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Anesthesia for Robotic Surgery

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KEY POINTS:

- Robotic surgery has witnessed explosive growth. Currently (2018) more than 3 million procedures have been performed using the da Vinci system worldwide.[1]
- Robotic surgery is not true autonomous surgery but instead the robot is used as mechanical "helping hands" aiding skilled surgeons.
- By creating three-dimensional views, allowing increased movement of laparoscopic instruments within a patient's body, and allowing precise movements, robotic surgery can enhance a surgeon's ability to visualize pathologies and to perform complex procedures.
- Given the size of robotic equipment and the need for specific patient position during procedures, robotic surgery may present unique challenges for anesthesia providers.
- To facilitate surgical exposure, robotic surgery often requires insufflation of a body cavity with carbon dioxide. Insufflation and resorption of carbon dioxide can lead to a variety of physiologic changes.
- Robotic surgery has been successfully used to care for patients receiving urologic, gynecologic, colorectal, hepatobiliary, otolaryngologic, cardiac, and thoracic procedures.

What Is a Robot?

According to Merriam-Webster, a robot is "a machine that resembles a living creature in being capable of moving independently (as by walking or rolling on wheels) and performing complex actions (such as grasping and moving objects)." Developed in the 1980s by the National Aeronautics and Space Administration (NASA), a robot is a remotely controlled device that allows tasks to be performed in spaces removed from human presence. Eventually, robots began to perform tasks aboard NASA spaceships. While the initial concept of robotic science was useful in space exploration, the U.S. government began looking for other applications of the technology.

The US Department of Defense (DOD) began working to apply the robots that were useful in space to the battlefield. Recognizing that an inordinate number of American soldiers died on the battlefield from hemorrhage or untreated surgical wounds, the DOD looked to use these technologies in surgical theaters. With the goal of having a surgeon remotely operate on patients in difficult-to-reach locations, the military invested in developing remotely controlled articulating arms that could perform surgical procedures.

At the same time, the world's first laparoscopic cholecystectomy was performed in France. This procedure forever altered the course of traditional surgery, and the minimally invasive era of surgical procedures began.

Over the next decade, several companies developed a variety of medical robots and rapidly advanced the science. The first such device appeared in the early 1990s, when an instrument was created to pulverize bone and create space for hip prosthesis during orthopedic surgery.

As work progressed on creating devices to perform procedures, work also continued on allowing remote control of devices. In the mid-1990s, voice recognition software was used to control a laparoscope's position and to aid in organ retraction during traditional laparoscopic surgery. This device, called Automated Endoscopic System for Optimal Positioning (AESOP), is still available today (Fig. 71.1). In many ways, this device was the precursor to the smart devices in our homes and on our persons.

Arguably the greatest advancement in robotic surgery occurred in 1991 when a master-slave version of a robot was developed. This device allowed a surgeon to sit apart from his/her patient and remotely control articulating arms. Two similar devices, the da Vinci Robotic Surgical System, and the ZEUS Surgical System, appeared on the market at similar times. The parent company of da Vinci, Intuitive Surgical, acquired the intellectual property rights to the ZEUS system and discontinued the product. As a result, only the da Vinci Robotic Surgical System is available for use today (Fig. 71.2).

Eventually, high-definition, three-dimensional cameras were added to robots, allowing surgeons to explore a patient's anatomy and access traditionally difficult-to-reach surgical sites from a console located next to the operating table. While several robotic companies have developed products, at the moment, only two remain: AESOP and da Vinci.

The da Vinci robot has four components (Figs. 71.2 and 71.3):

1. Surgeon console (Figs. 71.4 to 71.6)
2. EndoWrist instruments (Figs. 71.7 and 71.8)
3. Optical vision cart
4. Patient cart with four movable arms (Fig. 71.9)

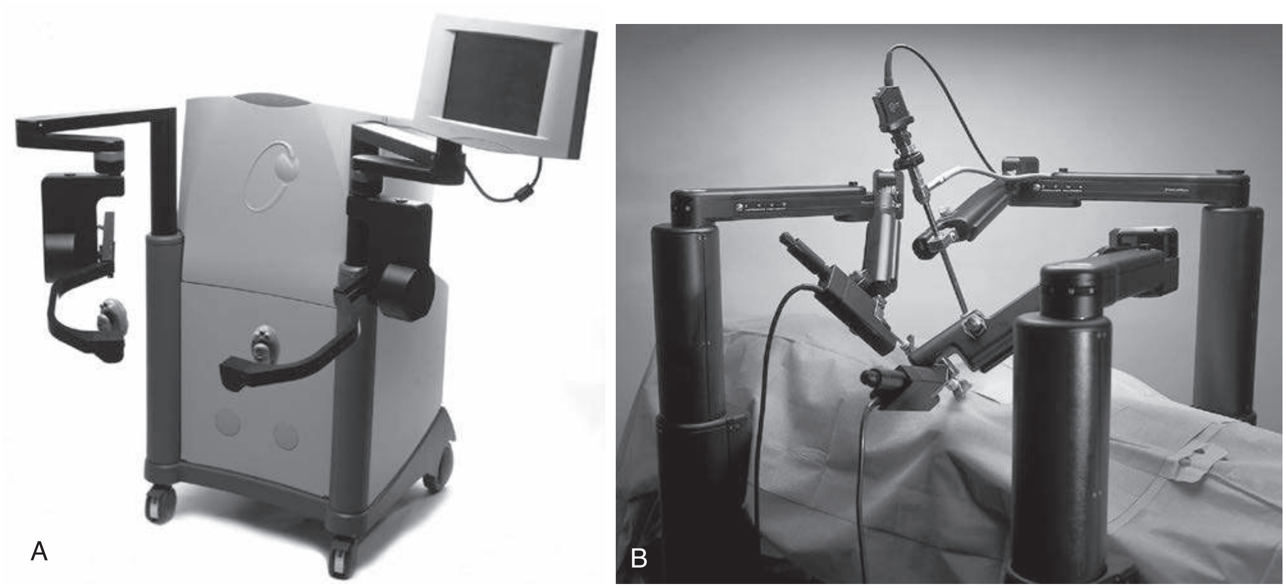

Fig. 71.1 (A) The console of the ZEUS robotic telemanipulation system consists of a video monitor and two instrument handles that translate the surgeon's hand motions into an electric signal that moves the robotic instruments. (B) Two table-mounted Automated Endoscopic System for Optimal Positioning (AESOP) arms hold instruments, and a third arm controls the camera. (Courtesy Computer Motion, Sunnyvale, CA, USA.)

Fig. 71.2 The da Vinci Robotic Surgical System: two surgical consoles, patient-side cart with four mounted surgical arms, and an optical tower. (Courtesy Intuitive Surgical, Sunnyvale, CA, USA.)

The surgeon sits at the surgeon console (see Figs. 71.4 and 71.5) and remotely controls the EndoWrist instruments that are attached to the patient cart. Anesthesia personnel, surgical assistants, and circulating nursing staff may see the procedure in real time via the screen on the optical vision cart (see Fig. 71.2).

During an operation, the surgeon views two high-definition monitors that mimic a binocular or microscope. This two-monitor view creates three-dimensional images. The surgeon's arms rest on the master controls, and his/her fingers manipulate the levers that control EndoWrist articulation. Foot pedals control electrocautery, movement of the robotic camera, and disengagement of robotic instruments. To facilitate collaboration and training, the da Vinci machine will often have two consoles allowing two surgeons to participate in the patient's care.

Why Is the Robot Preferred?

The robot is preferred to open procedures because it allows a minimally invasive approach to surgical pathologies. Less tissue manipulation leads to fewer adhesions and potentially faster recovery from surgery. Fewer wound complications, including infections and incisional hernias, and shorter hospitalizations make robotic surgery attractive when compared to other minimally invasive or open techniques.[2] Further, the robotic approach to surgical procedures allows discrete movements that are helpful in microsurgical dissection and re-attachment of tissues. In comparison with human arms, robotic arms permit seven degrees of free movement. These movements can be categorized into: gross arm movement by the da Vinci robot, fine movements by the articulating arms,

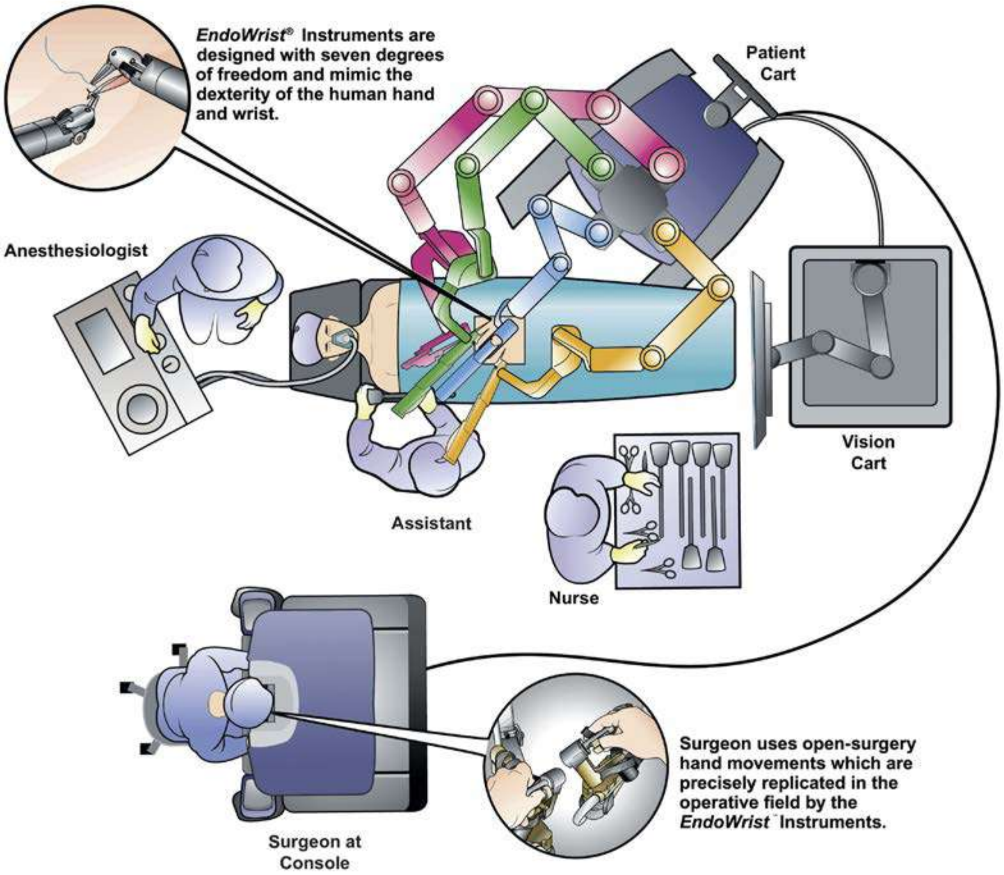

Fig. 71.3 Operating room schematic of the use of a robotic surgical system in general surgery. (Courtesy Intuitive Surgical, Sunnyvale, CA, USA.)

Fig. 71.4 The da Vinci Robotic Surgical System: the surgeon console. (Courtesy Intuitive Surgical, Sunnyvale, CA, USA.)

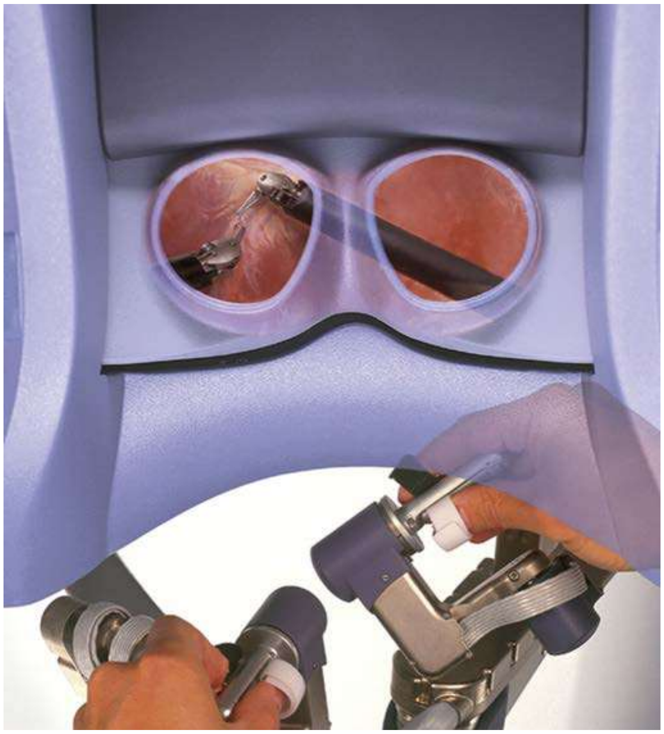

Fig. 71.5 The da Vinci Robotic Surgical System: stereo viewer that creates a virtual three-dimensional stereoscopic image. (Courtesy Intuitive Surgical, Sunnyvale, CA, USA.)

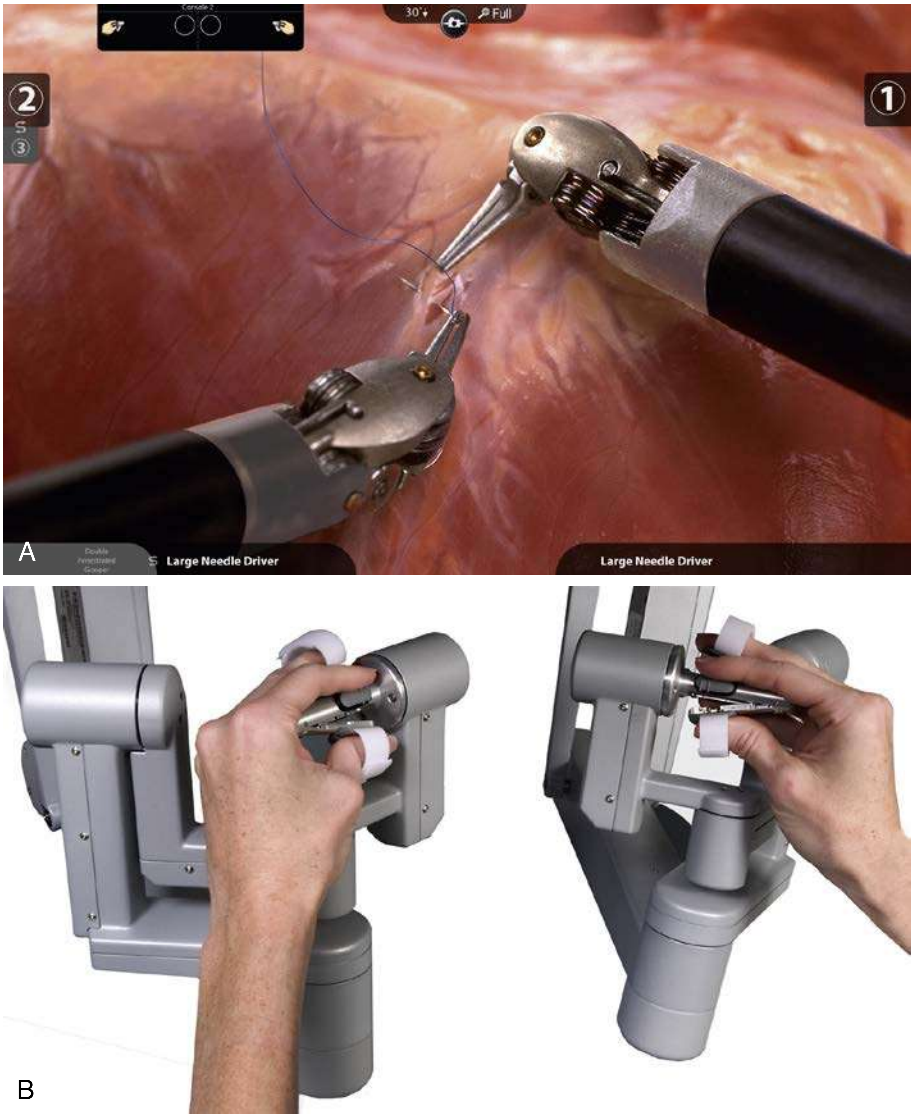

Fig. 71.6 The da Vinci Robotic Surgical System. (A) Virtual three-dimensional stereoscopic image of the surgical field. (B) Master controls that translate the surgeon's hand, wrist, and finger movement into real-time movements of surgical instruments inside the patient. (Courtesy Intuitive Surgical, Sunnyvale, CA, USA.)

and surgical actions performed by the articulating arms (Table 71.1, Figs. 71.7 and 71.8).

These articulating arms are not limited by constraints associated with human wrist joints. Additionally, the robot allows for larger, more coarse movements to be miniaturized in the operating field. For example, moving the controls by 5 mm may move the articulating arms by only 1 mm. This miniaturization permits more fine control. Furthermore, robotic software can reduce or eliminate hand tremors, thereby improving the safety and precision of surgery.

When Is the Robot Used?

The robot is used in hysterectomy, prostatectomy, nephrectomy, cardiac surgery, colectomy, general laparoscopic, thoracoscopic, and transoral otolaryngologic procedures. Although most procedures performed using the da Vinci robot are urologic (prostatectomy) and gynecologic (hysterectomy), a wide range of new applications are being discovered.

Essentially, robotic surgery is helpful whenever microsurgery is necessary and the target organ is difficult to reach. It is especially valuable if its usage converts what is traditionally an open procedure to a minimally invasive procedure.

Future Applications of Robotic Surgery

As imaging modalities and artificial intelligence are applied to robotic surgery, the field will evolve. It is probable that nonrigid, flexible articulating arms of progressively smaller size will ultimately replace the current, rigid articulating arms. "Snake-like" articulating arms will facilitate fewer and smaller incisions to be made in a patient and allow less invasive, perhaps even scar-free, surgery to be performed. Finally, as artificial intelligence evolves, it is possible that semi-autonomous robotic surgery will develop with computer algorithms guiding surgical instruments.

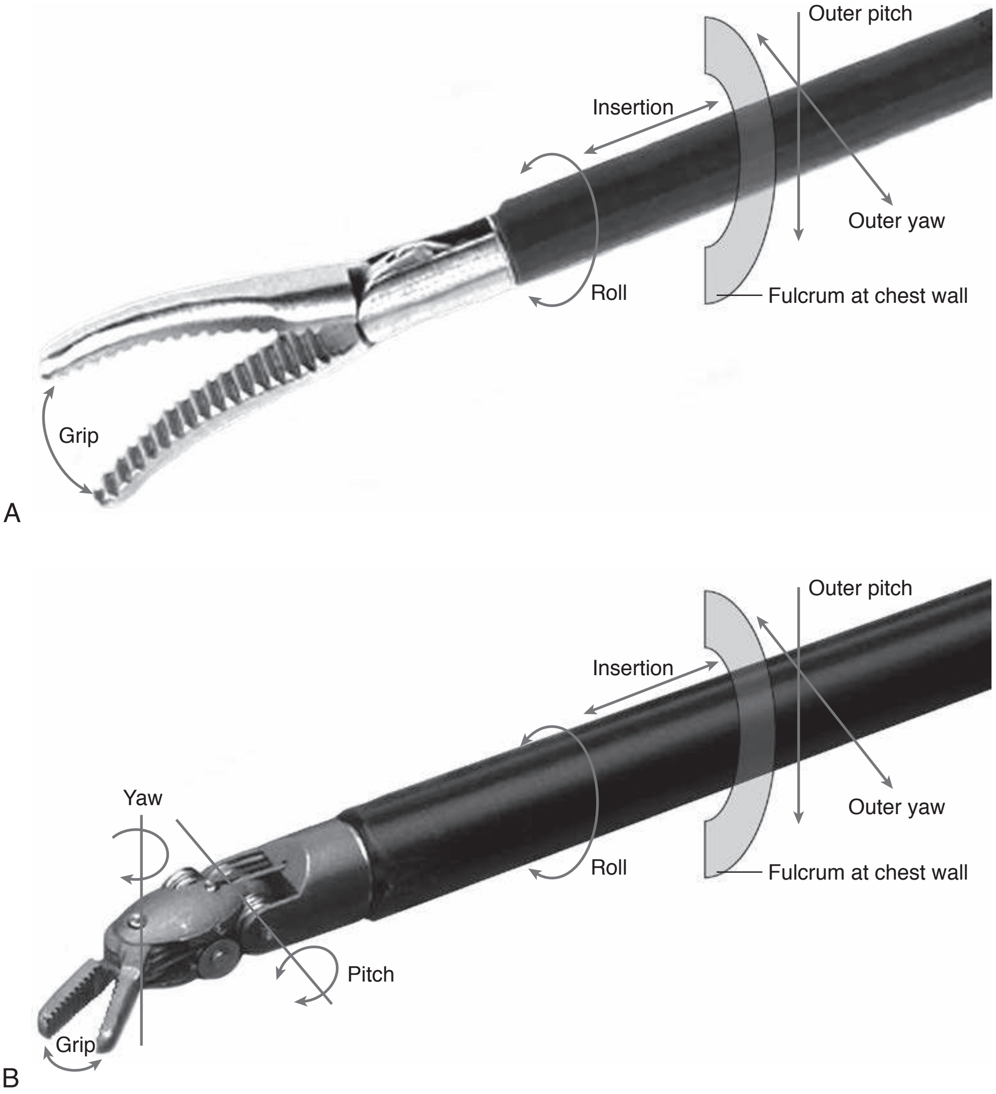

Fig. 71.7 Degrees of freedom (DOF) in motion. (A) Conventional laparoscopic instruments have only four DOF and grip. Insertion (i.e., movement in the *z*-axis), roll, and movement along the *x*- and *y*-axes outside the body relative to a fulcrum point constitute the four DOF. (B) Depiction of the EndoWrist instrument with two added intracorporeal joints, producing seven DOF. (Copyright 1999 Intuitive Surgical, Sunnyvale, CA, USA.)

ROBOTICALLY ASSISTED INTUBATION

There have been reports of successful robotic intubations. The Kepler Intubation System (KIS), developed by Thomas Hemmerling, has been shown to intubate mannequins successfully by an operator who has either a direct or indirect view of the patient. KIS is a low-cost system consisting of a joystick, a robot arm, the Pentax videolaryngoscope, and a software control. The intubations occurred within 40 to 60 seconds with a 100% success rate on the first attempt. This system also allowed for semiautomated (a computer system replayed prior operator driven movement sequences) intubations that occurred in less than 45 seconds and had a 100% success rate.[3] The system has also been used on 12 patients and was successful with a first-pass intubation in 11 of the 12 patients (1 was unable to be completed due to fogging of the equipment). The intubations were done in approximately 93 seconds.[4,5] It remains to be seen if a robot intubation system will have widespread use. However, it may have applications in settings where it would be difficult to transport a trained anesthesia provider to the location, such as deep space exploration.

ROBOTIC SURGERY PHYSIOLOGY

Robotic surgery causes a number of physiologic changes. Positioning, insufflation with carbon dioxide (CO_2) to allow visualization of the surgical field, and physiologic changes associated with increasing intracompartmental pressure (i.e., abdominal, thoracic, or oral) are all seen with robotic surgery. Therefore, it is imperative that anesthesia providers are aware of these perturbations so that appropriate compensatory plans may be created.

Insufflation With CO_2

Except for otolaryngological procedures, inert gas must be insufflated into a patient's body to visualize the surgical field. CO_2 is the inert gas of choice because it has a high diffusion coefficient and the risk of a gas emboli is minimized since CO_2 is easily excreted from the body through the respiratory

Fig. 71.8 The EndoWrist instrument of the da Vinci Robotic Surgical System mimics the natural kinematics of the surgeon's hand and wrist. This design allows more degrees of freedom. (Courtesy Intuitive Surgical, Sunnyvale, CA, USA.)

Fig. 71.9 **The da Vinci Robotic Surgical System: patient-side cart.** (Courtesy Intuitive Surgical, Sunnyvale, CA, USA.)

TABLE 71.1 Seven Degrees of Free Movement Permitted by Robotic Arms

Gross Arm Movements	Wrist Movements	Surgical Actions
In and out	Yaw (side-to-side and left-right)	Grasp or cut
Up and down	Pitch (up and down)	
Side-to-side	Rotation and roll	

system.[6] As CO_2 is insufflated into the abdomen, surgeons exercise caution to keep intraabdominal pressures below 20 cm of water. By minimizing intraperitoneal pressure, the vagal stimulation from elevated intraabdominal pressure is minimized. However, if the patient has a particularly pronounced resting vagal tone or a significant vagal response to peritoneal insufflation, pharmacologic intervention by the anesthesia provider or reduction of pneumoperitoneum may be necessary.

Insufflating the surgical site with CO_2 also may lead to sudden increases in CO_2 in the blood stream because it is absorbed from lymphatic and venous plexi.[7] As a result, increasing minute ventilation is necessary to maintain normocarbia and to keep the patient in homeostasis.

Another potential untoward effect of CO_2 insufflation is gas embolism.[7] Although rare, a gas embolus may have catastrophic effects on the cardiopulmonary system if the embolus becomes lodged in the pulmonary system. Additionally, if a patient has an atrioseptal or ventriculoseptal defect, he or she may develop a gas embolus in the cerebrovasculature with potentially devastating complications.

A more common and less devastating complication of gas insufflation and increased intraperitoneal pressure is atelectasis. This is exacerbated by the effects of insufflation on diaphragmatic excursion.[8] CO_2 insufflation may lead to pneumomediastinum or subcutaneous emphysema (incidence of 0.43%-2.3%). Although this finding typically has no clinical consequences, it may be associated with prolonged CO_2 excretion postoperatively causing hypercarbia and acidosis. Also, there have been reported cases of pneumothorax caused by extension of insufflated gas through diaphragmatic congenital channels into pleural cavities (incidence of 0.03%). An increased incidence is associated with an increased number and size of trocars, longer surgical time, higher gas flow rate, intensified gas pressure, loose trocars, and difficult trocar placement. Due to a number of factors, such as lack of external visualization and haptic feedback during robotic surgery, there is an increased incidence of gas extravasation.[9]

Pulmonary Vasoconstriction

Pulmonary vasoconstriction results from insufflation due to:

1. CO_2 absorption, and
2. physical compression of the lungs.

CO_2 absorption results in hypercarbia and acidosis. The pulmonary system's response to hypercarbia is vasoconstriction, in order to preserve gas exchange by preferentially shunting blood away from less ventilated portions of the lungs. Therefore, carbon dioxide insufflation has a vasoconstricting effect on the pulmonary vasculature.

In addition, during robotic surgery, pneumoperitoneum results in compression atelectasis as the intrathoracic pressure competes with elevated intraperitoneal pressures resulting in lung tissue compression. This process is worsened by Trendelenburg positioning. Nasogastric or orogastric tubes may facilitate gastric decompression and help reduce, albeit not eliminate, increased intraabdominal pressures. As functional residual capacity decreases, patients may experience increased lung collapse and atelectasis. This phenomenon combined with the vasoconstriction due to the CO_2 insufflation increases the ventilation/perfusion mismatch. This mismatch results in decreased oxygenation.

Atelectasis also leads to hypoxic pulmonary vasoconstriction (HPV). HPV is a compensatory mechanism that allows the body to preferentially divert blood from oxygen-poor regions of the lungs to oxygen-rich regions. and improves gas exchange by shunting blood to areas of the lung that are ventilating normally.[7] This effect appears to be caused by mitochondrial sensors inspiring voltage-gated calcium channels to increase the cytosolic calcium, thereby leading to vasoconstriction.

Insufflating the peritoneum also decreases respiratory compliance and elevates airway pressures. This process makes ventilation increasingly difficult and worsens the aforementioned hypercarbia.[10] To improve ventilation it has been recommended to switch mode from volume control ventilation to pressure control ventilation (PCV). However it has been shown in a randomized trial of patients for robot-assisted laparoscopic radical prostatectomy that aside from lower peak airway pressures and improved compliance in the PCV mode, there was no benefit in other parameters, such as: central venous pressure, mean pulmonary arterial pressure, pulmonary capillary wedge pressure, cardiac index, arterial oxygen pressure, mean airway pressure, physiological dead space, and intrapulmonary shunt fraction.[11]

Elevated CO_2 levels also shift the oxyhemoglobin dissociation curve to the right via the Haldane effect. This shift in the dissociation curve helps deliver oxygen to the tissues and results in slightly less ischemia than would be expected.[12-14] A potential explanation for this phenomenon is that carbon dioxide inspires the Haldane effect and HPV.

Cerebral Vascular Effects

Increased absorbed CO_2 from insufflation also leads to cerebrovascular dilation. Although CO_2 leads to blood being preferentially shunted away from the pulmonary vasculature, CO_2 in the cerebral circulation leads to cerebral vascular dilation. Anesthesiologists must be mindful of the potential increase in intracranial pressure (ICP) that may arise from elevated CO_2 levels.[15,16] Additionally, a number of robotic procedures require steep Trendelenburg positioning to allow surgical visualization of pelvic structures, which also results in increased ICP. Anesthesiologists must be cognizant of possible increased ICP especially in cases where patients need a ventriculoperitoneal shunt due to baseline increases in ICP.

Systemic Effects of Hypercapnia

Hypercapnia will lead to a respiratory acidosis as CO_2 is combined with water and is metabolized into bicarbonate and hydrogen ions. Since bicarbonate does not effectively buffer the acidosis induced from hypercarbia, a respiratory acidosis occurs.[17,18]

Hypercapnia will augment anesthetic effects. Acute hypercapnia will also result in depressed consciousness when $PaCO_2$ exceeds 80 mm Hg.[19] Increased CO_2 also decreases myocyte contractility and can potentially increase the myocardial susceptibility to arrhythmias.[20]

Patient Positioning. Patient positioning during robotic surgery can present a challenge. By definition, robotic surgery requires remote operation of laparoscopic equipment and surgical instrumentation. Therefore much of the normal feedback between surgeon and patient is altered, as surgeons are removed from their patients and replaced by bulky steel instrumentation. Therefore, patients are at much higher risk of iatrogenic injury than their nonrobotic peers. Also, this separation from the patient, and working from the inside of the surgeon console, makes communication between the operating room team and the surgeon difficult.

To minimize nerve injuries, careful attention must be paid to patient positioning. Given the size of the robot, a patient's arms are tucked at his or her sides and are often inaccessible during an operation. Once a robot has docked, access to the patient is hampered. Therefore, if an anesthesia provider is considering additional intravenous/arterial access, consider placing these lines after induction of the anesthesia and prior to docking of the robot. A best practice is to place at least two intravenous catheters in addition to an extra noninvasive blood pressure cuff with an extra connector and hose prior to docking of the robot. This allows more flexibility with intraoperative monitoring of the patient, even during periods of very minimal access.

Further, the type of surgical procedure creates unique positioning considerations. If surgeons are operating on pelvic organs, patients require steep Trendelenburg positioning. Alternatively, if patients are receiving abdominal wall surgery, then the supine positioning is often required.

If a patient is to be placed in steep Trendelenburg position, then the best practice is to tuck a patient's arms at his or her sides to minimize brachial plexopathy from hyperextension of the arms. In addition to minimizing the risk of brachial plexus injury, a patient's arms may be tucked at his or her sides to also allow the robot access to the patient. Foam padding and silicone pads are employed to protect vulnerable nerves. If the patient's arms are not tucked at his or her sides, then care must be paid to making sure brachial plexus injuries do not occur from hyperextension of the arms. Additional padding may be necessary to protect a patient's face, head, and neck from robotic arm movements, and vigilance by an anesthesia team is mandatory.

Given the need for patient immobility during a procedure, continuous neuromuscular blockade is paramount as patient movement resulting from intense surgical stimulation in the setting of inadequate anesthesia or insufficient neuromuscular blockade may lead to significant patient injury. To allow for titratable paralysis during robotic cases, many clinicians infuse neuromuscular blocking agents. As a result, continual monitoring of neuromuscular blockade is imperative. Many anesthesia providers place *multiple* intravenous lines so that boluses of medications and fluids may be given through one line while infusions of vasoactive or neuromuscular blocking agents may be given through another.

Please note that the robot arms and the patient's operating room table may not move together. Therefore, once the robot is docked and the robot arms are inside the patient, it is paramount to avoid dyssynchronous movement of the operating room table to avoid tearing injuries of tissue inside the patient.

Physiologic Changes Associated With Patient Positioning

CARDIOVASCULAR EFFECTS

Robotic urologic and gynecologic procedures require steep Trendelenburg positioning to facilitate surgical exposure. When patients are in a steep "head-down" position, blood is funneled from the lower extremities to the right atrium, thereby increasing pre-load. Studies demonstrate a variety of conclusions with respect to the effect of Trendelenburg position on cardiac index and output.[21-24] Patient comorbidities, anesthetized state, and preoperative medications may potentially alter the cardiac output changes induced by Trendelenburg positioning. In general, healthier patients with a robust cardiovascular systems are better able to adjust for hemodynamic changes and tend to have unaltered cardiac output. Also, increases in cardiac output are typically seen only when patients are euvolemic.[25,26]

INTRAOCULAR EFFECTS

Intraocular pressure increases with progressively steeper Trendelenburg positioning. Additionally, longer procedures tend to correlate with greater increases in intraocular pressure.[28-30] If patients suffer from intraocular pathology, that pathology may be exacerbated by longer surgeries and steep Trendelenburg positioning.

URINARY OUTPUT

Urinary output significantly decreases with pneumoperitoneum.[31] However, the decreased urinary output caused by pneumoperitoneum does not appear to negatively impact renal function over time. The decrease in urine output during insufflation does make fluid management more challenging.

After steep Trendelenburg, injuries seen more frequently with robotic surgeries than normal laparoscopic surgeries include urinary retention, infections of the urinary tract, and subcutaneous emphysema.[27]

Types of Robotic Surgery

A large variety of surgeries may be performed using a robot. The most common include urologic procedures such as prostatectomies, cystectomies, and nephrectomies. Also, common gynecologic procedures are hysterectomies, myomectomies, and oophorectomies. Hepatobiliary procedures, colectomies, cholecystectomies, and hernia repairs are also frequently performed.

UROLOGIC PROCEDURES

The first commonly performed robotic urologic procedure occurred in the 1980s with the development of the Unimate Puma robot by Unimation.[32] The Unimate Puma was a machine with six-axes of movement that allowed rapid transurethral resection of prostatic tissue (TURP). This increased efficiency and decreased operative time led to less absorption of irrigation fluid, which resulted in less risk of TURP syndrome.[26,33] As interest in robotic applications to urologic surgery grew, clinicians sought new applications for robotic surgery, including robotic prostatectomies, nephrectomies, and cystectomies, which were being performed by urologists.

Robotic-Assisted Retropubic Prostatectomies

Arguably the most commonly performed robotic urologic procedure is the robotic-assisted retropubic prostatectomy (RAPR). When compared to traditional open prostatectomies or laparoscopic prostatectomies, RAPR appears to have decreased transfusion rates, facilitated faster recovery of urinary continence, and decreased erectile dysfunction. Additionally, RAPR appears to be easier to learn than traditional laparoscopic prostatectomy techniques.

In many ways, the anesthetic plan for a RAPR is like the anesthetic plan for laparoscopic prostatectomy. A standard intravenous induction followed by tracheal intubation is required. Most clinicians advocate for two intravenous lines, as the patient's arms will be tucked at his sides after he is placed in the lithotomy position. A blood bank sample is necessary, as trocars may unexpectedly invade large blood vessels. Neuromuscular blockade is also of extreme importance, as movement by the patient while the robot is docked may lead to significant and serious complications.

As described above, most anesthesia providers recommend placing a second noninvasive blood pressure cuff with a connector and hose on the patient's other arm, in case of difficulty with blood pressure measurement intraoperatively.

To facilitate surgical exposure of deep pelvic organs, patients are often placed in steep Trendelenburg position. As described above, insufflation of the abdomen with steep Trendelenburg positioning leads to an increase in intracranial and intraocular pressures. Since the positioning can result in physical objects hitting the patient's face, it is important to have facial and ocular shields to prevent harm during the case. Several case reports of postoperative blindness and visual field defects have been reported.[34,35] Gastric contents may drain via gravity onto the eyes and potentially cause ocular damage. Therefore, many clinicians advocate decompressing the stomach with an orogastric tube. Although the exact mechanism of ocular damage is not completely understood, decompressing the stomach may help minimize the risk of a trocar advancing into the stomach in addition to protecting the patient's eyes. Increased ICP can lead to strokes or hemorrhages in vulnerable populations.

Fluid management is also very important during robot prostatectomies and requires a delicate balance. Too much fluid given prior to the reattachment of the bladder and the urethra is associated with an increased risk of postoperative anastomotic leak.[36] Since the head is the dependent structure during the case, too much fluid is also associated with glottic and periocular edema. However, using fluid management that is too restrictive can be associated with acute tubular necrosis and the possible risk of a compartment syndrome due to hypotension in the legs. The risk of compartment syndrome is probably less than 0.5% and is associated with longer cases, obesity, and poor positioning.[37]

Robotic-Assisted Radical Cystectomy

Cystectomies are traditionally a difficult operation, as fluid shifts, fluid management, and patient comorbidities present unique challenges. Perioperative management of these patients is sufficiently challenging that nearly 1 out of every 4 patients are readmitted to the hospital following radical cystectomy.[38,39] Unfortunately, readmitted patients often remain in the hospital for roughly a week.[39,40]

Since 2003, robotic-assisted radical cystectomies have been performed in operating rooms around the world.[41] While a number of randomized controlled trials exist, there is a heterogeneity in the data, and diverse conclusions have been drawn based on the patients' long-term results.[42-45] Overall, robotic-assisted radical cystectomy appears to have lower blood loss when compared to open cystectomies. However, this decreased blood loss appears to come at the cost of increased operative times. Of note, there does not appear to be a difference in length of hospital stay[46] or 2-week readmission rates.[47]

Anesthetic considerations for patients receiving robotic-assisted radical cystectomy mirror the considerations for patients receiving robotic-assisted radical prostatectomy. Steep Trendelenburg, increased ICP, and increased ocular pressure are possible. Additionally, the need for CO_2 insufflation is required for visualization.[48]

Robotic-Assisted Nephrectomy

During the past 10 years, radical nephrectomy has been performed to treat renal cancers and is often viewed as the standard of care for patients with T1 and T2 kidney tumors. This surgery, which may result in a cancer-free state, has been performed using an open or laparoscopic technique. In addition, over the last decade, surgeons have begun turning to robotic assistance to perform these surgeries.[49]

Robotic-assisted surgery, when compared to traditional laparoscopic surgery, may allow enhanced visualization of the surgical field and increased degrees of articulation of the surgical arms. Additionally, several meta-analyses demonstrate similar or slightly improved perioperative outcomes when laparoscopic procedures are compared to robotic procedures.[50,51]

Despite many literature reviews and meta-analyses that compare laparoscopic and robotic surgery, there are very few prospective studies comparing perioperative complications and surgical costs. However, there are documented increases in costs and operative times associated with robotic nephrectomies compared to a traditional laparoscopic approach.[49]

GYNECOLOGIC SURGERY

Since 1999, robotic surgery has been used in gynecologic procedures. Robotic procedures were initially used to perform fallopian tubal re-attachment following permanent sterilization, and are currently being used with hysterectomy, salpingo-oopherectomy, vesicovaginal fistula repair, sacrocolpexy, and ovarian cystectomy.[52]

Robotic-Assisted Hysterectomy

After the first gynecological robot-assisted surgery, robotic assistance was quickly applied to hysterectomies, the second most common surgical procedure performed in the United States.[53]

However, despite the large number of patients receiving robotic hysterectomies, it is unclear whether robotics is superior to traditional laparoscopic approaches.[54]

Robotic surgery for endometrial cancer resection does appear to require more surgical operating time, particularly as surgical teams work to become more comfortable with the procedure[55]; proficiency performing the surgery, as approximated by surgical time, appears to improve after 20 to 30 cases.[56] There has been increased concern about the utilization of the robot during endometrial cancer resection surgery since the outcomes appear similar to laparoscopic hysterectomy, but the cost and operative times are greater.[53,57] The American College of Obstetricians and Gynecologists (ACOG) continues to recommend vaginal hysterectomy as the preferred approach for benign disease, where feasible, due to its lower complication rate and faster recovery time. ACOG states that robotic surgery needs to be better studied to discover if a particular subgroup of patients would be best served by this approach.[53]

Providers have begun performing robotic procedures on morbidly obese patients given the physical surgical demands associated with traditional laparoscopy and the greatly increased morbidity associated with an open abdominal approach. In general, the perioperative outcomes appear to be similar.[58,59] However, the positioning of morbidly obese patients into steep Trendelenburg position can be very challenging. Steep Trendelenburg positioning combined with the pneumoperitoneum necessary to facilitate surgical exposure can create cardiovascular and ventilation challenges. While it is possible that this subgroup of patients (body mass index [BMI] > 40), who would otherwise require an open abdominal approach, could benefit from minimally invasive robot surgery, these cases involve a great number of anesthetic challenges.

Other Gynecological Surgeries

Due to the rather steep learning curve for sacrocolpopexy, robot assistance is believed to facilitate this technically difficult procedure. Randomized, controlled trials have shown similar outcomes with robotic versus laparoscopic surgeries. However, the robotic cases can have increased operative time, postoperative pain, and cost.[53] Myomectomies with robot assistance may allow for more minimally invasive surgeries that would otherwise occur due to fibroid location and high patient BMI.

Robot-assisted surgery for gynecological malignancies has been poorly studied with only retrospective comparisons available. Robot assistance was preferred versus an open approach due to decreased cost, length of stay, and complications. A recent meta-analysis focusing on endometrial cancer concluded that robot versus laparoscopy had a similar duration of surgery but shorter hospital stay, less blood loss, fewer conversions to laparotomy, and overall complications, but a higher cost.[60]

ACOG does not recommend the use of the robot for short-duration and low-complexity surgeries such as tubal ligation, simple ovarian cystectomy, ectopic pregnancy, or bilateral salpingo-oophorectomy.[53]

General Surgery

Colectomy. In 1997, general surgeons in Belgium applied robotic techniques to their patients when the first robotic-assisted laparoscopic cholecystectomy was performed.[52]

However, despite many peer-reviewed studies, a recent meta-analysis did not find significant differences between laparoscopic and robotic colectomy surgeries. This lack of difference is perhaps in large part because of the low number of patients in these studies. Additionally, significant heterogeneity existed in the studies, which might have obscured any results.[61]

In a quality improvement analysis, robotic colectomies were associated with statistically significant increases in operative costs when compared to traditional laparoscopic techniques and longer operative times.[62] However, this economic argument may be tempered by a potentially decreased length of stay, as evidenced by a retrospective review of a National Surgical Quality Improvement Program database of 17,000 colectomies.[24]

Cholecystectomy. Another application of robotic surgery is in robotic-assisted cholecystectomy. In this procedure, a single incision is performed, and robotic arms are introduced into the patient's body. This approach is a contrast to the traditional laparoscopic cholecystectomy that requires multiple incisions.[63]

Patients are gravitating towards single-port robotic cholecystectomy procedures for decreased surgical scarring. The daVinci robot has been successfully used in Europe since 2011 before being brought to the United States.[64] Traditional thinking viewed robotic-assisted cholecystectomy as excessively expensive and not warranting a shift away from laparoscopic cholecystectomy,[65] as a recent meta-analysis showed increased operative times for robotic versus laparoscopic cholecystectomy. However, much of this time occurs in the pre-incision phase of the operation.[63]

Additionally, robotic-assisted cholecystectomy is associated with a significantly higher risk of incisional hernia[64] as the incisional hernia rate is approximated to be between 7% and 20%.[66,67] This increased hernia rate may require additional operations and therefore will increase overall healthcare costs.

Hepatobiliary. The liver's unique location deep in the abdominal cavity and its abundant blood supply has slowed surgeons from aggressively adopting and implementing laparoscopic techniques.[68]

Hepatic surgery was first successfully described in 1954 by Claude Couinaud.[69] Since the initial description, laparoscopic approaches to liver surgery have become more common. Additionally, there does not appear to be a difference in tumor recurrence, tumor spread, or survival for patients who receive laparoscopic hepatectomies.[70] Furthermore, minimally invasive techniques appear to be correlated with decreased blood loss when compared to open procedures.[71]

However, the need for greater articulation of surgical instruments, increased mobility of laparoscopic arms, and enhanced surgical visualization has limited wider adoption of laparoscopic surgery, particularly when compared to open procedures.[72] To address these limitations, hepatobiliary surgeons have begun looking to the da Vinci robot. Experienced surgeons usually do not have difficulty transitioning from the traditional laparoscopic approach to robotic surgery.[73] Additionally, robotic surgery allows three-dimensional imaging of a surgical site.[74]

While robotic surgeries are associated with increased intraoperative costs, overall costs of these robotic procedures may be decreased as they generally are associated with shorter lengths of stay compared to open procedures.[75] Thus, robotic surgery in the management of patients requiring hepatobiliary surgery remains an evolving field.

Otolaryngology

There are over half a million cases of head-and-neck cancers in the world.[76]

As otolaryngologists modernize their approach to both benign and malignant pathologies, they have looked to robotic-assisted approaches to replace larger and more invasive neck dissections that were needed to remove oral cancers.

TONSILLECTOMY

Tonsillectomies are one of the most commonly performed procedures in the United States. Although the practice of routinely removing tonsils in childhood has been replaced by more conservative medical management, tonsillectomies are still performed for refractory tonsillitis. As a result, patient demographics are shifting, and patients are presenting later in life with comorbidities not often seen in childhood. Surgeons are looking to innovate and find modern approaches to removing tonsils and adenoid tissues. The robotic articulating arms allow a more minimally invasive approach to resecting the tissue.[77-79]

HEAD AND NECK DISSECTION

Robotic surgery was first applied to oral and maxillofacial surgery in 1994 by Kavanagh,[80] and has rapidly expanded. Now, robotic surgery incorporates the resection of lesions from the base of the tongue, pharynx, piriform sinus, and nasopharynx.[81] Adoption of this technology has even spread to encompass transaxillary thyroid and parathyroid resection as well as uvulopalatopharyngoplasty.[82]

Even though robotic technologies have existed for quite some time, head and neck surgeons in the United States did not immediately adopt them. In fact, for many years, robotic procedures were not approved by the U.S. Food and Drug Administration (FDA). However, in 2009, the transoral approach to oropharyngeal cancers was approved by the FDA.[83,84] While this approach has not been commonly adopted, European studies have shown promise.[85]

CARDIAC (SEE ALSO CHAPTER 54 ANESTHESIA FOR CARDIAC SURGICAL PROCEDURES)

Robotic surgery has been performed in cardiac operating rooms for quite a few years. In 1997, internal mammary artery harvesting was first performed using an endoscope by Nataf et al.[86] The following year, Loulmet and colleagues[87] reported the first completely endoscopic coronary artery bypass surgery. Cardiothoracic applications of robotic-assisted surgery have expanded to include atrial septal defect closures,[88-90] mitral valve repairs,[91] patent ductus arteriosus ligations,[92] totally endoscopic coronary artery bypass grafting,[93,94] minimally invasive atrial fibrillation surgery,[95,96] and left ventricular pacemaker lead placement.[97] Although minimally invasive surgery may eventually make surgical sternotomy obsolete, surgeons still must be prepared to convert to an open sternotomy if the need arises.

Anesthesiologists must be familiar with cardiac and thoracic anesthesia when performing robotic-assisted cardiac procedures. The ability to perform one-lung ventilation and manage the associated physiologic changes are mandatory proficiencies, and the ventilation strategy is like that typically used during thoracic surgery. Poor pulmonary function test results or pulmonary hypertension may be contraindications to robotically assisted cardiac surgery since prolonged one-lung ventilation may not be tolerated. Additionally, many anesthesiologists turn to transesophageal echocardiography (TEE) to monitor cardiac physiology under anesthesia.

To allow surgical exposure for robotic cardiac surgery, several cannulae must be placed before cardiopulmonary bypass may be initiated. Femoral vessels are usually accessed. However, as iatrogenic dissection of the femoral arteries may occur, some hospitals require preoperative imaging to evaluate for atherosclerotic disease. Other centers use TEE to guide venous cannulation of the right atrium/inferior vena cava junction or superior vena cava (Fig. 71.10). These cannulae are often flushed with 5000 units of heparin, or infused with a heparin drip to maintain patency.

In addition to the cannulae required for cardiopulmonary bypass, an additional cannula is advanced into the pulmonary artery to vent the heart and to allow surgical visualization. Again, TEE can be helpful with placement of these venting cannulae.

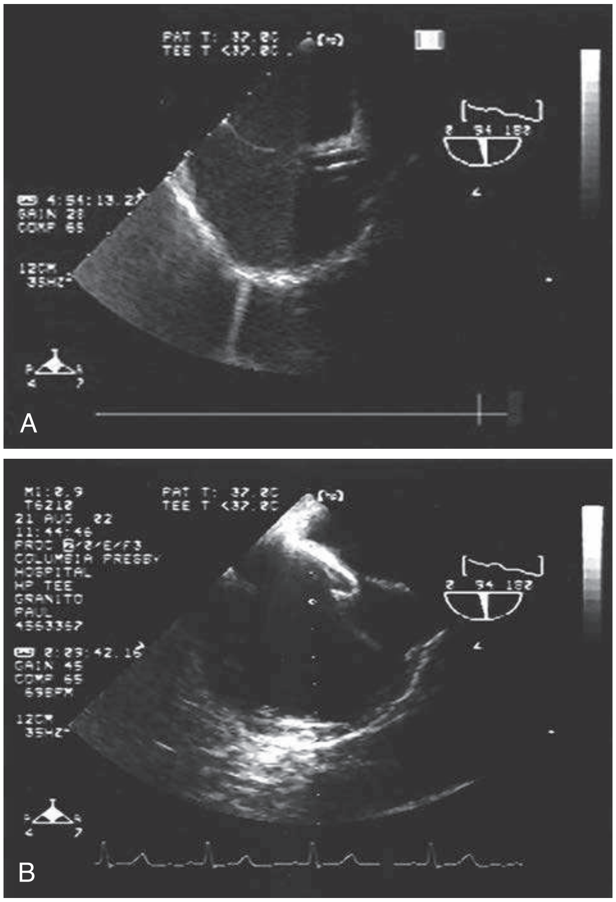

Fig. 71.10 (A) Ultrasound image of the superior vena cava cannula. (B) Ultrasound image, bicaval view, depicting the inferior vena cava containing a J guide wire. Both views are helpful in correctly placing cardiopulmonary bypass venous cannulae.

Mitral Valve Replacement

In 1997, two different reports of robotic-assisted mitral valve replacement appeared in the literature. In November 2002, the FDA approved the use of robot-assisted surgery for this procedure. For the robotic mitral valve procedure to be successful, a patient must be anesthetized, and single-lung ventilation must be initiated. Patients are then positioned with their right shoulder elevated by 30 degrees while their pelvis remains supine. Keeping the pelvis in the supine position allows the femoral vessels to be more easily accessed.

After positioning, trocars are introduced into the fourth or fifth intercostal space by the surgical team and exposure is achieved before the robot is docked. It is imperative that the anesthesia team keeps the patient completely paralyzed from this point forward until the robot is undocked to minimize iatrogenic injury.

Cardiopulmonary bypass is subsequently initiated using femoral cannulae, and cardioplegia is introduced into the coronary vasculature. The ascending aorta is subsequently cross-clamped, and the mitral valve is replaced. Following replacement, the valve's function is evaluated using TEE.

The procedure concludes with the aortic cross-clamp removed, and the patient is weaned from cardiopulmonary bypass. The patient's double-lumen endotracheal tube is ultimately exchanged for a single-lumen endotracheal tube if the patient is to be intubated postoperatively. There are several reasons why a particular patient may not be a candidate for robotic mitral value surgery (Box 71.1).

BOX 71.1 Exclusion Criteria for Robotically Assisted Mitral Valve Repairs

- Severely calcified mitral annulus
- Severe pulmonary hypertension
- Ischemic heart disease
- Surgery requiring multiple valve repairs
- Previous surgery to right hemithorax
- Severe aortic and peripheral atherosclerosis

Coronary Artery Bypass Grafting

Robotic-assisted coronary artery bypass graft surgery is a safe and effective procedure, which is gaining in popularity.[94] Potential exclusion criteria for robotic coronary artery bypass grafting are listed in Box 71.2.[96]

For coronary artery bypass graft procedures, patients are prepared and monitored for anesthesia in a manner similar to mitral valve surgery. Cardiac function and cannulae

BOX 71.2 Exclusion Criteria for Robotically Assisted Endoscopic Coronary Artery Bypass Grafting

- Contraindications to one-lung ventilation
- Ejection fraction <30% or decompensated heart failure (NYHA class III or IV)
- Moderate to severe aortic and mitral valve disease
- MI in preceding 30 days or MI requiring emergent CABG or postinfarction angina
- Calcified or intramyocardial LAD artery or diffuse LAD artery disease
- Large heart within left chest
- Morbid obesity (BMI > 35 kg/m^2)
- Severe peripheral vascular disease
- Severe noncardiac health issues
- Previous thoracic surgery, pleural adhesions, or radiation therapy of mediastinum or thorax

BMI, Body mass index; *CABG*, coronary artery bypass graft; *LAD*, left anterior descending; *MI*, myocardial infarction; *NYHA*, New York Heart Association.

placement are verified using TEE. In addition, anesthesiologists may consider pulmonary artery catheters when appropriate.

To harvest the internal mammary artery for the bypass grafts, single-lung ventilation is initiated using a double-lumen tube or a standard endotracheal tube with a bronchial blocker. Once single-lung ventilation commences, the patient is placed in a modified right lateral decubitus position, a 30-degree tilt to the right from the supine position. External defibrillation and pacing pads are then applied to the left posterior chest and anterolateral right chest. To improve surgical exposure to the left internal mammary artery, the left arm is raised. Conversely, to allow better exposure to the right internal mammary artery, the right arm is subsequently raised (Fig. 71.11). Very minimal CO_2 insufflation (usually 5-10 mm Hg) is needed to displace the mediastinal fat pad and allow surgical exposure. When single-lung ventilation is initiated and the left hemithorax is insufflated with CO_2, bilateral arteries are often able to be visualized.[98] When cardiopulmonary bypass is anticipated, the left femoral artery is cannulated with a 17- or 21-Fr remote access perfusion catheter (Fig. 71.12) with an aortic occlusion balloon. The remote access perfusion catheter

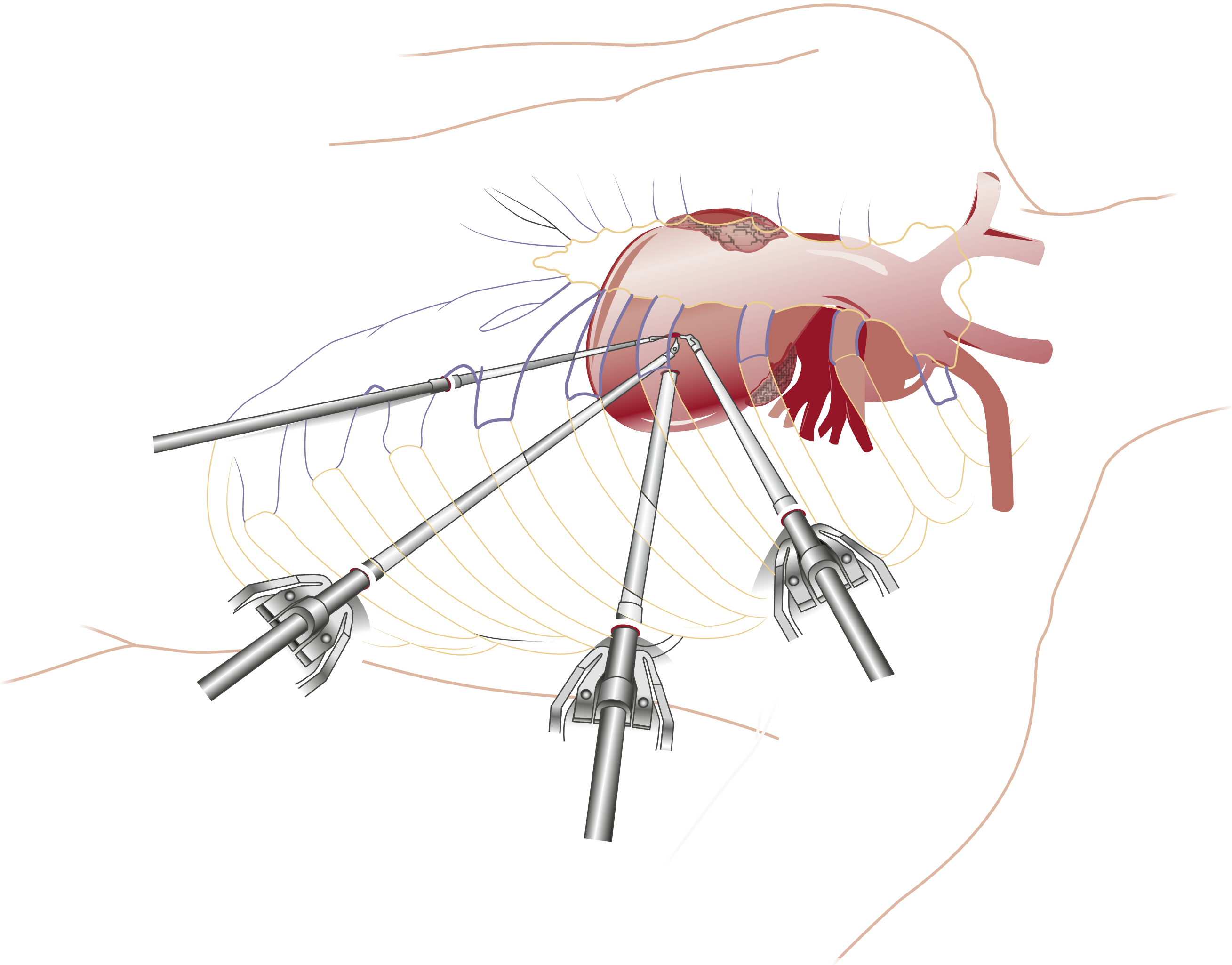

Fig. 71.11 Incision ports for coronary artery bypass grafting. Trocars are placed in the third, sixth, and eighth intercostal spaces. Similar port positions are used for bilateral internal mammary artery dissection.

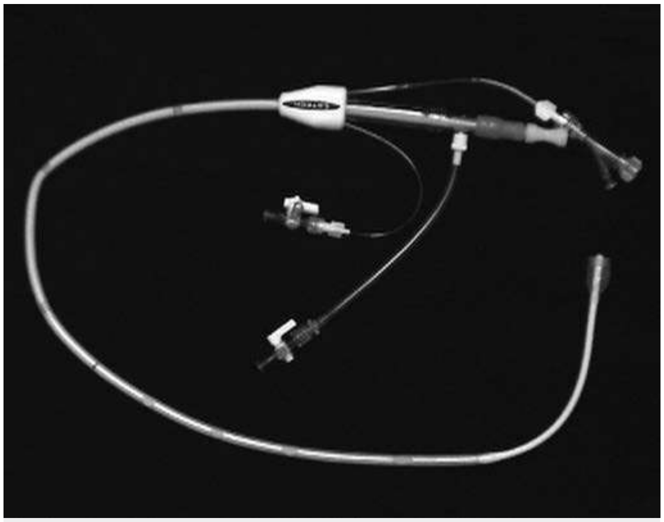

Fig. 71.12 Remote Access Perfusion (Estech Systems, Plano, TX, USA) catheter. The endovascular catheter has a cylindrical balloon for endovascular aortic clamping. The catheter provides anterograde perfusion of the aortic arch at a rate of 5 L/min.

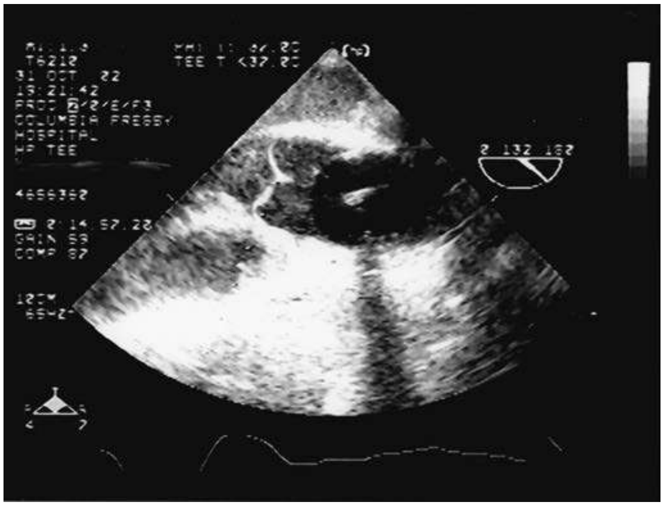

Fig. 71.13 Ultrasound image of Remote Access Perfusion (Estech Systems, Plano, TX, USA) catheter balloon in situ. Transesophageal echocardiography allows the anesthesiologist to keep track of the migration of the catheter balloon. The balloon should be positioned in the ascending aorta 2 to 4 cm distal to the aortic valve. Right radial pressure catheter signal damping can detect balloon malposition when occlusion of the innominate artery occurs.

allows anterograde flow of 4 or 5 L/min. The aortic cannula is subsequently positioned in the ascending aorta, roughly 2 cm above the aortic valve, using TEE (Fig. 71.13). The endovascular balloon is inflated with a volume equal to the diameter (in milliliters) of the sino-tubular junction of the aorta. A balloon pressure greater than 300 mm Hg usually provides complete occlusion of the aorta.[99] Residual flow around the balloon can be seen and monitored with color flow on TEE. The use of bilateral radial arterial lines is useful in detecting the migration of the occlusion balloon toward the innominate artery. Proximal migration of the balloon can be seen most easily with TEE, preventing balloon herniation through the aortic valve.

Single-lung ventilation is then initiated, and the right lung is collapsed. By insufflating the right hemithorax with CO_2, three 1-cm ports may be placed at the third, fourth, and fifth intercostal spaces on the anterior axillary line (see Fig. 71.11). The patient's pericardium is then dissected to expose the heart. Arrhythmias in the early postoperative period are common. Antiarrhythmics, such as amiodarone and β-adrenergic blockers, can be helpful.[100-102]

ROBOTIC-ASSISTED THORACOSCOPIC SURGERY (SEE ALSO CHAPTER 53 ANESTHESIA FOR THORACIC SURGERY)

Video-assisted thoracoscopic surgery (VATS) is a commonly performed procedure for cancerous tumor resection (wedge resections and lobectomies), esophagectomy, hiatal hernia, and lung volume reduction.[103-107] VATS is preferred to open procedures when possible to reduce length of stay, blood loss, pain, and morbidity as long as clinical outcomes are equivalent. However, as it is difficult to do complex surgeries (e.g., a pneumonectomy or a thymectomy) using minimally invasive techniques such as VATS, the hope is that a robotic approach (robotic-assisted thoracoscopic surgery [RATS]) will allow the application of minimally invasive techniques to these more complex surgeries and generate some of the same benefits as open procedures. While several centers are exploring RATS lobectomies, segmentecomies, and mediastinal mass resections, RATS pneumonectomies have been reported at only a couple of pioneering centers.[108] Robotic-assisted surgery usually increases the operative time and cost compared to its laparoscopic alternative.[109]

Robotic-assisted thoracoscopic surgery presents with similar challenges to robotic-assisted cardiac surgeries. Accommodating a more rigid chest wall and moving heart, lungs, and mediastinum can be challenging. In addition, initiating and maintaining prolonged one-lung ventilation and hemodynamic instability associated with CO_2 insufflation of the hemithorax presents unique concerns. Despite these challenges, the robot has been specifically used for thymectomies, mediastinal mass resections, fundoplications, esophageal surgery, and pulmonary lobectomies.[110-112]

Patient positioning is particularly important to expose largely inaccessible areas, as mediastinal structures are heavy, mobile, and change position in response to gravity (see Chapter 53). Supine or slight lateral decubitus position (raising one side 15-30 degrees) is most ideal for anterior mediastinum pathology. This position requires the elevated arm to be at the patient's side as far back as possible to allow the robot to dock successfully. However, hyperabduction of the elevated arm can cause a brachial plexus injury.[111] A full lateral decubitus position (90 degrees) may be optimal for hilar masses and lobectomies. Alternately, a prone or slightly modified prone position can create better exposure for posterior mediastinal masses.[113]

Since the patient will generally be rotated 90 degrees to allow the robot to dock, it is important to achieve lung isolation prior to rotation. Also, the anesthesia circuit, intravenous line, and arterial line tubing may require extensions. It is suggested that the circuit and lines be combined into one bundle to move them out of the way of surgical personnel and monitoring devices. It is also recommended to have two large-bore intravenous lines since the arms will be difficult to access once the robot is docked. The patient undergoing RATS should generally have an arterial line placed prior to the robot being docked to allow for close monitoring of blood pressure and $PaCO_2$. Intraoperative confirmation of lung isolation will be difficult, so a plan of how to access the airway with a fiberoptic bronchoscope should be established prior to initiating the robotic portion of the case. It is important to note that a failure of lung isolation will result in an inability to complete the surgery via RATS.[110]

CO_2 insufflation helps achieve adequate surgical exposure by mobilizing the mediastinum and simultaneously compressing the lung away from the operative site. Unfortunately, CO_2 insufflation can lead to hemodynamic instability and difficulty with hypercapnia during one-lung ventilation. It can also cause venous gas embolism, decreased venous return, and cardiac collapse if right heart failure develops.

The anesthesiologist must also be ready for potential conversion to open thoracotomy due to bleeding or an inability to obtain adequate surgical exposure.[111] In a recent meta-analysis, the incidence of conversion from RATS to open thoracotomy during pulmonary resections was 0% to 19%.[114,115] The learning curve for new surgeons is also quite steep during the first 20 cases. An increase in operative issues must be anticipated for surgeons learning to use the robot.[114,115]

Another possible pitfall of RATS is that damage to the pleura may allow CO_2 insufflation to spread to the ventilated lung causing difficult ventilation and possibly causing a tension pneumothorax or severe subcutaneous emphysema—both of which can produce hemodynamic compromise.[114]

Studies comparing outcome data from VATS versus RATS in more common procedures are increasing. As might be expected for any complex procedure, outcomes for RATS lobectomies are better at high-volume centers.[116] As shown in other surgical disciplines, longer duration RATS lobectomies have similar outcomes to VATS lobectomies. However, robotic surgery does have increased costs in comparison to laparoscopic alternatives.[117,118] In an investigation of open versus VATS versus RATS treatment of early-stage thymomas, the robotic approach was associated with a reduced length of stay and had a similar complication profile to VATS.[119] In the case of esophagectomies, RATS—while having a longer surgical duration than a minimally invasive approach—has a similar outcome profile.[120]

As robotic instead of open approaches are starting to be used on more complex surgeries, we expect to see an improvement in patient outcomes and possibly a reduction in costs.[108,121]

Summary

Anesthesia for robotic surgery is an exciting and dynamic field. As surgeons and patients look for new innovations and technologically rich approaches to healthcare, it is reasonable to expect that more operations will be performed using robotic techniques. However, there is a real need to investigate the outcomes and costs of a robotic approach versus a more traditional approach. More data are needed to identify the type of cases and patient populations that will improve patient outcomes and reduce costs via robotic surgery. Recognizing the unique physiologic changes and positioning challenges that accompany robotic surgeries will allow anesthesiologists to best care for their patients.

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