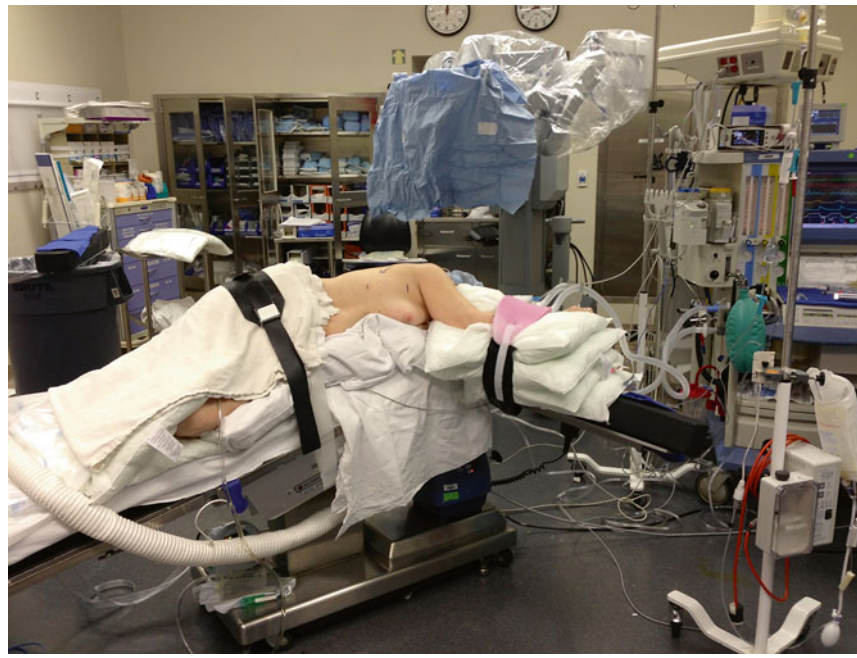

Fig. 12.2 Table positioning prior to docking

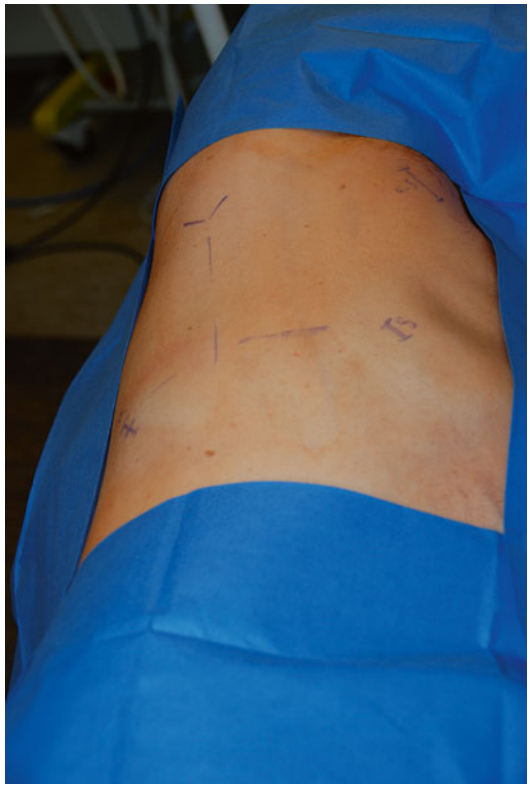

Fig. 12.3 Incision strategy for VATS-based robotic pulmonary resection

or 6th ICS in line with the 9th ICS incision if so desired. Once the skin incisions have been made, the surgical cart is brought into position from the posterior aspect of the patient with the center column and camera arm angled over the scapula at an approximately 45° angle with respect to the longitudinal axis of the patient (Fig. 12.4). This allows for the field of dissection to include the hilar structures and the majority of the chest. When docking the surgical cart, it is important to avoid positioning the surgical cart too close to the patient and maintain adequate spacing between ports (handbreadth). This will eliminate instrument arm conflicts and maximize range of motion of the instruments.

Once the surgical cart is in position, the camera arm is attached first to the port, and the robotic thoracoscope is introduced and secured to the camera arm. The 8 mm metallic robotic ports are introduced through each of the other incisions and attached to their respective arms. This is accomplished under direct vision both from outside the patient and from within the patient's thorax. In the case of the access incision, the port is placed in the midpoint of the incision with room above and below to introduce

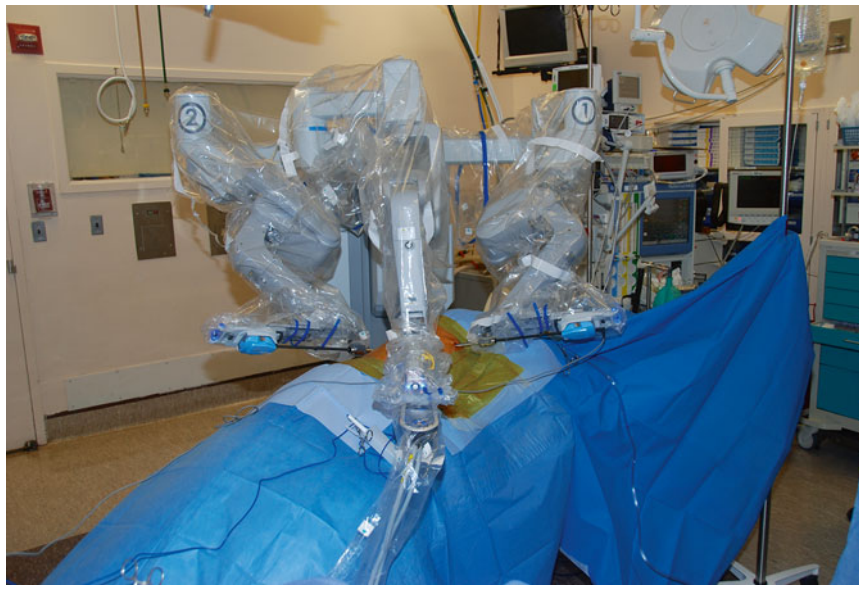

Fig. 12.4 Docking of the surgical cart

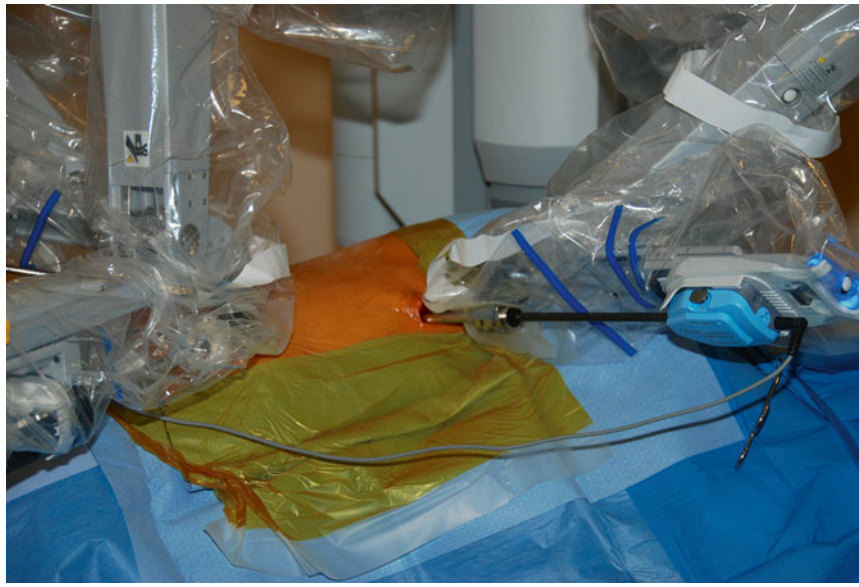

Fig. 12.5 Positioning of the instrument arm through the access incision

additional instruments (lung retractor, suction). Care must be taken to ensure that each instrument arm has full range of motion and does not collide with one another or with the patient (Fig. 12.5).

Once the ports are in place and attached to the robotic arms, the surgical instruments are introduced under direct thoracoscopic vision. A Cadiere forceps is most commonly controlled by one hand for grasping tissue, and a cutting instrument (monopolar spatula, Maryland bipolar, monopolar hook) is used in the other hand. If the fourth arm is employed, it is typically used for a lung grasper or suction irrigator. After the instruments have been introduced, the operating surgeon moves to the surgeon's console. The bedside assistant stands at the anterior aspect of the patient and provides additional exposure through access incision.

Completely Portal Robotic Approach (CPRL-4)

Cerfolio and colleagues have developed a robotic incision strategy that avoids an access incision under the premise that no exposure of the intrathoracic cavity to air may have additional benefits over and above lack of rib-spreading [8]. There are four robotic arm incisions, all placed in the 6th ICS spaced 9–10 cm apart beginning from the midaxillary line to the paraspinal area (Fig. 12.6). In addition, there is a fifth, non-robotic 15 mm assistant access port through which the endovascular staplers are passed. The surgical cart is then brought in over the head of the patient, with the camera view replicating the traditional thoracotomy view.

Mediastinal and Hilar Lymph Node Dissection

Dissection is performed with the Cadiere forceps and the monopolar cautery spatula. Wherever possible, the entire nodal packet is removed without fracturing the nodes into fragments (Fig. 12.7). Large bronchial vessels or lymphatic can be clipped, and when indicated suspicious lymph nodes are sent for frozen section analysis to identify occult N2 disease. For a right upper lobectomy, it is easier to perform the paratracheal node dissection after the specimen has been removed. Similarly, it is often advantageous to

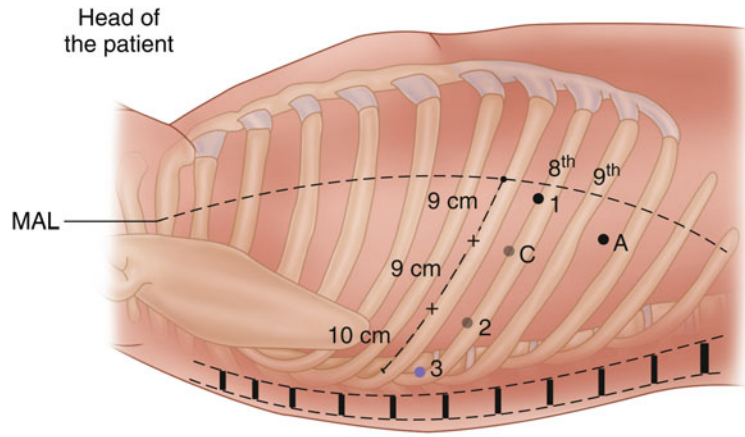

Fig. 12.6 Incision strategy for a CRPL-4 approach

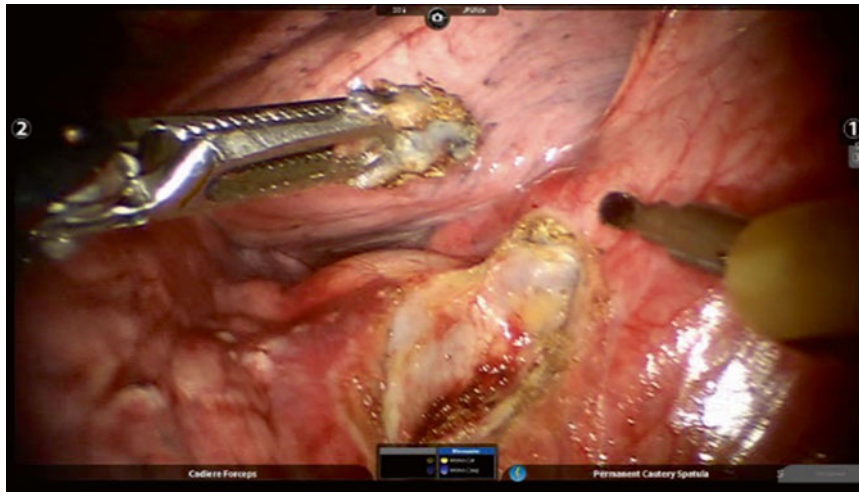

Fig. 12.7 Right-sided interlobar hilar lymph node dissection

perform the subcarinal lymphadenectomy by retracting the stump of the lower lobe to elevate the mediastinum.

Hilar Dissection

If there are no contraindications to resection, individual isolation of the hilar structures proceeds with dissection around the hilar vessels and bronchi performed through a combination of cautery, sharp, and blunt dissection. Complete removal and labeling, rather than sweeping of all regional nodal tissue is performed both for adequate staging and to facilitate isolation of the hilar structures. When either a vessel or the bronchus is mobilized sufficiently, the Cadiere forceps are used to isolate the structure, using the seven degrees of freedom to articulate the instruments at near right angles to do so (Fig. 12.8). Ligation and division of the named vessels and bronchus are performed with endovascular staplers introduced either through the posterior inferior or access incision. This requires temporary removal of one of the robotic ports followed by replacement of the arm after stapler firing.

The precise order in which the structures are divided depends on the particular lobectomy or segmentectomy being performed, the approach (anterior versus posterior), and presence of anatomic variation. Descriptions of suggested strategies for each lobectomy and the most commonly performed segmental resections are provided.

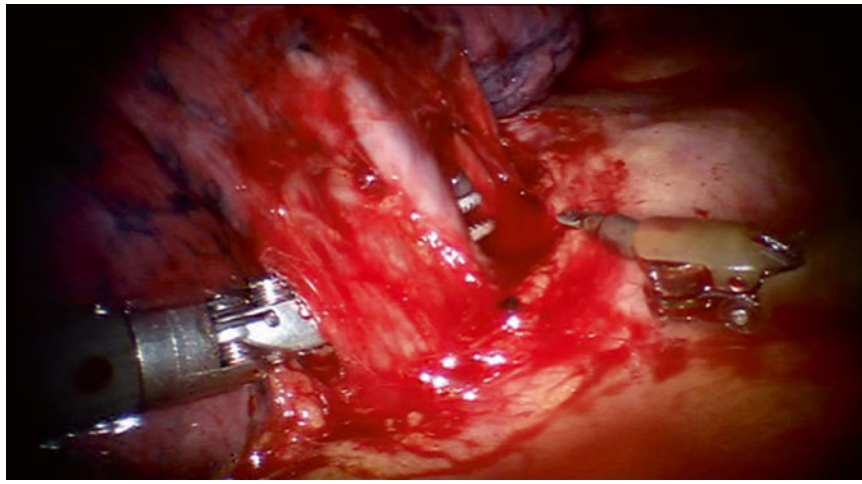

Fig. 12.8 Robotic isolation of the right upper lobe superior vein

Right Upper Lobectomy

The lung is retracted laterally in order to place the superior hilar vessels on tension (Video 12.2). The mediastinal pleura over the superior pulmonary vein is incised in order to delineate the entire extent of the upper lobe vein. The superior extent is where the vein meets the truncus arteriosus, while the inferior extent is at the takeoff of the middle lobe vein. Care must taken to identify the middle lobe vein inferiorly and to preserve it. There are typically hilar lymph nodes in these two areas, and they should be excised or mobilized away from the vein. Prior to isolation and division of the upper lobe vein, the ongoing pulmonary artery should be identified and avoided. Once isolated, the upper lobe vein is divided with an endovascular stapler introduced through the posterior, inferior port. Next, the truncus arteriosus is mobilized from the surrounding hilar lymph nodes inferiorly and the upper lobe bronchus posteriorly and divided. At this juncture if the hilar and peribronchial lymph nodes have not been previously excised, they should be removed completely. The lung is retracted anteriorly, and the posterior pleura between the bronchus intermedius and the upper lobe bronchus is incised. The interlobar lymph nodes are removed, exposing the posterior ascending branch of the upper lobe and the upper lobe bronchus. These two remaining hilar structures may then be divided in whichever order is practically easiest. The bronchus is typically stapled with a 4.8 mm stapler or may be divided sharply and sewn closed with 3–0 or 4–0 absorbable suture. Lastly, the horizontal fissure is completed with multiple fires of a linear stapler.

Middle Lobectomy

The right lower and middle lobes are allowed to separate naturally, and the major fissure is explored. The mediastinal pleural overlying the anterior portion of the fissure between the middle and lower lobes is divided to allow identification and excision of the interlobar lymph nodes, exposing the basilar pulmonary artery and the takeoff of the middle lobe bronchus. The lung is retracted laterally, and the remaining anterior portion of the fissure may be divided with a stapler or simply with electrocautery if the fissure is complete. The mediastinal pleura between the lower lobe and middle lobe pulmonary veins is divided and the middle lobe vein is isolated and divided with a vascular stapler. The hilar and peribronchial lymph nodes are excised to expose the middle lobe bronchus which is then isolated and divided. The remaining middle lobe artery or arteries are easily identified, isolated, and divided. The horizontal fissure is stapled last.

Lower Lobectomy

The approach for the right and left sides are nearly identical (Video 12.3). The inferior pulmonary ligament is divided by cautery up to the inferior pulmonary vein. The inferior ligament lymph nodes are excised, and the pleura is divided posteriorly up to the most superior aspect of the hilum. The posterior hilar nodes are excised. The inferior pulmonary vein is isolated but not divided immediately. If the anterior portion of the major fissure is sufficiently complete, the mediastinal pleura is divided, and the interlobar lymph nodes are removed exposing the basilar artery. If the fissure is complete, the remaining pleura of the anterior portion of the major fissure may be divided with cautery. If it is incomplete, a stapler may be used to divide it. All structures may be divided by introducing the stapler through the anterior access incision. The inferior vein is divided, and the lung is retracted cephalad. The plane between the lower lobe bronchus and basilar artery is developed, and the lower lobe bronchus is isolated and stapled. Care must be taken to ensure the bronchial anatomy is explicitly defined prior to division to avoid inadvertent division of the middle lobe (right) or main bronchus (left). Lastly, the basilar pulmonary artery is isolated and divided, and the remaining posterior portion of the major fissure is completed.

Left Upper Lobectomy

The lung is retracted laterally in order to place the superior hilar vessels on tension (Video 12.4). The mediastinal pleura over the superior pulmonary vein is incised in order to delineate the entire extent of the upper lobe vein. The superior extent is where the vein meets the left main pulmonary artery, while the inferior extent is at junction of the superior and inferior veins. The superior vein is isolated and divided, and the mediastinal pleura is further divided superiorly and posterior around the entire superior hilum. Hilar lymph nodes between the upper lobe bronchus and the anterior and apical pulmonary artery branches are excised or mobilized. This allows the anterior and apical branches to be isolated and stapled. The peribronchial and interlobar lymph nodes between the upper and lower lobe bronchi are removed. The upper lobe bronchus is then exposed and divided. The lung is retracted posteriorly to expose the remaining pulmonary artery branches, including the lingular and additional posterior branches. These are sequentially isolated and divided. Alternatively, the left upper lobe arterial branches may be isolated and divided posteriorly prior to division of the bronchus should the need arise or based on surgeon preference. Once the remaining arterial branches have been divided, the major fissure is completed with multiple fires of the stapler.

RUL Posterior Segmentectomy

The lung is retracted anteriorly, and the posterior mediastinal pleura is incised at the junction of the upper lobe and bronchus intermedius. The interlobar lymph nodes should be removed in order to identify the posterior ascending and lower lobe superior segmental arteries. It is helpful to excise the interlobar lymph nodes. The posterior portion of the major fissure is divided either by cautery or by stapler. The ascending branch is then isolated and ligated either with an endovascular stapler or cut between clips. The peribronchial tissue is dissected distally to expose the posterior segmental bronchus which is encircled and divided by stapler. The posterior segmental vein is then identified, isolated, and divided. Lastly, the segmental fissures are divided with multiple fires of the endoscopic staplers.

LUL Trisegmentectomy (Lingla-Sparing Left Upper Lobectomy)

The lung is retracted laterally, and the mediastinal pleura is incised over the superior vein. The lingular vein is identified and preserved. The remaining branches to the upper lobe are isolated and stapled. The hilar lymph nodes between the bronchus and the anterior artery branch are removed, and the artery is mobilized and divided. The peribronchial lymph nodes are excised,

exposing the distal branches in order to spare the lingular bronchus. The apicoposterior and anterior bronchial branches are divided. Lateral and posterior retraction of the lung allows identification of the apicoposterior branches which are sequentially isolated and divided. The fissure is then stapled last.

Lingulectomy

With the lung retracted posteriorly, the mediastinal pleura is divided over the lingular vein which is divided either between clips or by endovascular stapler. The interlobar pleura is divided, and the interlobar lymph nodes over the basilar pulmonary artery removed in order to expose the lingular branch. The anterior fissure is divided by cautery or stapler. The lingular pulmonary artery is isolated and divided, exposing the lingular bronchus. Once the bronchus is divided, the fissures are completed by stapler.

Superior Segmentectomy

As with lower lobectomy, the steps for right and left superior segmentectomy are nearly identical. The lung is retracted superiorly and anteriorly and the inferior pulmonary ligament is divided up to the pulmonary vein. The posterior pleura is divided up to the superior hilum, excising the hilar lymph nodes. Distal dissection of the vein posteriorly exposes the superior segmental vein easily. On the right partial division of the posterior portion of the fissure is necessary to expose the junction of the superior and posterior segmental arteries, whereas on the left the main pulmonary artery origin is easier to identify and distal dissection reveals the takeoff of the superior segmental branch. Once the artery branch is isolated and stapled, the bronchus will be visible. Removal of the segmental peribronchial lymph nodes will facilitate isolation of the bronchus which is then divided. Lastly, the segmental vein is stapled, followed by the segmental fissures.

Basilar Segmentectomy

The inferior pulmonary ligament is divided up to the level of the inferior vein. Distal dissection is performed to expose the basilar vein exclusive of the superior segment branch. Attention is then paid toward the anterior fissure. As in the technique for lower and middle lobectomy, the mediastinal pleura is divided to identify the basilar pulmonary artery. Once again, removal of the interlobar lymph nodes great delineates readily the anatomic relationships. The anterior portion of the fissure is divided by cautery or stapler to expose the relationship between bronchus and the artery. The basilar vein is stapled, allowing for mobilization of the bronchus away from the artery. If feasible, division of the basilar bronchus first will facilitate division of the basilar artery, but is not required. Once the bronchus and artery are divided, the fissures are completed.

Specimen Removal

The lobectomy specimen can be removed through the access incision in the case of a VATS-based incision strategy or by enlarging one of the port incisions in a completely portal approach. In the event that the primary tumor is large, the access incision may have to be enlarged in order to remove the specimen without inadvertently fracturing the ribs. The Anchor™ tissue retrieval bag (Anchor Products Company, Addison, Illinois) or other suitable bag is placed through it to retrieve the specimen. A durable nylon bag is preferable to plastic so that there is minimal chance of rupture and spillage.

Termination of the Procedure

Once the specimen has been removed and the systematic lymphadenectomy or sampling has been completed, the surgical arms can be undocked from the ports, and the cart can be moved away from the patient. The ports should be removed,

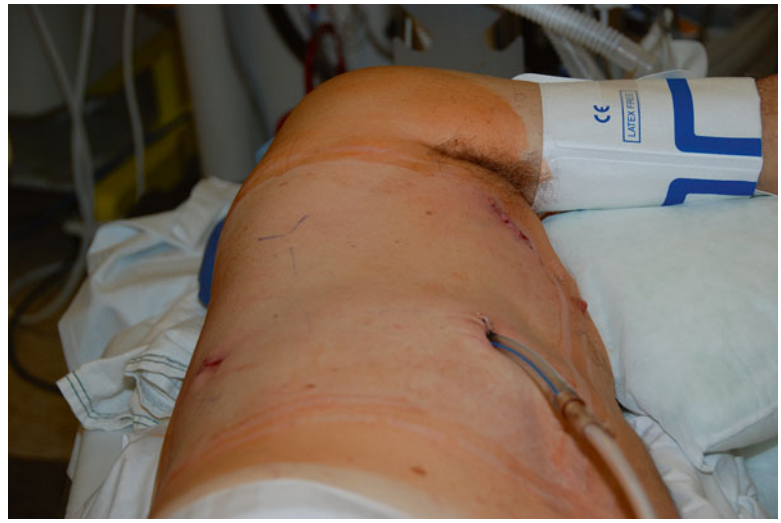

Fig. 12.9 Incision closure following right robotic lobectomy

and a single drainage chest tube placed through the anterior inferior camera incision and positioned with the tip at the apex of the chest posteriorly. The lung should be reinflated under direct thoracoscopic vision with the robotic scope placed in the access incision. The remaining wounds are closed in a standard fashion (Fig. 12.9).

Postoperative Care

Standard postoperative management should be undertaken. In virtually all cases patients should be extubated in the operating room and brought initially to the postanesthesia care unit. Chest tubes may be left to water seal unless the immediate postoperative radiograph demonstrates a large air space. Patient-controlled analgesia should be initiated through the use of an epidural or a peripheral narcotic combined with either intraoperative intercostal blocks or continuous subpleural local anesthetic infusion. Patients may be transferred to a surgical floor with telemetry. Early ambulation and chest physiotherapy is critical to prevent hypoventilatory atelectasis and pneumonitis. Removal of the chest tube should be performed once there is no evidence of air leak and fluid drainage is sufficiently diminished. Commonly, patients can be discharged once the chest tube is discontinued provided there are no other concomitant complications and pain control on oral medication is sufficient.

Perioperative Outcomes and Specific Considerations

Potential intraoperative and postoperative complications are no different between VATS, robotics, and thoracotomy. Major perioperative morbidity and mortality are consistent with the largest and best series of VATS and thoracotomy approaches (Table 12.1) [10]. However, there are unique aspects to robotic thoracic procedures and lobectomy that need to be considered:

1. *Lack of tactile feedback*. The robotic arms do not impart haptic feedback to the console (operating) surgeon. Therefore, both the console surgeon and the bedside assistant must be constantly vigilant about inadvertent injury to either the external patient or surrounding internal structures by the instrument arms or the instruments themselves. Externally care must be taken to ensure that the arms do not compress any part of the patient with undue force for a prolonged period of time. Internally, the surgeon must pay close attention to the visual feedback to prevent direct traction injury and compression injury by the shaft or heel of the instruments to adjacent structures.

Table 12.1 Perioperative results of 325 Robotic Lobectomies

Category	Result	
Operative time (min)[a]	206	(110–383)
Chest tube (days)[a]	3	(1–23)
Length of stay (days)[a]	5	(2–28)
Complications		
None	243	(75 %)
Minor	70	(21.5 %)
Major	12	(3.7 %)
Mortality	1	(0.3 %)
Pathologic stage[b]		
IA	176	(54 %)
IB	72	(22 %)
IIA	41	(13 %)
IIB	15	(5 %)
IIIA	21	(6 %)
Tumor size (cm)[a]	2.2	(0.7–10.2)
Lymph node stations removed[a]	5	(2–8)

Adapted with permission from Ref. [10]
[a]Median (range)
[b]7th edition TNM classification

2. *Visual magnification.* The robotic thoracoscope by design has greater magnification compared with the optics of the conventional camera. This is quite beneficial when working in a narrow, confined space, but results in decreased overall perspective view. This can be a disadvantage in the chest when one is attempting to delineate anatomic boundaries, such as lobar versus segmental structures or location of the minor fissure. It is critical to zoom out to the farthest extent possible when a greater overall view is required.
3. *Hemorrhage*. While the threat of catastrophic hemorrhage during major pulmonary resection is not unique to robotic procedures, absence of the operating surgeon at the bedside for immediate intervention is a necessary condition of the current master–slave robotic system. There are several strategies to maximize safety and minimize patient morbidity in the event of significant vascular injury. First, anticipation of a potential injury and maintaining a low threshold for conversion is key. Second, there must be a sponge stick ready and available for the bedside assistant to use for temporary tamponade of a bleeding vessel. Third, the bedside staff must be poised for rapid instrument removal and undocking of the surgical cart in preparation for conversion. With proper training this can be executed in less than 1 min, and use of robotic technology should never impede timely management of potentially catastrophic bleeding.

Future Directions

The future of robotic pulmonary resections is simultaneously clear and uncertain. Technologic advances, such as improved systems, innovative instrumentation (energy sources, vascular stapling), and advanced imaging (fluorescence, navigation), are imminently available and will extend the capabilities of the minimally invasive approach and what surgeons who employ them can accomplish. Specifically, it will allow more complex procedures and higher risk patients to be accessible by minimally invasive surgery.

The uncertainty of the future of robotics in thoracic surgery lies in two areas. The first is the fact that the overall penetration of minimally invasive techniques (VATS and robotics) is still well under 50 % despite the fact that advanced VATS pulmonary resections have been around for 20 years. In a recent study of the voluntary, national Society of Thoracic Surgery database designed to compare thoracoscopic to open lobectomy of the 6323 patients, only 20 % were performed by thoracoscopy [12]. However, there may be a role for robotics in affecting a larger transition from open to a minimally invasive approach. Kent and colleagues analyzed the nonvoluntary State Inpatient Databases to compare outcomes between open, VATS, and robotic approaches to lobectomy and segmentectomy [13]. During the study period (2008–2010), the authors observed that as a percentage of total pulmonary resections the percentage of thoracotomy decreased (66–57 %) and was accounted for entirely by increase in those done robotically (0.2–3.4 %) while VATS volume remained flat (40 %).

The second area of the unknown with respect to the future of robotics in pulmonary resection

relates to cost and changes in the economics of healthcare delivery. In the end the perioperative outcomes of VATS and robotics are similar, and it will be difficult to objectively demonstrate discrete patient or system benefits of robotics when compared with VATS alone. Because of the high cost of acquiring the system and ongoing instrumentation and service expense, advocates of a VATS approach will always be able to argue that utilization of robotics adds expense without demonstrating measurable benefit [14].

Summary

Robotic lobectomy is a feasible, safe, and oncologically sound surgical treatment for early-stage lung cancer. The technique is reproducible across multiple centers and yields results consistent with the best seen with conventional VATS. It should not be considered experimental, but an accepted minimally invasive thoracic surgical technique. Successful and safe implementation into clinical practice requires preparation and commitment on an institutional and multidisciplinary team level. The future directions for study of this technology include further refinement of the technique, validation of the adequacy of the oncologic results, and determining methods to compare it with conventional VATS and thoracotomy techniques.

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Single-Site Surgery

13

Dan Eisenberg and Sherry M. Wren

Historical Origins

Single-incision laparoscopy was introduced as a technical advancement of multiport minimally invasive surgery, with a theoretical advantage of less postoperative pain and improved cosmesis. With increasing surgical experience, and after demonstration of feasibility and safety, there has been an increase in the types of procedures being performed using laparoendoscopic single-incision surgical techniques. While over 4,000 single-incision operations have been reported, its clinical potential, efficacy, and risks are not yet clear [1]. Single-incision laparoscopic surgery, like much of early therapeutic multiport laparoscopic surgery, emerged from the field of gynecology. The first reports were published in 1972 from the Johns Hopkins Hospital, where a two-port and two-incision laparoscopic approach to tubal ligation was modified to a single-incision approach [2–4]. Through a single incision at the umbilicus, a 10-mm fiberoptic laparoscope with a 90° offset eyepiece was introduced into an insufflated abdomen. Straight laparoscopic biopsy forceps were introduced through the operating port to perform the bilateral partial salpingectomy. The operation was performed on an outpatient basis, and because it employed a single incision, it was touted to reduce operative time, decrease wound complications, and even reduce the "hazard of visceral perforation" that arises from additional port insertions. Interestingly, cosmesis, although commented on, was not a primary outcome measure.

The field of multiport laparoscopic surgery evolved quickly with emerging technologies over the ensuing several decades, which included the development of automatic insufflators, fiberoptic light cables, and high-resolution video cameras [5]. In 1980, a German gynecologist, Kurt Semm, performed the first totally laparoscopic appendectomy, employing a laparoscope and rudimentary instruments [6]. The first laparoscopic cholecystectomy was performed in Germany 5 years later and successfully performed in the United States in 1989 [7, 8]. It took a few more years before the first single-incision laparoscopic general surgical operation – an appendectomy– was performed and reported by an American gynecologist in 1992 [9].

The field of laparoscopic, minimally invasive surgery continued to develop and expand dramatically, becoming standard of care for numerous operations and routine for operations of the gallbladder, appendix, stomach, colon, adrenal gland, kidney, and abdominal wall [10]. The progression

This chapter contains video segments that can be found on the following URL:

Electronic supplementary material Supplementary material is available in the online version of this chapter at 10.1007/978-3-319-09564-6_13. Videos can also be accessed at http://www.springerimages.com/videos/978-3-319-09563-9.

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of single-incision laparoscopic surgery, however, has been much slower. Navarra et al. described the first laparosopic single-incision cholecystectomy in 1997 [11]. It was performed using two 10-mm umbilical ports and three transabdominal sutures to the gallbladder. The sutures to the gallbladder fundus, neck, and infundibulum were used for traction and countertraction to expose Calot's triangle. Thus, after the retraction sutures were placed, the dissection was performed in the standard manner, using regular laparoscopic instruments and laparoscope. Their main focus was the ability to perform standard operations with fewer surgical scars, without compromise of patient safety or surgical technique. The authors later questioned the safety of this approach and the increase in operative time and continued to modify the technique [12].

In the early 2000s, though, interest in innovation and scar-reduction laparoscopic surgery shifted towards natural orifice translumenal endoscopic surgery (NOTES) when experiments in porcine models demonstrated the ability to access the abdominal cavity through a per-oral transgastric approach [13]. In this study, a gastrotomy was performed using a needle-knife puncture and subsequently closed with endoclips. At that time, transvaginal (NOTES) nephrectomy had already been described in animal models using a 5-mm abdominal port for a laparoscope, and transgastric and transvaginal NOTES appendectomy and cholecystectomy in humans were to be reported a few years later [14–16].

Technical limitations of instruments, in addition to clinical limitations stemming from the creation of an access hole in the stomach, vagina, or rectum, has slowed the adoption of pure NOTES into routine clinical practice. Yet, it renewed the interest in single-incision laparoscopic surgery as a less invasive approach to standard multiport laparoscopy. Concurrently, new advances in instrument and scope design, as well as access devices (ports) specifically designed to have multiple channels, were being developed in response to this interest by surgeons and patients alike. These changes increased the popularity of single-incision procedures and increased the types of operations being performed [17]. Surgeons continue to innovate and are eager to decrease the invasiveness of procedures, develop new techniques, and incorporate available technology to clinical practice. Patients also have shown interest in increasingly minimally invasive approaches and a desire to decrease the number of incisions when undergoing laparoscopic surgery [18, 19].

Laparoendoscopic Single-Incision Surgery

Many different terms have been used to describe abdominal surgery performed using laparoscopic techniques, through a single abdominal incision. Some of the more commonly found in the literature include SPA (single-port access), SILS (single-incision laparoscopic surgery), SPL (single-port laparoscopy), NOTUS (natural orifice transumbilical surgery), and E-NOTES (embyonic natural orifice transumbilical endoscopic surgery) [20]. With a growing body of literature describing single-incision laparoscopic techniques since 2007, the need for a consensus and standardization became obvious. The term LESS (laparoendoscopic single site) is considered the standard for reporting [21, 22], yet the other terms are still commonly used in the surgical literature.

With the move to LESS, there have been some challenges, the major one being the loss of triangulation of camera and instruments on the target anatomy. Physical constraints of the single-incision approach cause the camera and instruments to be in a parallel, instead of a triangulated approach to the target anatomy. Multiport laparoscopic surgery relies on this concept of triangulation to allow for a well-visualized approach to the targeted structures. By approaching the target anatomy from several points separated in space, the surgeon is able to gain a three-dimensional understanding of the two-dimensional image projected on the screen. In addition, the crowding of instruments in the single incision leads to collisions between instruments within the abdomen, awkward hand and body configurations for the surgeon, and interference of the laparoscope's light source with other instruments.

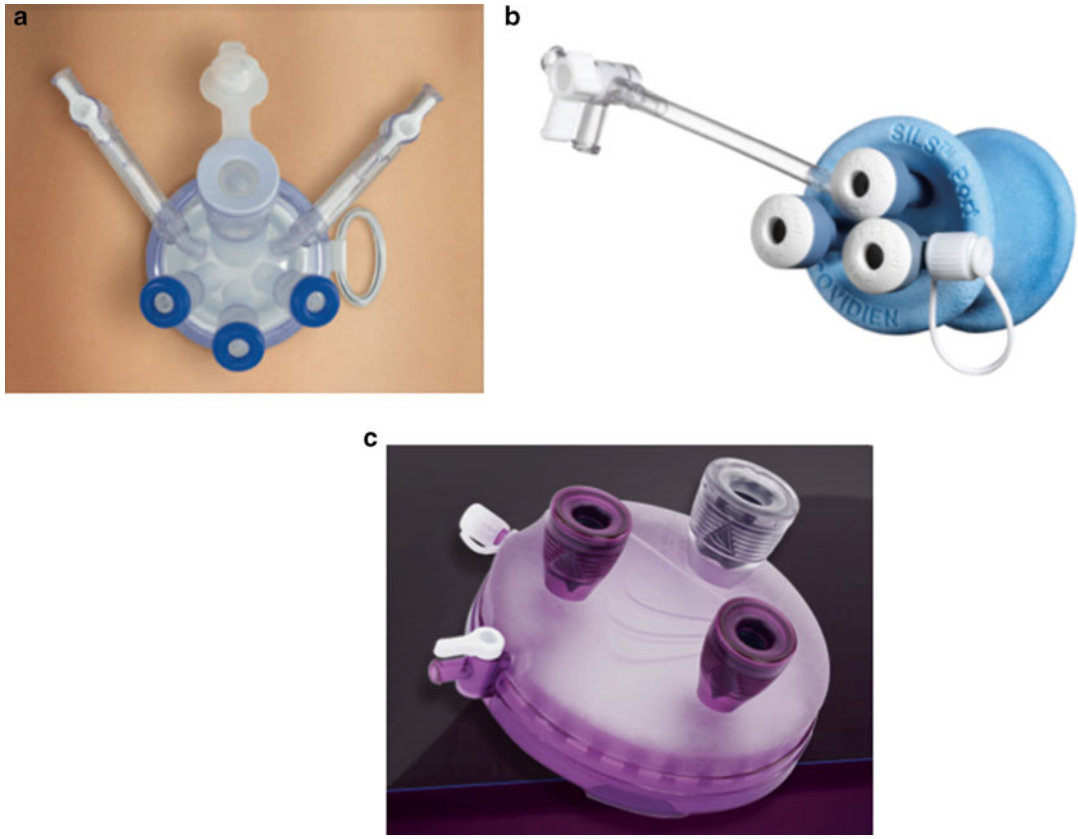

Fig. 13.1 (**a**–**c**) Multichannel ports commonly used in single-incision surgery. (**a**) Triport™ (Courtesy of Olympus, Center Valley, PA); (**b**) SILS Port™ (Copyright © 2013 Covidien. All Rights Reserved. Used with Permission of Covidien.); (**c**) Gel Port (Courtesy of Applied Medical, Rancho Santa Margarita, CA)

Similarly, collisions between instruments and the laparoscope can increase the level of difficulty of basic surgical techniques by making retraction and tissue exposure inadequate [23, 24].

In order to mitigate some of these difficulties, specialized equipment for LESS has been developed to accommodate the need for multiple port entry into the abdomen from a single incision, allow entry of the laparoscope and necessary instruments, and minimize the resultant collisions. The SILS Port™ (Covidien, Mansfield, MA), Gel Port™ (Applied Medical, Rancho Santa Margarita, CA), and TriPort™ (Olympus, Center Valley, PA) are examples of single-incision multichannel ports in common use (Fig. 13.1a–c). They share an ability to be inserted into the abdomen through a skin incision averaging 1.8 mm in length (range 15–30 mm) [25] and contain three-port channels, which allow the entry of two instruments and a laparoscope. Wound complications, such as seroma formation and hernia recurrence as high as 4 %, have been reported at the single-incision site [26].

In an effort to reduce the cost of commercially available multichannel ports, surgeons have devised makeshift devices that serve the same purpose of multiple entry points into the abdomen, through a single skin incision. The use of commonly available, cheap sterile materials, such as surgical gloves, can be used to create a seal through which laparoscopic ports and instruments can be passed [27] (Fig. 13.2). Approaches that are cheaper still employ no additional equipment whatsoever.

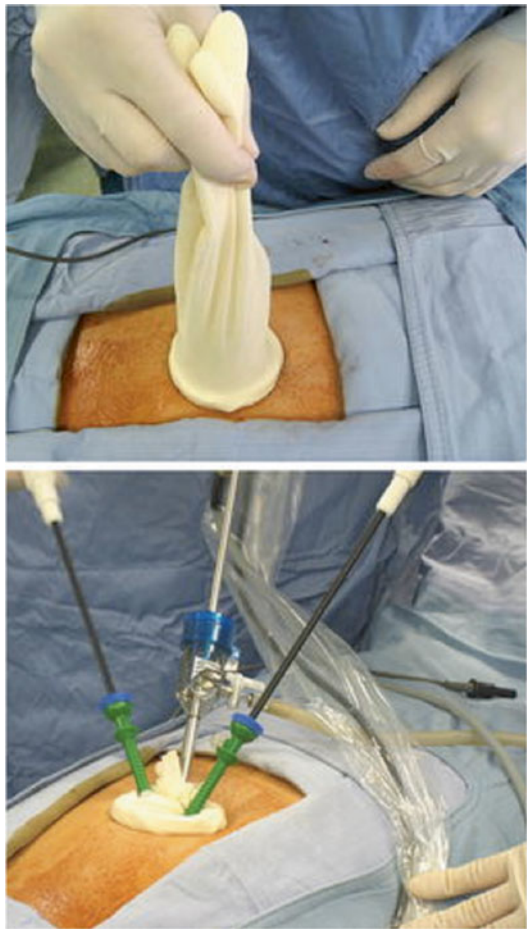

Fig. 13.2 Surgical glove fashioned to serve as a multichannel single-incision port (Used with permission from Ref. [27])

A different approach also employs a single umbilical incision, but relies on skin and soft tissue flaps raised from the underlying fascia to allow insertion of instruments through separate fascial incisions [28]. This technique does not use a specialized port and allows for three instruments and a laparoscope and an additional thin rigid retracting instrument to be introduced into the abdomen. While wound complications still occur, the reported rates of incisional hernia and skin dehiscence remain low [29].

Triangulation on target anatomy remains a problem regardless of which access port or technique is utilized. The LESS approach with standard instrumentation by definition compromises

Fig. 13.3 SILS Hand Instrument™ demonstrating curvature at the distal end of the instrument, which is controlled at the handle (Copyright © 2013 Covidien. All rights reserved. Used with permission of Covidien)

this fundamental concept of laparoscopic surgery. Multiport laparoscopy is typified by standard operative approaches that optimize port and camera placements to facilitate visualization and surgical approach with rigid instruments from preselected points on the abdominal wall. In LESS surgery all the instruments and camera are working from a single fulcrum (typically at the umbilicus); the surgeon's attempts to avoid extracorporeal collisions can result in a sensation of working in mirror image intracorporeally. Flexible or angulated instruments and laparoscopes have been designed to overcome the lack of triangulation, by attempting to reintroduce triangulation inside the abdominal cavity. Instruments that can assume a curved shape in the shaft of the instrument can mimic an eccentric approach to the surgical field (Fig. 13.3). Several instruments such as the SILS Hand Instruments™ (Covidien, North Haven, CT) the Laparo-Angle™ (Cambridge Endoscopic Devices, Framingham, MA), and Spider™ (TransEnterix Surgical Inc., Durham, NC) have been designed specifically for this purpose. This allows for the distal portion of the instrument to approach the surgical field from nonparallel angles and increase the distance between the extracorporeal handles located at the umbilical port, thus avoiding internal and external instrument collisions and re-approximation of triangulation. Often, the design allows for the curvature to be controlled at the instrument handle, by the surgeon's grasp. Such devices exist with instrument heads that are

graspers, shears, hook, and needle drivers [30]. The proper and facile use of these instruments introduces an additional learning curve for the surgeon attempting laparoendoscopic single-site surgery. The curvature of these instruments results in additional degrees of freedom, so that each instrument has a roll, pitch, and yaw motion for which the surgeon must account [31]. Such that not only is the position of the instruments demanding, but attaining proficiency with the use of the instruments is also challenging. In addition, the mechanical grasping forces of these instruments are diminished compared to their rigid counterparts [32]. There may be insufficient joint forces in the articulating instruments to meet the usual operative needs, and a common practice among surgeons who use these instruments is to compensate by using a single rigid instruments along with the single articulating instrument. Many surgeons have not opted to use these more complicated and expensive devices and still also commonly perform LESS surgery with standard, rigid laparoscopic instruments only [33]. This offers the advantage of using readily accessible instruments that are commonly used by the surgeon, as well as avoiding extra costs.

Another technological innovation to try to address some of the limitations of the LESS surgical technique is laparoscopes with flexible tips and those with high-degree lenses. The EndoEye Flex™ and Flex 3D™ (Olympus, Center Valley, PA) and EndoCAMeleon™ (Karl Storz GmbH & Co., Tuttlingen, Germany) are examples of laparoscopes that offer the potential advantage of moving the surgical field of view, without moving the camera itself. The performance of flexible scopes, however, was not shown to be superior to rigid laparoscopes in conventional multiport surgery [34, 35], and studies showing their superiority are lacking in single-incision platforms. These new technologies, however, can paradoxically increase the surgeon's disorientation, make the surgical field seem less familiar, and further lengthen the learning curve of laparoendoscopic single-site surgery. In addition, complex laparoscopic skills, such as suturing, can become a significant challenge [36].

Clinical Experience of LESS Surgery

Since the initial experience with single-incision cholecystectomy in 1997 [11], the LESS cholecystectomy has been reported in a large number of publications, involving hundreds of patients, with acceptable morbidity and a favorable cosmetic outcome [17, 37–45]. In these studies, surgeons employed the multiple approaches as described above, with no individual technique gaining prominence outside of the use of using a single skin incision at the umbilicus to introduce a laparoscope and dissecting instruments. Results have been conflicting for outcomes of pain and hernia formation, but there is a consensus that patients prefer the cosmetic aspects of the single incision. In a prospective, randomized trial of laparoscopic multiport versus single-incision cholecystectomy for biliary colic or biliary dyskinesia, Phillips et al. found the LESS approach to be feasible and safe, with no difference in total adverse outcomes [46]. However, they did note increased operative times and superficial wound complication rates in the single-incision, compared to the multiport approach. Overall superficial wound complications were more than three times greater in the LESS cholecystectomy, yet the rate of postoperative hernia formation was not significantly different. Early postoperative pain was not improved with the LESS approach; however, self-reported scores for cosmesis demonstrated a preference for the single-site approach over multiport surgery [46–48]. Weiss et al. found an overall wound complication rate of 2.5 % in a study of more than 1,000 consecutive patients undergoing single-incision laparoscopic procedures [49]. Factors that were associated with complication included high body mass index, a longer incision, and use of multiple transumbilical ports compared to a single-port device.

In a randomized prospective multicenter trial comparing LESS surgery to standard multiport cholecystectomy, LESS was associated with higher scores for cosmesis, but higher pain and poorer quality of life assessments in follow-up. Wound complications and hernia formation were significantly increased in the LESS approach.

Interestingly, despite this, there was an absolute patient preference for the single-incision technique, and patients were willing to pay more for the LESS technique [26].

Minimizing the number of skin incisions without compromising patient safety while at the same time improving cosmetic outcome and patient satisfaction has been the main motivation for the continued evolution of all laparoendoscopic single-site surgery over the past two decades. Overall morbidity specific to the operation has been consistently shown to be comparable in single-incision and multiport approaches. Yet studies of outcomes specific to the umbilical incision vary in their results. It is hypothesized that a single umbilical incision will have less postoperative pain compared to traditional laparoscopic surgery requiring multiple abdominal incisions. Results are often contradictory. A randomized, controlled trial of 40 patients demonstrated significantly lower pain scores after single-incision cholecystectomy, especially between 12 and 72 h after surgery [50]. In contrast, in a larger prospectively randomized, single-blinded trial, postoperative pain on days 3, 5, and 30 was found to be consistently worse in the single-incision group [26]. Meanwhile, Hao et al. in a meta-analysis of 15 studies and 1,113 patients failed to show an overall significant difference in pain at 24 h postoperatively, with other studies also showing no significant difference at postoperative days 1, 2, and 3 [48, 51, 52]. Patients' perception of cosmesis more consistently favors the single-incision surgical approach compared to multiport surgery. The potential concern, however, is whether improved cosmesis comes at the price of increased hernia formation.

Marks et al. found a significantly higher rate of incisional port-site hernia formation in a prospectively, randomized, single-blinded study with 12-month follow-up data [26]. The overall higher rate of incision-related adverse events, including superficial erythema and cellulitis, correlated with the eventual higher rate of hernia formation. Interestingly, other factors such as body mass index, age, and smoking history were not related to hernia formation. However, this point has not yet been definitively elucidated, as multiple studies failed to show a similar increase in hernia formation at the umbilical incision in single-site versus multiport abdominal surgery [53–55].

The second most common LESS procedure is appendectomy, which has been performed in thousands of patients using single-site surgery, since its first description by Pelosi et al. in 1992 [9]. In the vast majority of cases, appendectomy is performed for presumed acute appendicitis, both in the adult and pediatric population [56, 57]. Amputation of the appendix can be performed either intracorporeally or extracorporeally [58, 59], with removal of the appendix through the umbilical incision. Although operative time trended to be longer in single-incision appendectomies, overall morbidity in general, and wound complications specifically, has not been shown to be significantly different between single-incision appendectomy and conventional three-port laparoscopic appendectomy [58, 60–62].

More complex general surgical operations have been performed as well, including colon resection for benign and malignant disease [63–65] and Heller myotomy for achalasia – although the technical difficulties of single-incision surgery may be increased in these more challenging operations [66–68]. Solid organ resections using single-site techniques have been shown to be feasible, effective, and safe, compared to traditional multiport laparoscopy. Splenectomy, adrenalectomy, nephrectomy, partial hepatectomy, and distal pancreatectomy have all been performed through a single umbilical incision [69–75]. These operations rely, to varying degrees, on technical modifications that allow for tissue and organ retraction to achieve adequate and safe surgical resection. Examples include using transcutaneous sutures to suspend organs to the abdominal wall, using a sponge to encircle an organ and tug on it in a specific direction ("tug-exposure" technique), retracting balloons, and extreme operative table positioning to exploit gravity [74, 76]. LESS surgical approaches are also reported with increasing frequency in urologic and gynecologic surgery.

Robotic Platform for Laparoendoscopic Single-Incision Surgery

Despite the growing number of single-incision operations being performed and the development of specialized ports, instruments, and cameras for LESS surgery, the loss of triangulation, instrument collisions, difficult visualization, and poor ergonomics remain a challenge (Video 13.1). To mitigate these difficulties imposed on the operating surgeon, the standard instrumentation of the da Vinci® robotic surgical system (Intuitive Surgical, Sunnyvale, CA) was utilized in single-incision approaches to common operations [77–80]. The wristed instruments of the robot have the potential to improve visualization in a LESS surgical approach, and the ergonomic difficulties of laparoscopy decreased since the surgeon now is operating at the console. Instrument crowding and external collisions of the robot arms, however, remained a challenge as three rigid robotic instruments were introduced through an umbilical port. In an attempt to decrease collisions, a "chopstick" surgical technique was employed in which the robotic arms cross at the level of the abdominal wall, while the console is instructed to control the right instrument with the surgeon's left hand [81].

To address the difficulties in adapting standard robotic instrumentation to a single-incision approach, a novel robotic single-site™ surgical platform was designed for the da Vinci® robotic system (Fig. 13.4a–c). This platform was designed specifically to address the limitations of single-incision laparoscopy. The platform includes a multichannel access port that allows for an insufflation port, 8-mm camera port, two curved 5-mm cannulae, and a 5-mm assistant port. The curved cannulae cross at the middle at the port, establishing the abdominal wall as the fulcrum and thereby reestablishing triangulation with the camera at the target anatomy and minimizing robotic arm collisions [82]. Then, to compensate for the crossed instruments, the left robotic arm instrument is programmed by the touch of a button on the console, such that it is controlled by the surgeon's right hand and the right instrument controlled by the surgeon's left hand. Thus, the image on the screen matches the orientation of the operating hands, and the surgeon's hands remain uncrossed. This advancement restores intuitive control of the instruments and the surgeon is free to operate in a familiar laparoscopic environment.

The instruments of the single-site™ da Vinci® platform are not wristed. Nonetheless, with the restoration of triangulation with curved instruments, offsetting of ergonomic issues, decreased crowding, and avoiding the need of crossing hands, the da Vinci® single-site™ platform user experience closely simulates standard, multiport laparoscopy. Complex surgical tasks, such as knot tying, can be performed with significant ease using the da Vinci® single-site™ platform, compared to laparoscopic single-incision platforms with rigid or curved instruments [82]. Wren and Curet demonstrated the feasibility of cholecystectomy in a first human clinical study using this platform and also showed that operative times were comparable to multiport laparoscopy [83]. In a multicenter study of 100 consecutive robotic cholecystectomy operations using the da Vinci® single-site™ platform, Pietrabissa et al. demonstrated a very short learning curve and suggested that this is due to the ability of the robotic platform to overcome the current limitations of LESS surgery [84]. Meanwhile, Spinoglio et al. directly compared the robotic single-site™ surgical platform to single-incision laparoscopy in performing cholecystectomy. They found the cystic artery and duct dissection, ligation, and transection easier and safer to perform using the robotic platform [85]. They were able to demonstrate this with a significantly shorter operative time in the single-incision robotic cholecystectomy group, thus suggesting that the robotic single-site™ surgical platform has successfully minimized the limitations encountered in laparoscopic single-incision surgery in cholecystectomy.

More recently, they showed how real-time near-infrared fluorescence can be incorporated with the single-site robotic platform to enhance the surgeon's experience and compensate for

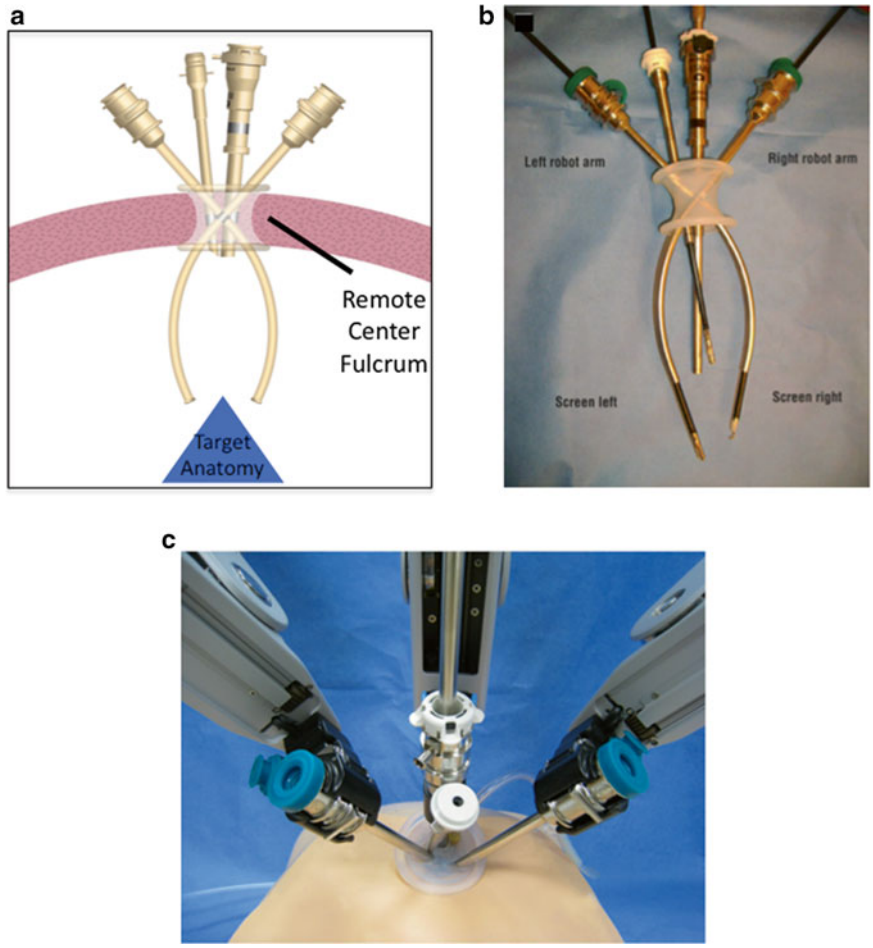

Fig. 13.4 (**a**–**c**) Multichannel port and curved instruments designed for the da Vinci® robotic single-site™ surgical platform (Intuitive Surgical Inc., Sunnyvale, CA). (**a**) Schematic diagram of the multichannel port demonstrating the curved instruments reestablishing triangulation to the target anatomy, with the fulcrum at the abdominal wall. (**b**) Actual da Vinci® single site™ platform with curved instruments, rigid assistant instrument, and laparoscope. (**c**) Single-site platform with robotic arms docked

possible single-site visualization. Indocyanine green near-infrared fluorescent cholangiography is used using this platform in lieu of intraoperative cholangiography to identify the bile duct structures [86] (Fig. 13.5a, b).

In addition to cholecystectomy, the use of this platform has been expanded to include a spectrum of operations that also include splenectomy, nephrectomy, colectomy, and hysterectomy [87–90]. The restoration of triangulation and minimal instrument collisions are credited with decreasing operative time and shortening of the learning curve, while increasingly complex operations are performed. The number and scope of operations performed using the da Vinci® single-site™ platform and reported in the literature has increased over a short period of time, possibly reflecting obvious advantages and ease of use [91].

The rapid adoption of this technology now extends beyond the abdominal cavity. Single-port robot thyroidectomy has been described, using a single incision in the axilla [92]. The operation was associated with acceptable operative times, decreased postoperative pain, and an excellent cosmetic outcome.

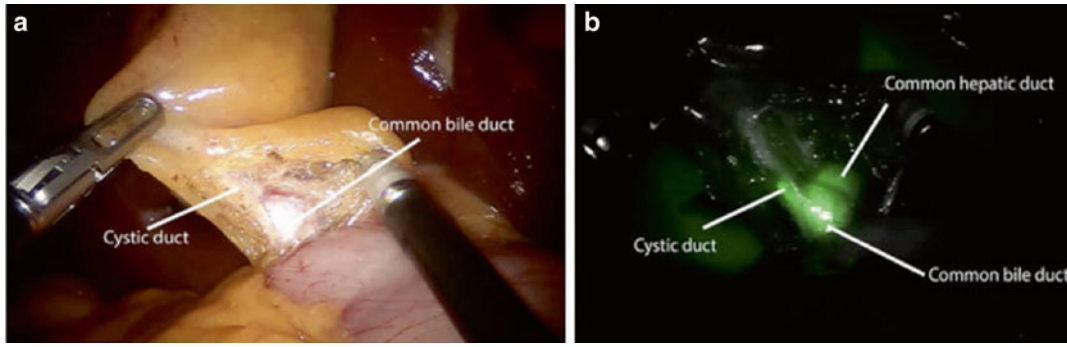

Fig. 13.5 (**a**, **b**) Use of real-time near-infrared fluorescence to demonstrate biliary duct anatomy. (**a**) robotic view of dissection of Calot's triangle. (**b**) Fluorescent cholangiography demonstrating cystic and common bile ducts (Used with permission from Ref. [86])

Conclusions

The number and scope of laparoendoscopic single-site operations continues to increase, as the effort to perform increasingly complex operations with less invasive techniques continues to grow, despite the lack of clear data to suggest its clinical benefit. Limitations due to loss of triangulation, disrupted visualization, instrument collisions, and ergonomics continue to require specific surgeon skill and a long learning curve to master. The single-site™ da Vinci® robotic surgery platform was designed to address these limitations and has been shown to shorten the learning curve, decrease operative time, and increase safety of single-incision operations. The clinical application of this technology continues to grow and the great utility of it may prove to be the ability to assimilate new technologies to this platform.

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Advanced Imaging, Teleproctoring, and Off-Site Surgery

14

Trang Kim Nguyen and Kevin El-Hayek

Introduction

Robotic surgery can be categorized as being a part of the larger context of computer-assisted or computer-integrated surgery [1–3]. In its currently utilized form, robotic-assisted surgery with the da Vinci® system (Intuitive Surgical, Sunnyvale, CA) serves as an intraoperative surgeon extender [3]. The robotic console serves as the hub of information flow with the surgeon receiving input via a magnified, three-dimensional view of the operating field with the surgeon's hand movements being outputted as tremor-filtered, motion-scaled actions by the robotic arms [2].

However, there is potential to expand the scope of robotic surgery beyond the operating room into other aspects of computer integrated surgery with preoperative planning and surgical rehearsal, offline simulation, intraoperative image-guided navigation and teleproctoring, and finally remote location surgery (Fig. 14.1) [4]. The future of robotic surgery will likely be based on furthering the amount of information that goes into the operating console and broadening the output of the console to off-site locations.

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Improving Input into the Robotic Console with Advanced Imaging

The intersection of imaging and robotic surgery was present at the very beginning of robotic surgery with what is considered the first robotic assisted procedure, a computed tomography (CT)-guided brain biopsy, on April 11, 1985, using the Unimation Puma 200 robot [5, 6]. The options for advanced imaging are to utilize either intraoperative images or preoperatively obtained imaging. Each has its own advantages and disadvantages. In its simplest form, imaging integration consists of making images available at the console screen for the surgeon to review. More sophisticated integration consists of merging images with the live camera image.

Current Status of Imaging Integration into Robotic Surgery: TilePro™ and FireFly®

The two options currently available for integrating imaging for use with the da Vinci robot are TilePro™ and Firefly® (Intuitive Surgical, Sunnyvale, CA). The TilePro™ software allows multi-input displays from two data sources to be shown simultaneously with the surgical field at the console [7]. Up to six data sources can be used through S-video or digital visual interface (DVI) inputs. Possibilities for input data include still images or videos such as intraoperative

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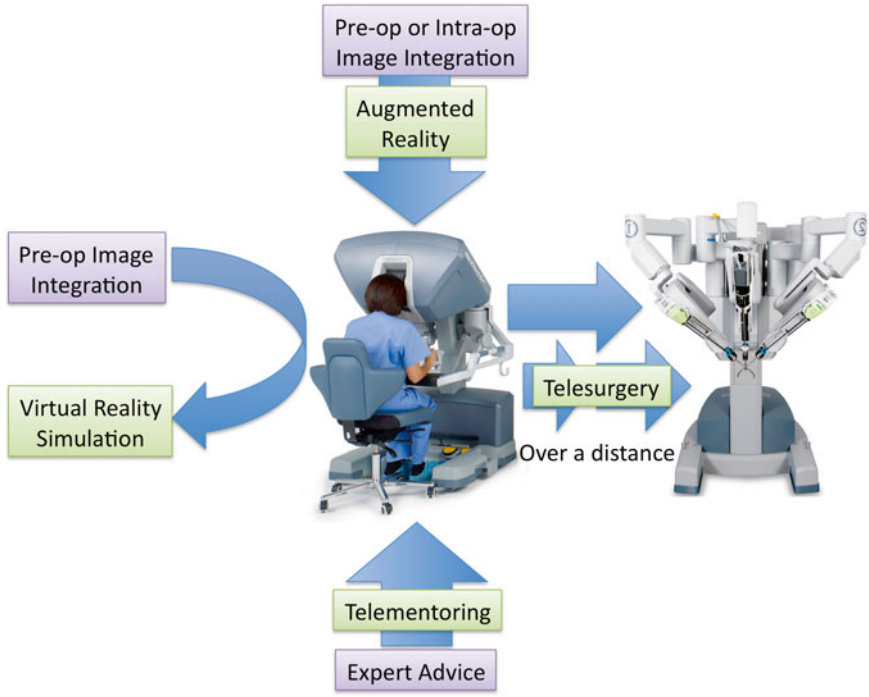

Fig. 14.1 Future directions of robotic surgery. Advances in robotic surgery will be based on expanding the information flow into and out of the robotic console. Image integration will allow for preoperative virtual reality simulation and intraoperative augmented reality. The robotic surgery system also allows future opportunities in telemedicine including telementoring and telesurgery (Image of robotic console and patient cart provided courtesy of Intuitive Surgical)

ultrasound and EKGs [7, 8]. The sources can be toggled to show any two inputs at the same time within the surgical field [7]. These images can be displayed not only at the surgeon's console but also on operating room monitors for other individuals in the operating room. The surgeon can manage the displayed inputs by clicking the camera foot pedal. The surgeon can control the scale of the TilePro™ inputs with a resolution of 512×384 pixels for a 50 % display dimension (Fig. 14.2).

The only intraoperative imaging integration for the da Vinci® system that is currently commercially available is in the form of real-time fluorescence imaging through the Firefly® system [9]. The Firefly® imaging system was approved by the United States Food and Drug Administration (FDA) for the visible and near-infrared fluorescence endoscopic visualization of vessels, blood flow, and related tissue perfusion in February 2011 and of extrahepatic biliary ducts in September 2013 [10, 11]. The system consists of injection of intravenous indocyanine green (ICG) dye and then visualization of the dye with near-infrared fluorescence (NIRF) imaging [12]. The da Vinci® endoscope, in addition to capturing conventional white light, has a near-infrared light (803 nm) to excite the ICG dye and capture the fluorescence with NIRF imaging (Fig. 14.3). The white light and NIRF imaging modes can be switched by the console surgeon using the foot pedal, with the finger clutch, or through the control menu [13, 14]. When in NIRF imaging mode, the NIRF image is overlaid onto a black and white image of the live video [14]. The use of ICG dye and NIRF in robotic-assisted general surgery operations has included standard and single-port cholecystectomy [13–16], partial adrenalectomy [17], low anterior resection (LAR) [12, 18], abdominoperineal resection (APR) [12], and thymectomy [19].

ICG is a water-soluble, non-ionizing, tricarbocyanine compound that absorbs near-infrared

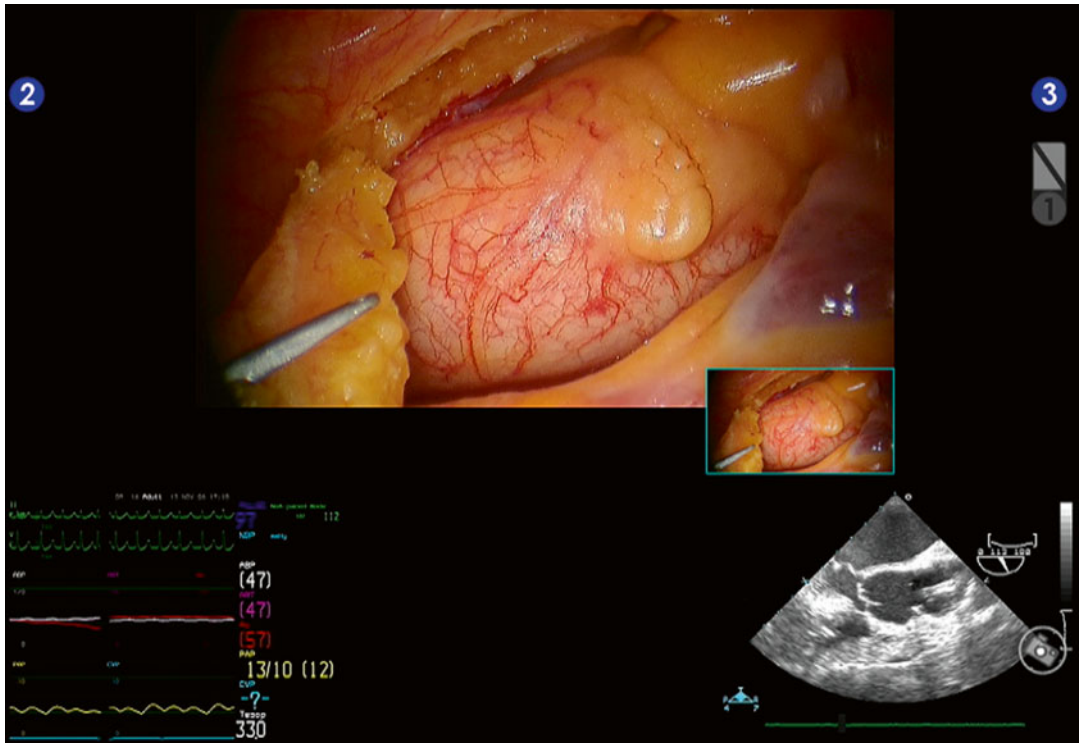

Fig. 14.2 TilePro™. The TilePro™ software allows for simultaneous display on the robotic console of two data sources from S-video or DVI inputs (Courtesy of Intuitive Surgical)

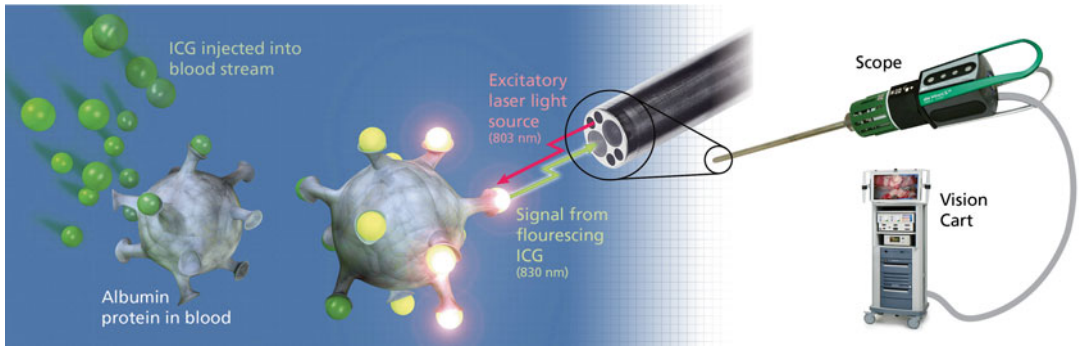

Fig. 14.3 FireFly®. This intraoperative imaging system utilizes an endoscope equipped with NIRF imaging capabilities to detect ICG in blood vessels and extrahepatic bile ducts (Courtesy of Intuitive Surgical)

wavelengths of light with a peak spectral absorption of 800 nm and then emits light at a slightly longer infrared wavelength that can be detected by a NIRF camera [18, 20]. After injection, it binds rapidly to plasma proteins and stays in the vasculature with little leakage into the interstitium. The half-life of ICG is 2–5 min and it is cleared by the liver with no known metabolites [12, 18]. The maximum daily dosage of ICG is 2 mg/kg, and it has been FDA approved since 1959. There have been rare cases of adverse reactions (0.004 %) with ICG that include anaphylaxis, hypotension, tachycardia, hot flashes, sore throat, and dyspnea.

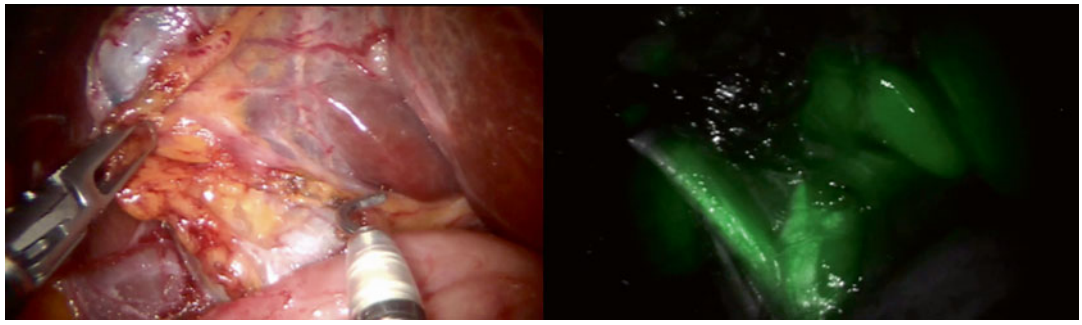

Fig. 14.4 FireFly® for extrahepatic biliary duct identification. White light and NIRF views of the cystic and common bile duct (Courtesy of Intuitive Surgical)

Since ICG is excreted predominated by the liver into the bile, it is useful as a noninvasive method for intraoperative cholangiography that does not require cannulation of a biliary duct (Fig. 14.4) [13, 14, 16]. An approved dosage protocol includes 2.5 mg ICG injected intravenously approximately 30–45 min before the operation and a second 2.5 mg dose of ICG if there is no detection in the liver after 60 min [13]. ICG appears unconjugated in the bile approximately 8 min after injection and its removal from the blood is dependent on hepatic blood flow, parenchymal function, and biliary excretion [14]. In a study of 44 patients who underwent robotic single-port cholecystectomy, 23 of which had intraoperative ICG fluorescence cholangiography and the rest without, Buchs et al. showed that in patients with a body mass index of less than 25, there was a trend towards decreased operative times ($p=0.06$) [15]. In a prospective study by Spinoglio et al. of 45 patients who underwent robotic single-port cholecystectomy, the rates of visualization for the cystic duct, common hepatic duct, and common bile duct prior to triangle of Calot dissection were 93 %, 88 %, and 91 % respectively. At least one of these three ducts was seen in all patients and the rate of visualization of all three ducts increased to 95 % following dissection of the triangle of Calot and a second dose of ICG was never needed. The mean operative time including the intraoperative cholangiogram time was 67 min with a range of 35–110 min [13].

FireFly® can also be used to assess anastomotic perfusion, particularly for low anterior resections (LAR). The optimal transection point is marked in white light mode and then 6–8 mg of ICG is injected intravenously to evaluate the proposed transection point in NIRF mode [18]. In a retrospect case–control study by Jafari et al. of 40 patients who underwent robotic LAR, 16 of which used ICG and NIRF imaging, 6 % had an anastomotic leak in the ICG/NIRF group compared to 18 % in the control group who underwent LAR without ICG/NIRF imaging. Nineteen percent of the ICG/NIRF group had revision of the proposed transection point after ICG/NIRF imaging compared to 5 % of the control group who had revisions based on visual cues such as dusky bowel in white light [18]. ICG/NIRF imaging can also be used during LAR to identify the line of demarcation of the ischemic area of the distal rectum to help determine the distal resection margin [12].

Another indication for Firefly® is for visualization of vascular anatomy. In a case series of three patients who underwent LAR or abdominoperineal resection (APR), the Firefly® system was used to identify the left colic branch of the inferior mesenteric artery [12]. Firefly has even been used to identify the contralateral phrenic nerve in robotic thymectomies through visualization of the associated pericardiophrenic vessels in the neurovascular bundle within 5–10 s after a 6.25 mg bolus injection of ICG followed by 10 ml bolus of normal saline.[19] The ICG is seen for a maximum duration of about 1 min. Repeat imaging, if needed, was performed in at least 5-min intervals to allow for clearance of ICG [19].

Image guidance with NIRF may also have a role in robotic oncologic operations. Although they are not currently FDA approved indications for Firefly®, sentinel lymph node mapping and intraoperative tumor imaging using NIRF imaging has been shown to be feasible during laparoscopic surgery [21]. Options for contrast agents include nonspecific agents such as ICG, methylene blue, or 5-aminolevulinic acid (5-ALA). Tumor-specific contrast agents in development include antibodies or peptides for cell-surface receptors and agents that target increased metabolic activity or tumor-specific proteases [22].

The Future of Incorporating Imaging into Robotic Surgery: Augmented Reality

The proposed advantages of robotic surgery include image magnification and three- dimensional stereoscopic visualization. There are many potential avenues for the incorporation of imaging into the robotic platform, both for preoperative planning and for intraoperative visual enhancement. Advancements in intraoperative visualization can be improved by allowing the detection of important structures beyond the visible surface or by merging preoperative or real-time imaging [23].

The intraoperative merging of images onto the live image of the patient is known as augmented vision or augmented reality [24, 25]. This concept allows for the surface tissue to become virtually transparent and for underlying structures to be visualized [26]. A cornerstone of augmented reality is the registration of the spatial information from imaging modalities to the patient [27]. Image-guided surgery was incorporated previously in neurosurgery, otolaryngology, and orthopedic surgery since fixed, bony landmarks facilitate image registration [1, 6, 24]. The abdominal cavity poses a greater challenge due to the limited number of fixed intra-abdominal reference points and the ongoing movement and changing shape of abdominal viscera by ventilation, heartbeat, patient motion, and surgical manipulation during an operation [26, 28].

For preoperatively obtained data, images must be converted into 3D for an augmented reality system. Several software programs exist for 3D conversion but can be complex to use, require significant training, and have long processing times [25]. One of the most well-known 3D rendering software for preoperative CT scans is OsiriX [29]. In 2012, Volente et al. reported the use of an OsiriX plugin that allows for the 3D rendered images to appear on the da Vinci® console using the TilePro™ display and manipulated using a 3D joystick for five robotic cases. The plugin was used to help identify biliary anatomy during two cholecystectomies, vascular anatomy and ureter location during two sigmoidectomies, and tumor location for a right colectomy [29]. While there was no merging of the preoperative imaging to the live images, this example does represent a solid first step towards creating an augmented reality system by demonstrating the feasibility of displaying a 3D representation of the preoperative images at the robotic console.

In 2009, Su et al. showed that the next step, registration of a preoperative 3D images to the 3D camera image, was possible [30]. This group generated a 3D surface model of the kidney from preoperative CT scans and registered it to video segments of robotic-assisted laparoscopic partial nephrectomies using points on the kidney surface as fixed reference points. While this was all done postoperatively, it shows promise that augmented reality for robotic-assisted surgery is in the foreseeable future.

The Role of Robotic Surgery in Telemedicine

Telemedicine is a term that is used to broadly describe "the use of audiovisual technology, at any distance, to facilitate patient care, administration, or education related to the field of medicine" [31]. Relevant aspects of telemedicine to surgery include telementoring (active guidance of an expert surgeon located remotely during an operation), teleproctoring (accreditation using audiovisual technology from a distance), and telesurgery (operating from a distance) [31, 32].

With an audiovisual technology as an interface, laparoscopic and robotic surgery lends itself to telemedicine and allowing the dissemination of surgical knowledge, skills, and techniques to remote areas [32, 33].

Several challenges are universal for implementing any component of telemedicine. These include having sufficient telecommunications bandwidth, decreasing telecommunication delays to inconsequential levels, setting up an appropriate telecommunications infrastructure, and determining medicolegal liability [33]. Most importantly, there must be an ethical need for telemedicine as the technology may be close to, but not equivalent to having the non-teleapplied version [31]. The need for telemedicine usually manifests when there is a lack of expertise in a given location and it is not feasible, either economically or physically, for in-person expertise [31].

An exemplary case for the use of teleproctoring was described by Okrainec et al. in what they referred to as telesimulation to train surgeons in Botswana in laparoscopic skills [31, 34]. Compared to a group of self-taught surgeons using Fundamentals of Laparoscopic Surgery (FLS) simulators, surgeons who were taught received mentoring from surgeons at the University of Toronto using a system of simulators, computers, webcams, and Skype™ communications and were all able to become FLS certified and achieved significantly higher posttest FLS scores. This training provided an adequate alternative to the costly travel of sending instructors to Botswana. However, due to regulations of the certification, the examination still had to be performed in person. As the use of robotic surgery grows, it is not hard to imagine that there will eventually be an accreditation system for evaluating robotic surgery skills similar to the FLS test.

Several examples of telementoring during surgical procedures have been published, ranging from the mentor being in another building to being on another continent [32]. One of the first reports was in 1994, when Kavoussi et al. reported having an inexperienced surgeon perform a cholecystectomy, splenectomy, and nephrectomy while being mentored by an experienced surgeon at a remote site who had control of the laparoscopic camera [35]. Another study showed that 20 Romanian medical students trained on a virtual reality surgical laparoscopic simulator with a mentor from the United States communicating via videoconferencing was as effective as a local mentor based on tool path length and time for task completion [36]. A review of telementoring publications in 2013 identified 433 operations, with the most common being via the laparoscopic approach [37]. Cases included laparoscopic cholecystectomy, endovascular aortic aneurysm repair, laparoscopic colectomy, and nephrectomy with 38 % of the cases being laparoscopic. Five percent were converted to open and 5 % had reported complications. There was a surgeon satisfaction rate of 83 %.

The Future of Robotic Surgery: Reaching for the Stars with Telesurgery

The initial development of surgical robot systems stems from a proposed study by NASA in 1972 to develop surgical care for astronauts in space using remote-controlled robots [2, 38]. Not surprisingly, the military has a continued interest in developing telesurgery for other harsh environments, such as on the battlefield. For example, the United States Army has a Telemedicine and Advanced Technology Research Center (TATRC) [38]. TATRC-funded research with Intuitive Surgical helped to reconfigure the first generation da Vinci platform into a design that was more suitable for telementoring, and this research supported the design of the da Vinci® Si™ [39].

The inherent challenges of implementing any aspect of telemedicine, such as the robustness and reliability of telecommunications, are even more important when progressing to telesurgery. An early concern was the time delay in carrying out remote surgical manipulations since the stream of data both ways would have to be compressed for transmission [32]. In 2001, the results of the first transatlantic robotic surgery was published by Marescaux et al. using the Zeus Robotic System (formerly Computer Motion, Santa Barbara, CA) and a high speed optical-fiber

network between Strasbourg, France, and New York City. In this study, six cholecystectomies were performed on pigs before performing a cholecystectomy on a human subject [40]. The time delay was 155 ms and the operating surgeons in New York found the system to be reliable and had high confidence in the control of their surgical movements [40, 41]. During a preliminary porcine operation between Strasbourg and Paris, they determined that an acceptable time delay in terms of the surgeon's perception of safety was approximately 330 ms [40]. The world's first telerobotic service was established in 2003 in Canada with the goal of aiding rural surgeons in providing advanced laparoscopic surgery [42]. Between 2003 and 2005, 22 robotic-assisted operations were performed between two hospitals 400 km apart using a commercially available IP-VPN network and the Zeus-TS surgical system [33]. The Zeus robotic system is no longer available commercially after the purchase of Computer Motion by Intuitive [38, 39].

TATRC, using modified da Vinci® consoles, reported on four nephrectomies on a porcine model that were performed over a public Internet connection in 2007 [38]. Resident surgeons operated on a console in the operating room that controlled one of three robotic arms while attending surgeons operated simultaneously on a second console that controlled two arms at distances of 1,300 and 2,400 miles away with a roundtrip time delay of 450– 900 ms [43]. In one of the procedures between Sunnyvale, CA, and Cincinnati, OH (2,400 miles), there was a significant amount of data loss which resulted in brief pixilated images that limited the distant surgeon to a mentoring role instead of active involvement in the procedure. The 900 ms delay was described as cumbersome while the delay of 450 ms was manageable.

Both the United States Department of Defense (DOD) and NASA have supported and conducted research in robotic telesurgery in austere environments. The DOD began the "Trauma Pod" project in 1994 with the goal having surgeons operate from a safe distance on wounded soldiers using autonomous and semiautonomous mobile platforms in an "operating room without people" by 2025 [4, 38]. One obstacle to carrying out telesurgery in a battlefield environment is that the installation of wireless networks is not currently feasible, and a reliable, high bandwidth, low latency network is required. In 2008, Harnett et al. addressed this dilemma by reporting on the first time use of a mobile surgical robotic system (the University of Washington's RAVEN) in an austere environment. This system was controlled by surgeons 30 meters away through a wireless link provided by an unmanned airborne vehicle [44]. The maximum time delay was 20 ms for the robotic control signals and 200 ms for the video stream [45].

NASA conducted several experiments under the NASA Extreme Environment Mission Operations (NEEMO) that have focused on telesurgery at the only existing permanent underwater laboratory, Aquarius [38]. The seventh NEEMO project in October 2004 included simulated procedures such as a laparoscopic cholecystectomy with an AESOP® (Automated Endoscopic System for Optimal Positioning, Computer Motion) arm being controlled 2,500 km away at the Canadian Center for Minimal Access Surgery. During the NEEMO 9 mission, the simulation of suturing skin was successfully controlled by a surgeon in Hamilton, Ontario, Canada, even with an intentionally induced latency delay of 2 s which resulted in a single knot tying taking 10 min [46].

Conclusion

The future of robotic surgery can be traced back to its roots considering the first robotic procedure was an image-guided brain biopsy and the original motivation for robotic surgery development was to perform operations in austere environments such as space. As a computer integrated system, there is potential to improve and expand the inflow and outflow of information into the robotic system. This will lead to the ability for preoperative planning and virtual reality simulation, intraoperative image guidance and augmented reality, and remote telementoring, teleproctoring, and telesurgery.

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Future Directions and Alternate Systems for Robotic Surgery

15

G. Dante Roulette and Myriam J. Curet

Introduction

Surgical robotics, or more accurately, computer-assisted tele-surgery, has two main purposes: first, to increase human performance beyond limitation of a person's inherent physical abilities and second, to perform a surgical procedure at a remote site [1]. As a concept, tele-surgery originated with a 1972 NASA proposal. The initial vision was to provide medical care for orbiting astronauts from a terrestrial base by introducing an electromechanical system between the surgeon and the patient [2]. In the 1980s and 1990s, minimally invasive surgical techniques were developed that allowed the performance of precise surgical tasks through a few, small, incisions using specially developed surgical instruments. Since the dawn of surgical robotics, with the rapid development of computers and a dramatic increase in computational power came the application technology to the execution of surgical procedures. This culminated with the vision of remote tele-operation of surgical robots in the battlefield and the initial funding necessary to develop the current generation of surgical robots [3].

According to Intuitive Surgical Inc., there have been more that 2,500 deployments of the da Vinci® Surgical System, the only surgical robot approved for clinical use. While initial applications were limited, the technology has developed significantly and the number of systems deployed for clinical use expanded greatly. From its initial use in cardiac surgery, indications for use have since grown to encompass many of the surgical fields including urology, gynecology, otolaryngology, and general surgery.

Current advancements in robotic surgery have been intended to minimize, or entirely eliminate, the perceived disadvantages of conventional laparoscopic surgery including restoration of wrist articulation, elimination of surgeon tremor and the fulcrum effect, three-dimensional imaging, and improvements in ergonomics. Future advances in robotic surgery are aimed at enhancing these improvements as well as extending the human senses and using the technical architecture to project and develop surgeon expertise.

Disclosure: Myriam J. Curet, MD, is Senior Vice President and Chief Medical Officer at Intuitive Surgical.

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Human-Machine Interface

Haptic Feedback

With the transition from open to robotic-assisted laparoscopy, surgeons have gradually lost haptic feedback due to interposition of endoscopic instruments or digital control systems [4]. As a

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consequence, when learning robotic-assisted surgery, surgeons must develop a sense of visual haptics. They are required to learn how different tissues deform and react with the various instruments at hand solely based on visual cues such as tissue blanching, deformity, and changes in color– an extrapolation process termed synesthesia [5]. The ultimate goal is of course full restoration of haptic feedback; however, there are significant technical challenges to be overcome, including bandwidth provisioning and cost [1].

These long-term challenges have led several researchers to examine the role of surrogates for direct haptic feedback. A group led by Dr. David Yuh has commented extensively on this idea. In an early publication, they examined substituting visual and auditory cues in place of haptic feedback. Four force-feedback conditions were examined: first, no feedback; second, a single tone when ideal tension achieved; third, graphic display of force levels for each hand; and, finally, a combination of (2) and (3) provided simultaneously. They found that force applied, and the consistency of that force in completion of a surgical task more closely approximated the ideal that without sensory feedback [6]. In a follow-up study, they sought to determine whether haptic feedback improved force application and decreased rates of error (e.g., suture breakage) among surgeons with varying levels of experience. They found that visual feedback reduced technical error and decreased applied force and inconsistency among inexperienced surgeons. In contrast, metrics for experienced surgeons were unaffected, suggesting greater benefit for novice surgeons [7].

Augmented Perception

Robotic-assisted surgery has the advantage of being able to provide a fully immersive, three-dimensional environment. The associated video processing capabilities make possible the inclusion of additional sources of information in this environment. In many cases, the current surgical paradigm makes preoperative imaging available for the surgeon during the procedure. Intraoperatively, this requires interpolation to account for tissue deformity based on landmarks, or fiducials. Several research groups have envisioned a future where the inherent video processing capacity of the surgical system could be utilized to impart real-time, augmented vision for the surgeon.

This requires accurate registration of images and anatomy intraoperatively and can be challenging if the tissues are deformed or altered during the procedure. At a high level, this is a two-step process that first requires gathering relevant preoperative data and the creation of a virtual model of the target anatomy. The second step is adapting the model based on intraoperative data (e.g., tissue deformation) and displaying that information visually [8] (Fig. 15.1a, b). Conceptually, this provides a type of "X-ray" vision during the procedure.

An extension of this work could be to provide haptic feedback based on imaging to guide the surgeon intraoperative. Using models developed base on imaging, it may be possible to define areas to avoid during procedures and provide force feedback during the procedure through the manipulators to the surgeon. In this manner, it may be possible to create a pathway to guide the surgeon to an anatomic target based on preoperative modeling.

Education and Simulation

Training of surgeons has typically followed an apprenticeship model in which the surgeon trainee learns from the master surgeon over a proscribed period of time [9]. An emerging trend in surgical education is the concept of surgical competence, which entails a combination of knowledge, technical skills, decision-making, communication, and leadership skills [10]. Evolution from an apprenticeship model to one based on competence necessitates a transition from subjective to objective evaluation of the surgical trainee [11].

The educational challenges of surgeons in training are unique with respect to robotic surgery. In conventional open surgery, and to a

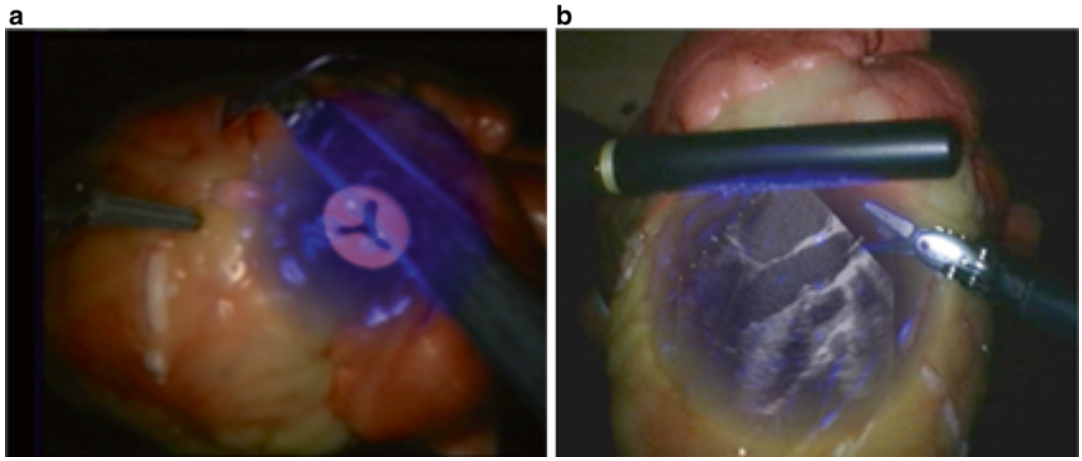

Fig. 15.1 (**a**, **b**) Augmented Reality Image showing (**a**) relation of artificial heart valve and (**b**) ultrasound images shown in-situ (Used with permission from Lee SL, Lerotic M, Vitiello V, Giannarou S, Kwok K-W, Visentini-Scarzanella M, Yang G-Z. From medical images to minimally invasive intervention: Computer assistance for robotic surgery. Computerized Medical Imaging and Graphics: the Official Journal of the Computerized Medical Imaging Society 2010; 34(1), 33–45)

limited extent during laparoscopy, the expert surgeon is adjacent to and shares educational intimacy with the surgeon in training. There is the capacity to assume control and complete the procedure should patient safety be threatened. In robotic surgery, the learner is physically remote in relative terms, with limited ability to assume control of the surgical procedure [12]. Fortunately, the very digital architecture inherent in robotic surgical systems also lends to new modes of teaching and assessment. In 2006, Lin et al. discussed a possible method for automated skill evaluation using motion data [13]. Many surgical procedures are comprised of a series of discrete steps. Using suturing as an exemplar, they first captured motion data using experienced surgeons. Repeating the experiment with inexperienced surgeons, they were able to compare motion data between the two groups to successfully differentiate skill levels. Automatic tracking of skill acquisition based on motion data seems a viable future option.

Surgical simulation allows for learner-centered teaching in a specialized, fully immersive environment. With surgical simulation, the learner is able to acquire baseline skills necessary for operation of the specific surgical platform and tailor learning to deficient areas. In the simulation environment, the learner gains hands-on time while operating in an environment where mistakes are permissible and at times encouraged. Multiple levels of validity have been established for surgical simulation; however, a standardized curriculum is not yet available [14–17].

Efforts at standardization of skills training involving simulation for robotic surgery are underway, with funding from a variety of sources including the Department of Defense and privately available research grants [18]. The most prominent of these are the Robotics Training Network and Fundamentals of Robotic Surgery [19]. These efforts presage a future where robotic surgeons will be required to meet a set of minimum standards prior to being credentialed by institutions.

Beyond surgical training, the future of surgical simulation is in patient customized simulation. The utility of presurgical rehearsal has been established, and the positive impact of simulation on retention of surgical has also been established [20, 21]. Future research is directed toward presurgical simulation based on preoperative imaging to allow the surgeon to practice in an environment substantially similar to what will be encountered at the time of the procedure. The most challenging aspect is the reconstruction and delineation of

anatomic structures [22, 23]. Efforts at developing haptic simulations for biopsy platforms have been described previously [24]. The same group advanced the technology, creating the Unlimited Laparoscopic Immersive Simulator (ULIS), a patient-specific simulator. The initial version of the simulator shows promise as a platform for creating a patient-specific simulation, with future work dedicated toward more automated generation of a realistic environment and integration of simulation software [25, 26].

Tele-mentoring

Much been published on the learning curve for robotic surgery [27]. It is accepted that surgical skill will advance with increasing numbers of cases, and they may benefit from the expertise of co-located surgeons. For surgeons performing laparoscopic procedures in remote locations, tele-mentoring has been shown to positively impact education [28]. The introduction of the robotic platforms and proliferation of high-speed communications networks has renewed interest in tele-mentoring, particularly in countries with remote populations. The Johns Hopkins Urobotics group has successfully tele-mentored several diverse procedures [29]. In a series of experiments, the group was able to use tele-mentoring over an increasing distance to assist in the performance of surgical procedures. This mentoring first occurred at a co-located site, expanding to 3.5 miles, and finally to both Innsbruck, Austria, and São Paulo, Brazil. This was done using previous generation robotic surgery platforms. Given the state of existing technology and the ability to concurrently display imaging studies intraoperative, the progression to the availability of intraoperative tele-mentoring seems reasonable.

Tele-surgery

As currently implemented, robotic-assisted surgery couples the location of the surgeon and procedure; however, this need not be the case. Long-distance tele-surgery is the performance of surgery using a robot platform over a communication link. Previous work on remote tele-surgery has determined latency constraints beyond which surgeons cannot operate; however, conclusive evidence is lacking to define the upper boundary beyond which safe surgery cannot be accomplished. In the initial "Lindbergh operation" between New York City, New York, and Strasbourg, France, a fiber-optic connection employing asynchronous transfer mode (ATM) technology was used to establish a 10 megabit per second (Mbps) connection [30]. The surgeons experienced 155 ms latency between the two sites owing to round-trip travel time and encoding/decoding at each terminus. The authors report average latencies of 135–150 ms for the procedure, with excursions up to 200 ms. Latencies greater than 200 ms resulted in unspecified difficulty adapting during the surgical procedure, with inability to complete procedures at greater than 500 ms latency [31]. Subsequent studies have generally confirmed these boundary conditions, though methodologies are not clearly reported in all [32–34].

Remote tele-surgery has been practically demonstrated between two locations in the Canadian province of Ontario, over a distance of 400 km. Together, two surgeons were able to collaboratively perform 22 procedures including, fundoplications, colon resections, and inguinal hernia repairs, using a Zeus TS surgical system (Intuitive Surgical Inc., Sunnyvale, CA) [35]. Historically, the dissemination of advanced surgical techniques, including minimally invasive procedures, has relied on the development and mentoring of a large body of experienced surgeons in a given community. Mentoring, while effective, is expensive and for many reasons impractical in remote locations [31]. It is anticipated that remote tele-surgery will augment dissemination of advanced surgical techniques. In addition, remote surgery may improve economic parameters and improve patient access to care by overcoming logistical limitations (e.g., proximity to referral centers or resource constrained healthcare systems).

Emerging Platforms

The introduction of robotic technologies into the surgical field has allowed surgeons to undertake increasingly complex tasks through ever-smaller incision, advancing the overall agenda of minimally invasive surgery. Developments in the surgical field tend toward minimizing the number and size of surgical incision, improvement in cosmesis, and decreased recovery time [36]. Future developments in robotics platforms are aimed at the development of flexible access surgery – the undertaking of complex procedures through single-incision or natural orifice routes [37].

da Vinci® Xi™ Surgical System

The da Vinci® Xi™ Surgical System (Intuitive, Inc., Sunnyvale, CA), the newest model from Intuitive Surgical, was recently released. It was designed to offer improved anatomical access, improved high-definition, three-dimensional vision, easier setup and guidance, and as a platform for advanced technologies. The da Vinci® Xi™ Surgical System combines the functionality of a boom-mounted system with the flexibility of a mobile platform (Fig. 15.2). This hybrid architecture enables placement of the surgical cart at any position around the patient while allowing four-quadrant anatomical access. The diameter of the surgical arms has been decreased, while the length increased to allow for a more flexible port placement. Redesigned arms and joints offer a greater range of motion, thus minimizing arm collisions (Fig. 15.3). A new patient-side cart graphical interface has been designed to be simple to use and easy to learn. Features include a guided walkthrough and voice assistance. A laser targeting system (Fig. 15.4) has been included to assist with placement of the patient cart. Once the camera arm is docked and the camera inserted, the surgeon points the scope at the target anatomy and the system will automatically position the boom to ensure an optimal arm configuration for the procedure. The endoscope has been redesigned, with a weight less than half the

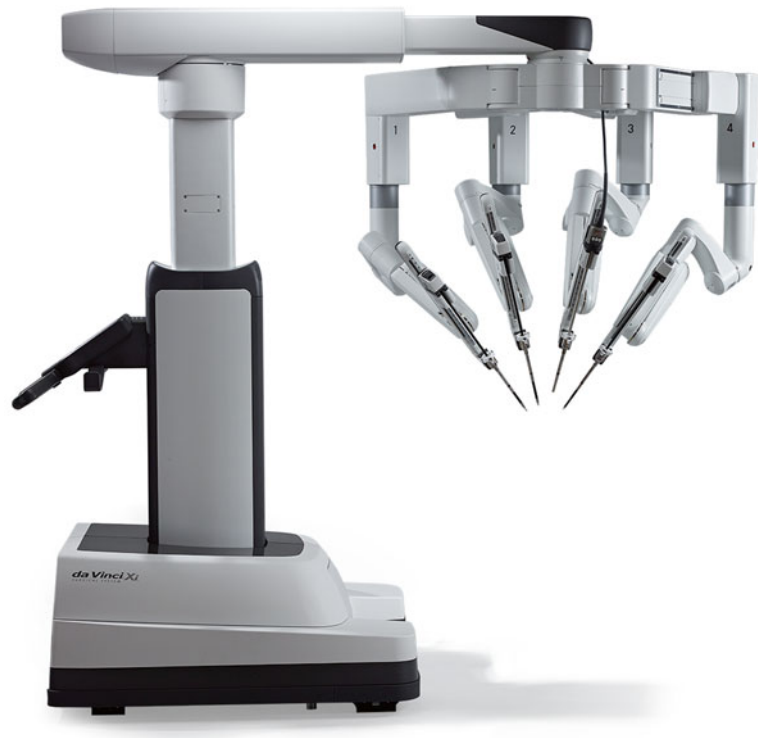

Fig. 15.2 The daVinci® Xi™ system (Courtesy of Intuitive Surgical, Inc.)

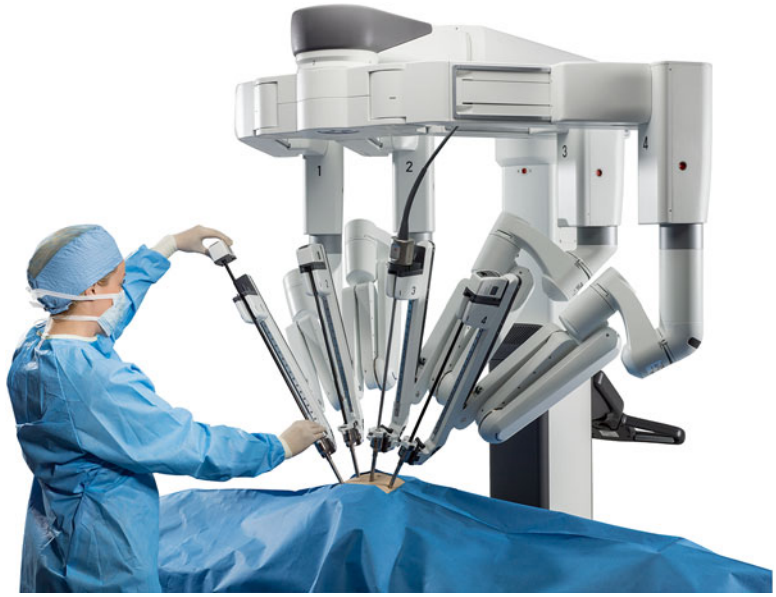

Fig. 15.3 Redesigned arm placement allowing for increased range of motion (Courtesy of Intuitive Surgical, Inc.)

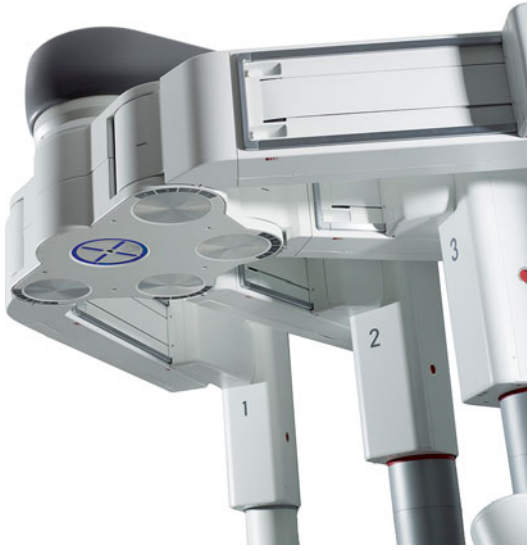

Fig. 15.4 The laser targeting emitter used to assist with docking (Courtesy of Intuitive Surgical, Inc.)

Fig. 15.5 The redesigned, smaller endoscope (Courtesy of Intuitive Surgical, Inc.)

previous generation systems, and optics are now mounted at the tip of the scope (Fig. 15.5). The camera, endoscope, and cable are integrated into one handheld design. The scope can be placed in any of the four arms, providing port hopping capabilities and increased flexibility for visualizing the surgical site. An additional benefit is the lack of camera draping, focusing, white balancing, or calibration. The capacity for fluorescence imaging has been added to each da Vinci® Xi™ system. Fluorescence imaging provides real-time visualization and assessment of vessels, bile

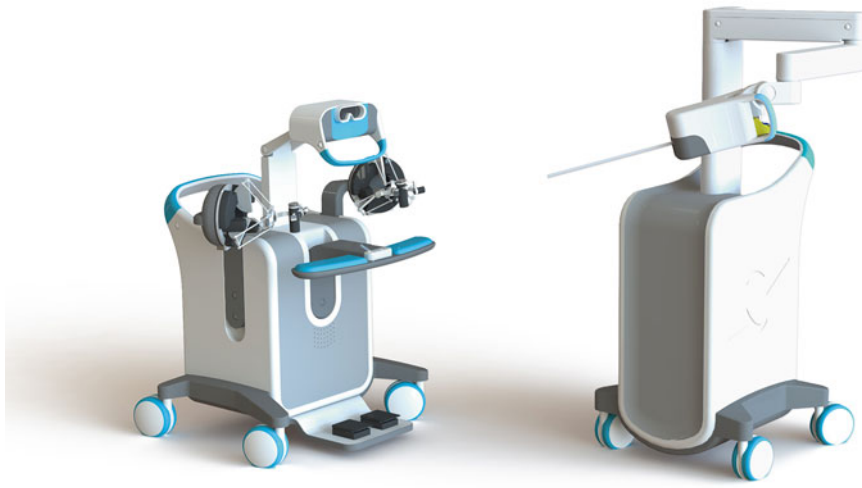

Fig. 15.6 The Single Port Orifice Robotic Technology (SPORT™) Surgical System consists of surgeon console (*left*) and patient-side operating console (*right*) (Copyright © 2014 Titan Medical Inc. Image for illustrative purposes only and does not represent the final product)

ducts, and tissue perfusion. As a platform, the da Vinci® Xi™ Surgical System is designed to seamlessly integrate innovations, such as advanced instrumentation, surgical skills simulation, software upgrades, and other future advancements.

Amadeus

The most anticipated competition to the most widely deployed robotic surgical system, the da Vinci® Surgical System (Intuitive Surgical Inc., Sunnyvale, CA), is Amadeus Composer™ (Titan Medical Inc., Toronto, ON, Canada). Like its competitor, if realized, the expectation is that it will be composed of a surgeon console, patient-side cart, and system-processing tower, and it is expected to include haptic feedback [1]. At this time, no information on development is available, and information regarding the system has been removed from the company website.

SPORT™

The Single-Port Orifice Robotic Technology (SPORT™) Surgical System (Titan Medical Inc., Toronto, ON, Canada) represents the commercialization of the previously known Insertable Robotics Effectors Platform (IREP) developed initially at Columbia University [38]. The system was created to address the market for a fully contained surgical system capable of deployment through a single incision. The system is comprised of a surgeon console and patient-side operating console. The first contains that actuation system for the operating components of the system, while the second houses the surgeon interface and imaging processing. Mechanically, the system consists of a single 25 mm instrument with two dexterous arms and a controllable stereoscopic imaging module. Each dexterous arm is comprised from a two-segment continuum snake robot containing two active segments and one passive segment. Each active segment bends in 2 degrees of freedom by push–pull actuation. The passive segment connects the active segments to the actuator. During introduction into the surgical area, deployment causes separation of the arms such that triangulation is possible [39]. As of November 2013, tissue testing has begun with full commercialization planned for 2015 (Fig. 15.6).

Flex® Robotic System

The Flex® Robotic System (Medrobotics Corporation, Raynham, MA) is the successor

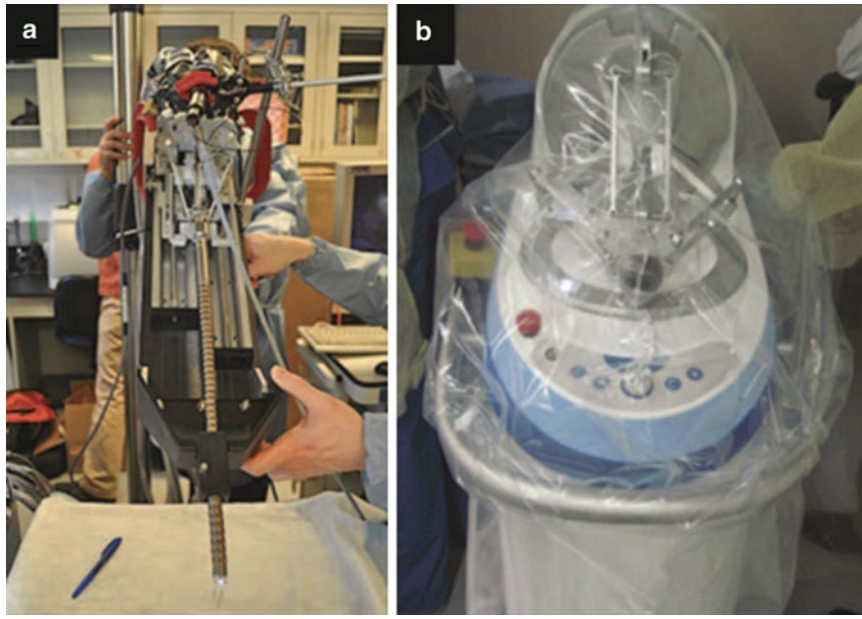

Fig. 15.7 (**a**, **b**) The Flex® Robotic System (Medrobotics Corporation, Raynham, MA). The flexible robot (**a**) is guided by controls on the surgeon console (**b**) (Used with permission of Rivera-Serrano CM, Johnson P, Zubiate B, Kuenzler R, Choset H, Zenati M et al. A transoral highly flexible robot: Novel technology and application. The Laryngoscope 2012; 122(5), 1067–1071)

system to the cardioARM and Highly Articulated Robotic Probe (HARP). The surgical system has since been modified to include a stiffening overtube with two lateral flexible ports for instrumentation. Initially developed to perform epicardial-based procedures via a subxiphoid incision, investigational procedures have since been expanded to include those where minimally invasive procedures are limited due to constrained anatomy [40]. The device is comprised of 50 rigid cylindrical links, serially connected by three cables, with a total length of 300 mm. The distal end is 10 mm in diameter. The device employs a "follow-the-leader" mechanism that preserves the previous three-dimensional configuration as it advances. There are separate units housing the mechanical instrumentation and a controller comprised of a 2 degree of freedom joystick, with button control for forward/backward movement. Initial porcine experiments have been limited to anatomic navigation and proof-of-concept procedures [41]. Recent cadaveric models for transoral surgery have demonstrated the usefulness of the system and the ability to execute basic maneuvers and visualization of human anatomy [42]. The system shows promise; however, the limited curvature radius and velocity need to be overcome (Fig. 15.7a, b).

MiroSurge

The MiroSurge (DLR, Germany) system is an attempt at the creation of a flexible robotic surgery platform. In contrast to clinically available systems that are comprised of monolithic units, the MiroSurg system is comprised of several independent units that have the capacity to operate singly or in concert [43] (Fig. 15.8). These units are controlled from a separate surgeon console, comprised of a general-purpose computer, with specialized software, and a stereoscopic display. The central component of the system is the MIRO robot, a general-purpose end-effector. This unit is attached to the operating table, thus decreasing the occupied space when compared to commercially available systems. With the MiroSurge system, the specialization of the

Fig. 15.8 The MiroSurge System (Courtesy of DLR. Copyright © DLR)

robotic arm is based on the MICA instrument that is attached. These instruments may take the form of a stereoscopic camera or one of several specialized surgical tools. Each arm provides 4 degrees of freedom of movement, which combine with the attached instrument to provide a total of 6 degree of freedom available to the surgeon during a procedure. The instruments are designed to provide haptic feedback to the surgeon through bimanual controllers. Alternatively, the surgeon may use specialized surgical forceps equipped with reflectors to control the system through a touchless interface [41]. Unique to this system is a patient registration procedure that assists with optimization of system placement. Prior to the procedure, insertion points are planned based on preoperative imaging and the type of procedure to be performed. After registration, the system automatically projects optimized location data onto the patient, thus assisting with setup [44].

Miniature Robotics

In contrast to the flexible endoscopy systems that incorporate robotics, an alternative is the use of several small intracorporeal robots that in concert are capable of complex surgical procedures. In this model, each independent robot would be simultaneously introduced, with each responsible for performing its designated task [45]. In an initial publication, Shah et al. commented on their work with small imaging robots [46]. These were designed for insertion into an insufflated abdomen, held aloft by magnetic interaction with a handle located extra corporeally (Fig. 15.9). An associated lighting robot was introduced, with a design similar, but containing light emitting diodes, also held in place through magnetic means. Both of these instruments could be moved by external manipulation of the electromagnets, with fine tuning performed via internal mechanisms. Mobile, in vivo robots, or modular crawlers, composed of two independently driving wheels, can be placed inside the peritoneal cavity to work in concert with imaging and lighting robots to execute surgical tasks via remote control [47] (Fig. 15.10a–d).

neuroArm

The neuroArm system (neuroArm Surgical, Calgary, Alberta, Canada) is an MRI compatible surgical robot composed of a surgeon console, system control cabinet, and two surgical manipulators on a moveable platform at the patient side.

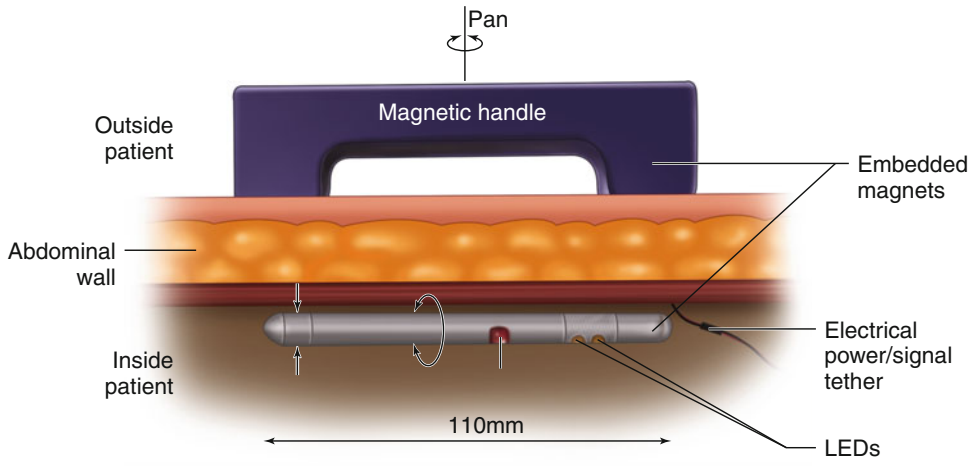

Fig. 15.9 Placement and manipulation of the imaging robot

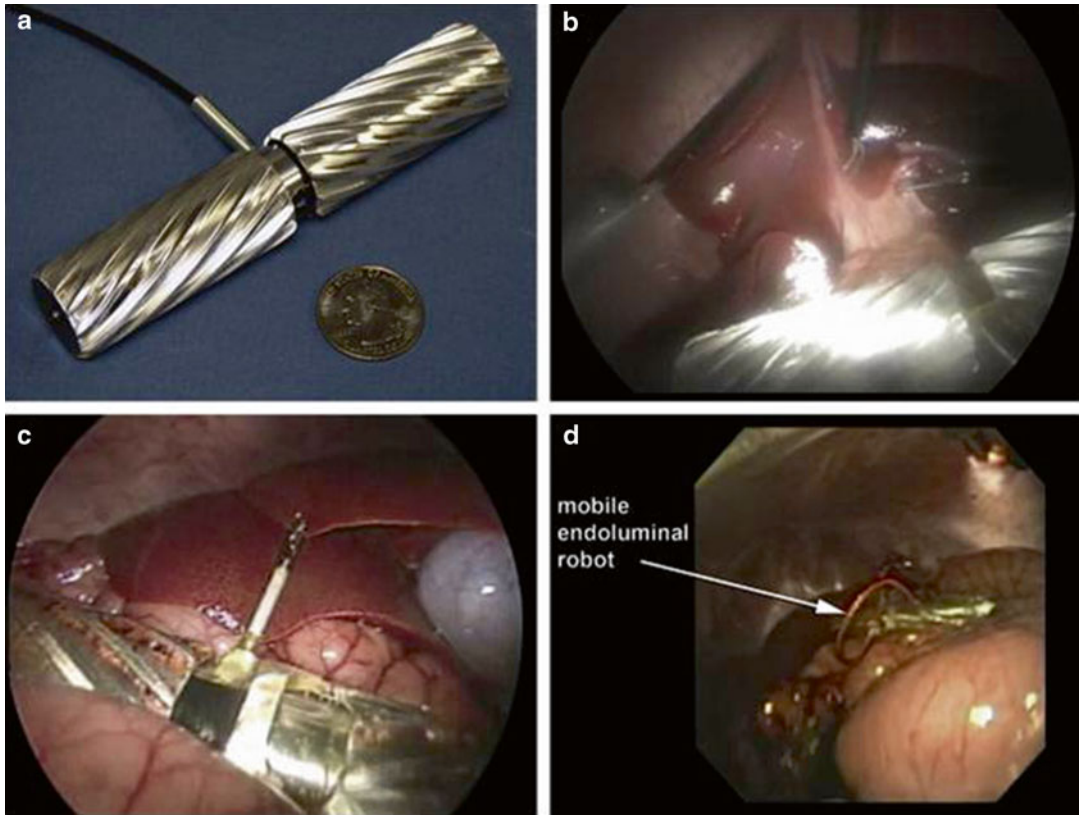

Fig. 15.10 (**a**–**d**) Multiple mobile crawler robots performing porcine liver biopsy (Used with permission of Elsevier from Shah BC, Buettner SL, Lehman AC, Farritor SM, Oleynikov D. Miniature in vivo robotics and novel robotic surgical platforms. The Urologic Clinics of North America 2009; 36(2), 251–63–x)

The surgical manipulators use existing and specially modified instruments and have 7 degrees of freedom. The arms are composed primarily of titanium and plastic composites for MRI compatibility. Haptic feedback is provided to the surgeon through stylus-equipped (Wanswer, Inc., Markham, Canada) PHANTOM hand controllers (SensAble Technologies, Inc., Woburn, MA). The surgeon console is physically isolated from the patient, who may be enclosed in the MRI unit. It includes a stereoscopic display unit, as well as integrating ancillary video monitors and touch screens. The system is unique in that it is capable of both stereotaxy and microsurgery. Thus, it is able to introduce and remove material from the brain and directly perform procedures [48]. The system has been used in 35 cases, primarily performing tissue dissection in the last 15, after the surgeons became experienced with its clinical operation. Beyond haptic feedback, unique features include the ability to designate virtual "no-go" zones, isolating the end effectors to the surgical site, and the "z-lock," enabling straight-line movement toward a target irrespective of controller input. The second generation, neuroArm II, is currently under development. Anticipated are smaller size, finer control and accuracy of movement, and the ability to operate at a smaller scale [49].

EXPERT

Neurological procedures require continuous, precise, maneuvers. Executing these maneuvers requires stabilization of the surgeon's hand and instruments in the appropriate position. Surgeons have the option of using a freely movable armrest for support during extended procedures; however, it is not widely used due to the need for frequent manual interaction [50]. A group in Japan has developed the EXPERT system, an intelligent armrest that uses robotic technology, to automatically provide support for the neurosurgeon [51]. Physically, the system is composed of an arm holder, holder support, and base attached to a standard operator chair. The arm holder is shaped to fit the forearm and contains a 6-axis force sensor between the arm holder and support. The arm support mechanism has 5 degrees of freedom. The surgeon wears a ferromagnetic wristband that connects to electromagnets in the arm holder through the sterile gown and drape. By analyzing the signal from the force sensor, the entire mechanism is able to transition between three working modes (transfer, arm-holding, and arm-free) without direct human input. In the transfer mode, the arm holder follows the surgeon's arm. The system supports the surgeon's arm weight in arm-holding mode, by fixing the arm holder in place. The surgeon's arm can move away from the patient in the arm-free mode. In clinical use, the system has been used in 13 surgeries without complication related to the instrument. The EXPERT system has been shown to decrease surgeon fatigue and markedly reduce tremor in initial results [48].

Natural Orifice Translumenal Endoscopic Surgery

Natural Orifice Translumenal Endoscopic Surgery (NOTES) combines techniques associated with traditional laparoscopy with endoscopy. This emerging approach presents several unique challenges related to instrumentation and currently has several drawbacks, including limited stability, triangulation, and dexterity, as well as inadequate visualization [43]. Attempts have been made at adopting current robotic platforms to perform NOTES procedures. While successful, these experiments have also revealed a need for technology specific to this method of access and type of procedure [52].

SPRINT

The Single-Port lapaRoscopy bImaNual roboT (SPRINT) is a tele-surgical platform specifically designed for NOTES procedures [53]. It contains a surgeon console, insertion tube, stereoscopic camera, and associated manipulators. When fully realized, the insertion tube will have a 30 mm diameter affixed to an external frame during

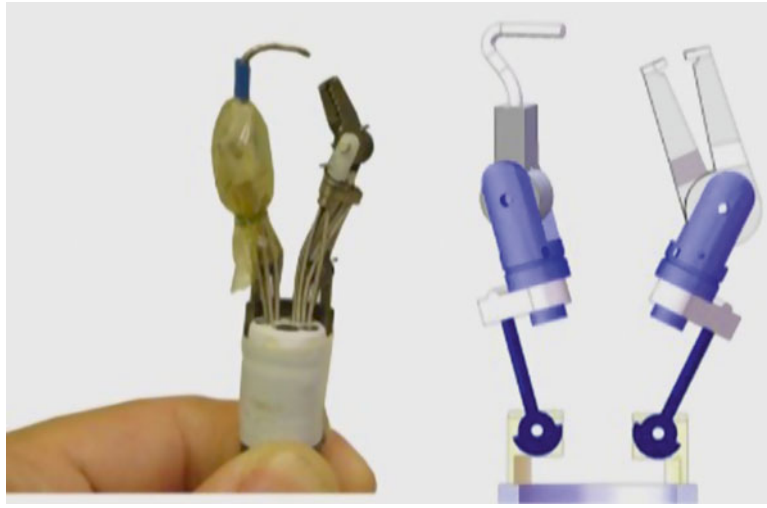

Fig. 15.11 The MASTER robotic slave manipulator adapted to the endoscope and the design of the end effectors (Used with permission from Phee SJ, Ho KY, Lomanto D, Low SC, Huynh V A, Kencana AP et al. Natural orifice transgastric endoscopic wedge hepatic resection in an experimental model using an intuitively controlled master and slave transluminal endoscopic robot (MASTER). Surgical Endoscopy 2010; 24(9), 2293–2298)

operative procedures to provide a stable base. The multi-arm manipulator will be introduced through the access port, providing 6 degrees of freedom, plus the gripper. The stereoscopic camera is also inserted through the same cannula, situated superiorly to allow for triangulation. The surgeon console contains a high-definition, three-dimensional display with two PHANTOM Omnio haptic controllers. The system is in prototyping, with the current version unable to fully realize the design configuration. The prototype system has been used in proof-of-concept models with a porcine model requiring midline laparotomy to perform bowel anastomosis with a running suture, and vessel ligation [54].

MASTER

The Master And Slave Transluminal Endoscopic Robot (National University of Singapore) is a prototype system meant to address the inherent constraints when performing natural orifice procedures [55]. It is specifically meant to address the visualization, dexterity, and triangulation issues encountered with traditional endoscopy. The system is comprised of a master controller, surgical workstation, and a single manipulator that houses a grasper and monopolar electrocautery hook (Fig. 15.11). The master controller is linked to the manipulator via electrical and mechanical cables that are routed through the two operating channels of a forward-viewing, dual-channel, therapeutic endoscope. The system is connected to a standard endoscopy platform and electrical surgical generator and manipulated via a custom master controller. No overtube is required. The end effectors each have 9 degrees of freedom (four for each arm, plus one gripper). A limited number of procedures have been performed, including trans-gastric endoscopic liver resection and endoscopic submucosal dissection [56–58]. To date, only animal trials have been completed, and no human clinical trials are available. As is common with adaptation of endoscopic instruments, the amount of grasping force was limited, and no attempt was made at tissue suturing. This will have to be addressed prior to widespread adoption.

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Index

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