

Anesthetic Considerations for Robot-Assisted Gynecologic and Urology Surgery

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Abstract

Robotic surgery was first conceived by the United States military in the 1980s. It rapidly developed in both complexity and utility and, in the early 21st century, modern robotic surgery for gynecologic and urologic surgery gained approval in the United States. Today, an ever-increasing number and variety of surgical procedures enlist robotic-assistance.

Numerous anesthetic considerations for robotic surgery exist. A few of the most important aspects of conducting a safe anesthetic include: investigating the patient's co-morbid conditions, realizing the risks associated with the robotic equipment, and positioning the patient with care.

This manuscript reviews the current literature on robotic-assisted surgery for gynecologic and urologic procedures with emphasis on history, marketplace, type, variety, and expansion of surgery in these fields. The review focuses on practical considerations for the anesthesiologist caring for patients undergoing robotic surgery. Preoperative, intraoperative and postoperative issues are explored in detail.

The rapid expansion of robotic surgery worldwide requires thoughtful consideration of the technique's weaknesses and associated risks. This review provides a roadmap to adequately prepare anesthesiologists for care of gynecologic and urologic patients undergoing robot-assisted surgery.

Keywords: Robotic surgery review; Robotic surgery; Robot-assisted; Anesthetic considerations; Anesthetic complications; Anesthetic risks; Gynecologic surgery; Urologic surgery; Perioperative management

Introduction

A robot can be defined as, "a powered, computer-controlled manipulator with artificial sensing that can be programmed to move and position tools to carry out tasks" [1]. Basic robotics has been used since the 1950s at the National Aeronautics and Space Agency (NASA) with simple, robotic arm technology. Robotic arm use expanded into industrial use by companies such as General Motors Co. (Unimate) in the 1960s. By the 1980s, advances in microelectronics, computer technology and charge-coupled devices in digital imaging, video electronics and display technology set the stage for robotic innovation. As the first entrant to the field of robotic surgery, the United States' Defense Advanced Research Projects Agency (DARPA) developed much of the technology behind telerobotic surgery in conjunction with NASA and the Stanford Research Institute. Using telepresence, the sensation of being in one place when you are actually in another, robots were seen as a feasible strategy for remotely operating on battlefield wounds [1,2].

In 1983, basic medical use of robots began with robotic arm assistance with orthopedic surgery. Brain biopsy guidance was also aided with robotic technology in the 1980s. The first prostate surgery to utilize robotic assistance was conducted in 1988. By the 1990s, robots were being used to hold cameras and various manufacturers were experimenting with voice control. Cyberknife (Accuray, Inc, Sunnyvale, CA) was used for stereotactic brain biopsy in 1994, and in 1998, first-generation precursors to the modern robot platform, the Zeus Robotic Surgical System (Computer Motion Inc), and the da Vinci Surgical Systems (Intuitive Surgical, Inc., Sunnyvale, CA) were employed for gynecologic reanastomosis of fallopian tubes and cardiac

bypass surgery, respectively.

In the first year of the new millennium, the Food & Drug Administration (FDA) granted the da Vinci system approval for use in urologic surgery. That same year, the first robot-assisted laparoscopic Radical Prostatectomy (RAP) was performed. In 2003, Intuitive Surgical, Inc. purchased Computer Motion, effectively creating a monopoly for Intuitive Surgical, Inc. in the robotic surgery marketplace.

Da Vinci Surgical Systems' robot was approved for gynecologic surgery in 2005 [3]. By 2008, over 80,000 robotic surgeries were performed worldwide at roughly 400 centers [1]. Surgical training has adapted accordingly; greater than 1,200 gynecologic surgeons were trained in use of robot-assisted surgery in 2010 [3,4]. By 2011, more than 1,600 systems were installed and over 1.8 million procedures were being performed in a number of disciplines with the da Vinci robot [2]. Annual growth of the da Vinci system has been estimated between 27 and 35% [2,5] and as of the most recent report in 2013, greater than 14,000 systems are in use throughout the United States [3].

Literature Review

A thorough search of the Pub Med, Medline and Scopus databases

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was employed to adequately review anesthetic considerations during robot-assisted gynecologic and urologic surgery.

Keywords that were input into the search engines included, “robotic surgery,” “gynecologic,” “urologic,” “anesthesia” concerns, perioperative “management,” “complications,” and, “outcomes.” Search queries were then reviewed by title and abstract for relevance, with preference afforded to more recent manuscripts.

Da Vinci Surgical Systems

The da Vinci Surgical Systems robot consists of three parts: 1. control console; 2. tower; and 3. robot. The control console provides an ergonomic-design for the operator to comfortably sit and remotely manipulate the robot. It has binocular, high-definition, 3-dimensional optics that improves the surgical view over 2-dimensional imagery. The viewer is equipped with an infrared sensor that is able to detect the presence of an operator. When the surgeon is not engaged in the viewer, the sensor prevents the robotic arms from movement as an advanced safety feature that minimizes the risk of unwanted robotic arm movement [1,3,4,6]. The camera allows for adjustment of magnification, or scaling of the surgical field, and the console automatically adjusts robotic arm motion to eliminate operator tremor, thereby improving fine motor control. Manual controls are anatomic, allowing for 7-degrees of movement at the tip with 360-degree range of motion and 90-degrees of instrument articulation control attached to the robotic arms. The meticulous surgical dissection that can be achieved with articulating instruments nearly matches the manual dexterity of open surgery. The movement of instruments is intuitive, as opposed to the counteractive adaptation required to maneuver laparoscopic equipment [7]. Arm 1 and 2 are the right and left-hand controls, arm 3 is the camera, and arm 4 is typically used as a retractor. A foot pedal serves to activate electrocautery, ultrasound, focal point adjustments, instrument disengagement, and alternation of arms controlled by the manual controls [1]. All of these advances lead to the opportunity for greater surgical autonomy and decreased fatigue for the operator [3].

The tower houses the da Vinci video equipment that records and displays images of the surgical field in 2-dimensions for the rest of the surgical team to view and appropriately assist in the management of the patient. The robot, the third component of the da Vinci system, has 4 arms and is positioned adjacent to the patient with the arms that lock into place above the surgical field. An assistant is required to exchange disposable instruments that attach to the robotic arms, to load sutures, and to fire staples when necessary [1,7].

The benefits of robotic surgery are potentially extensive, although long-term data in its use remains elusive due to the relatively recent advent of the technology. Several retrospective analyses have reported robotic surgery to be feasible and effective [8-10]. Surgical incisions are small and instrumentation is minimally invasive [1,11]. Surgical bleeding is reported to be quite low [3,10,12] as is the incidence of venous gas embolism [13]. Postoperative complications such as wound infections are reported to be minimal [10,14], narcotic usage is reported to be less [12,15], and postanesthesia care unit (PACU) stays are reported to be brief. Overall length of hospitalization is likewise shorter in duration, on average [1,3,4,15]. For oncologic surgery, initial data indicates better margin negative rates, and improved functional outcomes, including earlier return to activities of daily living [16].

Disadvantages to robotic surgery include the increased time required to operate, to position the patient, and to dock the robot,

contributing to longer total operative times. This extension of surgical time is particularly pronounced with surgical teams who are training to use the robot, corresponding to the initial phase of practice known as “the learning curve.” It is estimated that operating room staff proficiency is achieved after 25 cases, but that surgical skills continue to improve until 150–250 cases or beyond [17-19]. For example: surgeons need to adjust to the visual and tactile design, to develop muscle memory, and to discover preferences and limitations; nurses need to learn how to transport, set-up, calibrate, drape, and position the robot for surgery [1]. Prolonged operative time is compounded by the increased risk for morbidity during the learning curve [20]. Organized credentialing of providers, including attestations, case list submissions, and proctored case performance are only recently being considered by training programs, hospitals and other entities keen to ensure quality during the learning process [18].

Beyond the learning curve, there remain challenges to robotic surgery. Once the procedure has begun, there is no easy way to reposition the patient should that become necessary. Despite the intuitive controls, robotic surgery is still not able to exactly replicate the haptic sensation that an operator gets when they are directly or indirectly touching tissue with their hands or laparoscopic instruments [6,21]. Additionally, the equipment is bulky, accounting for a significant footprint in the operating theater [1]. This invariably decreases access to the patient, decreases the maneuverability of the surgical care team when called upon to circulate, and increases the risk of robotic arm collision with assistant, anesthesia workstation, or patient [1,4].

Long-term, prospective data validating robotic-assisted surgery’s utility and safety is still lacking. In the absence of long-term data, there is extensive marketing of the product by its sole provider that likely biases purchase decisions and patient demand [11]. Patients may be prone to misconstrue the term, “minimally invasive” to mean minor surgery, and consequently be at risk for falsely elevated expectations for recovery [11]. Further, a lack of competition typically leads to diminished responsiveness of a firm with respect to quality and pricing. Machine malfunction is a concern, particularly as costly units begin to age. Additionally, hospitals looking to purchase a robot can expect an upfront cost of 1.4-2.2 million dollars, \$100,000-\$150,000 for annual maintenance costs, and \$2,000 per instrument, which are fabricated with a 10-use limit [2,7]. Robot purchase costs, amortized over the lifespan of the machine, combined with annual maintenance costs account for roughly 70% of the additional costs of performing robotic surgery [5,17]. Discounting depreciation costs of the robot, the high cost of maintenance and consumables often make it the costlier surgical option [21].

Robot Surgery in Gynecology

The da Vinci Surgical System received FDA approval for gynecologic use in 2005. The first Robot-Assisted Radical Hysterectomy (RRH) was performed in 2006 [3]. By 2009, more Robotic-assisted surgical procedures were performed for gynecologic indications than for all other specialties combined [22].

Cervical cancer is the second most common cancer among women worldwide. Radical hysterectomy is the preferred option for patients with localized disease. Since the first reported RRH, many studies have documented feasibility, safety and efficacy of the procedure, including less blood loss, fewer complications, and briefer hospitalizations [3]; however, to date, no prospective studies have been reported. Early stage disease has been most extensively reported in retrospective reviews or cases series. Robotics has also been considered in fertility-sparing

operations for early disease. Locally advanced or recurrent disease is still considered experimental for surgery with robotic assistance. Pelvic exenteration surgery with robot assistance has only been reported in case reports.

The most common malignancy of the female reproductive organs is endometrial cancer. It is the leading indication for robotic surgery in gynecology following a number of favorable retrospective reviews and case series [3]. One study noted that robotic surgery reduces complications such as wound dehiscence, infection, ureteral injury, and renal failure [4]. Consensus opinion in the literature is that robotic surgery with hysterectomy and lymphadenectomy is preferable to open procedures and equivocal to laparoscopy [3]. In addition, retrospective data supports robot use for staging for endometrial cancer and suggests that perhaps robot surgery is superior to laparoscopy for morbidly obese patients [23,24].

Literature on robotic surgery for ovarian cancer is very limited, although it is being conducted at select centers for early stage disease [4]. This is due to the comprehensive staging required for this type of cancer as well as concerns for port-site metastases, cyst rupture and peritoneal seeding [4,25]. Salpingo-oophorectomies, pelvic mass resections and omentectomies are also being conducted for various indications with robotic assistance [26].

Robot Surgery in Urology

Young performed the first radical prostate surgery in 1904 via the perineum. In 1947, Miller performed the first retropubic surgery. Then Walsh improved on the technique with nerve sparing surgery in 1982 [19,27]. As mentioned above, RAP was performed in 2000 following the introduction of the da Vinci robot.

Prostate cancer is the second leading cause of cancer death in men [19]. It affects older men, typically with several co-morbid conditions. Radical prostatectomy is the best option for long-term cancer control in patients with localized, or organ-confined disease [28]. By 2010, robot usage in prostate cancer surgery had become so pervasive that one study assessed robotic prostatectomy as a new gold standard [11]. It cited improved pain, decreased length of stay, smaller incisions and improved functional outcomes with comparable cancer-free survival. Perioperative and delayed complications that have occurred include the same complications seen with open surgery, such as: bleeding, lymphocele, stricture, contracture, incisional hernia, rectal injury, incontinence, impotence and inadequate margins [27,29,30]. Longitudinal studies to support the potential advantages of robotic prostatectomy weighed against the significant costs are still few in number.

Bladder cancer was first treated with open radical cystectomy in 1949. Despite a reduction in mortality, complication rates remain significant [31]. Robotic surgery has recently been adapted to manage muscle invasive and high-risk non-invasive bladder cancer (superficial recurrent or chemotherapy resistant) with the hopes of decreasing patient morbidity with the procedure. Draining options include conduit diversion into small bowel and neobladder formation from bowel. Surgeons have been slow to incorporate robot into radical cystectomy due to concerns over the ability to adequately dissect lymph nodes, the feasibility of intracorporeal diversions, and the overall costs. Long term data is lacking for robotic cystectomy outcomes; however, more than 1,000 cases have been reportedly performed by a consortium of institutions [31].

Renal cancer is predominantly renal cell carcinoma. It typically

presents in the 4th to 7th decade and, while radical nephrectomy used to be the gold standard for localized disease, Partial Nephrectomy (PN) is now indicated for T1 small renal masses [17,32]. By sparing nephrons, PN achieves similar cancer-free survival outcomes to radical nephrectomy, but decreases long-term morbidity [17]. McDougall introduced laparoscopic partial nephrectomy in 1993; then in 2004, Gettman reported the first robotic partial nephrectomy (RPN) [33]. Surgeons are using novel techniques to eliminate ischemia during robot-assisted, deep tumor resection with some success [32].

Obstruction of the ureteropelvic junction requires a pyeloplasty operation. Endoscopic and laparoscopic approaches have taken the place of open procedures over the past 20 years for most patients; nevertheless, the laparoscopic approach is technically demanding [21]. Robotic Pyeloplasty (RP) offers an alternative, potentially easier platform for intracorporeal suturing [21]. Newer techniques that incorporate a single-site with modified da Vinci instrumentation may improve further upon the surgical learning curve, but must be weighed against increased costs [34].

Testicular germ cell tumors present earlier than the other urologic malignancies, typically in the 3rd or 4th decade of life. Over 75% are localized (stage I) at diagnosis. Stage I seminoma is highly sensitive to radiotherapy. Stage I Nonseminomatous germ cell tumor is usually confirmed with Retroperitoneal Lymph Node Dissection (RPLND). Chemotherapy is useful in stage II or III disease. Robotic surgery to perform orchietomy and RPLND has been reported [2]. Surgeons have also begun to use robots to assist with a host of benign renal conditions such as: pyelolithotomy, simple prostatectomy, diverticulectomy, spermatic cord denervation, simple cystectomy, sacrocolpopexy, urolithiasis, fistula repair, ureto-ureterostomy, ureterolysis, vasectomy reversal, vericoelelectomy, and live-donor nephrectomy [2].

Perioperative Concerns

The perioperative management of patients undergoing robotic-assisted gynecologic or urologic surgery involves numerous unique considerations for the anesthesia provider.

Preoperative assessment

A systematic review of the patient's history and physical examination is warranted prior to robotic surgery. Age, medications, allergies, surgical and anesthetic history should be noted. Baseline vital signs should be obtained and a thorough airway examination should be conducted.

Obesity: Patient height, and weight should be carefully considered as obesity (BMI >30) may be accompanied by physiologic changes such as obstructive sleep apnea and restrictive pulmonary disease, difficult intubation, delayed gastric emptying, difficult vascular access or co-morbid conditions such as cardiovascular disease or diabetes mellitus [35,36]. Obese patients may be at increased risk for conversion to open or aborted procedures [37,38]; consequently, serious deliberations should precede robotic surgery in obese patients, particularly as BMI approaches 40.

Cardiac risk: Cardiovascular risk should be assessed, taking into account the patient's symptoms, medications, studies, and exercise tolerance in addition to a consideration for the surgical risk, typically moderate for gynecologic or urologic robotic surgery. Current American Heart Association/ American College of Cardiology (AHA/ACC) guidelines should be followed when determining whether a patient has been optimized for surgery [39]. Beta-blocker medication should

be continued perioperatively. Heart failure is likely to be exacerbated by the positioning required for robotic surgery [1]. Furthermore, attention should be paid to patients presenting with cardiac stents; the risk of surgical bleeding with anticoagulation therapy must be weighed against the possibility of intraoperative stent thrombosis and the challenge of management during robotic surgery [40].

Neurologic and ocular risk: Caution must also be exercised in proceeding to robotic surgery in patients with a known increase in intracranial pressure, as the patient's positioning for robotic surgery will exacerbate the pressure. For shunted patients, shunt patency confirmation is mandatory preoperatively. Intraocular pressures will likely be elevated due to patient positioning for robotic surgery. One study reported elevations of intraocular pressures, on average, of 13mmHg in patients without preexisting eye pathology [41]. Dangerous pressures that risk retinal detachment, periorbital edema or neuropathy are possible in prolonged surgeries or in patients with pre-existing ocular pathology.

Pulmonary and renal risk: Patients with pulmonary disease may not tolerate the physiologic changes associated with patient positioning. Accordingly, patients should be screened for a history of smoking in addition to symptoms of lung dysfunction. Similarly, renal insufficiency will likely be exacerbated by robotic surgery due to mechanical obstruction, patient positioning and fluid restrictions, and so care must be taken to optimize renal function preoperatively [42].

Gastrointestinal risk: Assessment should also include a discussion of gastrointestinal laxatives or enemas requested in preparation for the robotic surgery in order to decompress the bowel and minimize the risk of fecal contamination should bowel injury occur [19]. Combined with fasting, hypovolemia is a considerable risk that may affect intravenous catheter placement and fluid management decisions.

Cancer risk: A unique consideration of 10-40% of renal cell carcinomas is the presence of paraneoplastic syndromes. If a patient has a paraneoplastic syndrome, the tumor may secrete ectopic hormones such as erythropoietin, renin, insulin or glucose that must be considered during surgery [33].

Cancer patients may have been previously treated with radiation therapy. Surgical resection could be considerably more difficult due to the fibrosis or bleeding resulting from previous radiotherapy. Chemotherapy can result in a number of systemic complications that affect intraoperative planning. Patients may have significant weight loss, anemia, nausea, and a predisposition to clot formation resulting in electrolyte abnormalities, hypothermia risk, decreased protein, malnutrition and embolism. Anesthetic planning should account for decreased protein binding and volume of distribution for medications; these changes may significantly alter pharmacokinetics. Additionally, a history of exposure to agents such as doxorubicin (cardiomyopathy) and bleomycin (pulmonary fibrosis) necessitates further preoperative testing [33].

At a minimum, preoperative studies for robotic cancer surgery should include electrocardiogram, chest radiograph, and blood work, notably: blood counts, coagulation status, renal function, and basic electrolytes. The patient's blood should be typed and screened for unusual antigens. Fasting blood glucose should be noted before surgery for diabetic patients. Reflux, infection and deep vein thrombosis prophylaxis should be considered with non-particulate antacid, antibiotics (within 1 hour of surgical incision), subcutaneous heparin and sequential compression devices respectively. After completing the preoperative assessment, an American Society of Anesthesiologists

(ASA) Physical Status score should be assigned, keeping in mind that a score of four or greater may be associated with increased risk for complications with robotic surgery [38].

Intra operative management

Intraoperative considerations for robotic gynecologic and urologic surgery will be considered in this section. While robotic surgery may appear similar to laparoscopic surgery, and therefore deserving of similar attention, many laparoscopic concerns are greatly exaggerated in robotic procedures and several unique features are present as well.

Space limitations: As the complexity of equipment required for surgery continues to grow, the physical space required to accommodate the larger footprint for equipment such as robotic chassis and control stations is greater. In spite of new requirements, many facilities are space-limited, with older operating theaters that were not designed with robotics in mind [1]. With robot-related equipment crowding operating rooms, the movement of personnel may be compromised, and visualization of key aspects of patient care such as intravenous insertion points or endotracheal tube positioning may be obscured [7,26].

Monitoring and intravenous access: For most gynecologic and urologic surgery with a robot, standard ASA monitoring is sufficient [43]. If the patient's medical condition warrants, if the procedure is technically difficult, or if the surgical team is still novice with respect to the learning curve, additional monitoring should be considered to account for patient co-morbidities, the risk of intraoperative bleeding, or longer operative times. Arterial line hemodynamic monitoring should be considered in the aforementioned cases. Basic intravenous access considerations should account for limited patient access while the robot is docked; two intravenous lines of adequate bore should be placed and sufficient length afforded to tubing such that the lines can be accessed proximal to the anesthesia workstation. Just as with monitoring, intravenous access should be expanded accordingly to account for patient or surgical concerns.

Induction: Standard intravenous induction is feasible, adjusting anesthetic planning based on the patient's medical condition. The endotracheal tube should be taped securely, appreciating that patient positioning may alter tube placement over time (unintended extubation or mainstem intubation), robotic instrumentation may dislodge a tube, and an obstructed view may delay recognition of a tube that has become dislodged [44]. Replacing an endotracheal tube would be challenging for robotic surgery patients based on positioning and the time delay associated with undocking. Post-induction, care should also be taken to balance the need for continued sedation against any hemodynamic instability that may result from the prolonged preparation time prior to surgical stimulus. Processed electroencephalographic monitoring such as BIS (Covidian, Inc, Mansfield, MA) or vasopressor agents may be required to bridge the time between induction and surgical incision.

Immobility: Trocar placement carries with it the risk of injury to an organ or major vessel. Furthermore, once the robot is docked, surgical instruments are rigidly attached to the patient via trocar insertion sites. Based on these factors, it is imperative that patients be completely immobilized throughout the procedure until the robot is undocked. Non-depolarizing muscle relaxant drug, either by bolus or infusion, should be sufficient to achieve patient immobility [26]. At our institution, surgeons have noted that pelvic floor musculature becomes mobile with patient respirations as paralysis wanes, often prior to twitch monitor evidence indicating the need for drug re-dosing.

Consequently, deep paralysis, often to the exclusion of train-of-four twitches, is required for visualization during gynecologic or urologic robotic surgery. Secondly, drug-induced paralysis may assist with mechanical ventilation for patients following pneumoperitoneum and steep trendelenberg positioning (see discussion below). Another safety measure that has been proposed to prevent accidentally patient movement is to turn bed controls to the "off" position while the robot is docked.

Pneumoperitoneum: After initial trocar placement, intra abdominal pressures are increased to 20 mm Hg with carbon dioxide (CO₂) insufflation. After all ports are positioned, pressures are reduced to 12–15 mm Hg [27]. CO₂ insufflation carries the risks for venous gas embolism, decreased venous return to the heart, vagal nerve activation of parasympathetics, and acute cardiovascular collapse. For prostate surgery, risk for venous gas embolism is greatest during the dissection of the dorsal venous complex [13,45]. Management of gas embolism involves supportive care while undocking the robot, positioning the patient in the left lateral decubitus position, and aspiration of gas via a multiport central venous catheter, if possible [19]. Hypercarbia is common; however, hypercarbia has never been reported as the cause of a clinically significant problem intraoperatively [19]. Subcutaneous emphysema, pneumomediastinum, hypothermia, and pneumothorax are all possibilities, although studies to investigate possible pathology should be guided by clinical suspicion rather than routine order sets. Physiologic changes, such as decreased pulmonary compliance and cardiac output occur with pneumoperitoneum and will be expanded upon in the discussion below.

Positioning: For the majority of gynecologic and urologic surgeries that utilize robotic assistance, the positioning is modified lithotomy in stirrups with steep (30 degree) trendelenberg in order to utilize gravity to pull abdominal structures cephalad [1,41]. Arms and hands are heavily padded and tucked in a neutral position at the patient's side, taking note of the functionality of monitoring and intravenous lines post-positioning. Egg crate foam padding or a padded beanbag is used to prevent sliding and the chest is bound in the form of an "X" [35]. Particular attention should be paid to padding shoulder braces to prevent injury with prolonged head-down positioning. Other possible strategies for positioning include: taping a gel pad to the bed to prevent sliding, or placing a Mayo stand over the patient's head to prevent instrument-related facial injury [6,27]. At our institution, one patient developed alopecia as a result of prolonged pressure on the scalp following robotic gynecologic surgery that led to the local recommendation for intermittent head repositioning intraoperatively.

Nerve injury can result from compression or stretching if improperly positioned and padded during robotic surgery. Injury to one or more nerves represents 16% of closed-claims complaints [38]. These injuries, when mild are reversible, but may be permanent if severe as a result of axonal denervation. Common nerve injuries to protect against include: brachial plexus, ulnar, and lateral femoral cutaneous nerves. Attention should be paid to the degree of limb extension, stirrup location, padding of bony prominences, and duration of immobility [19]. Prolonged, steep trendelenberg could result in plethoric facies and laryngeal edema as well [33].

Partial nephrectomy is performed with alternate positioning. Patients are placed in the lateral decubitus position with a kidney rest at the iliac crest. The lower hip is flexed, resulting in blood pooling in the lower extremities, decreased blood return and cardiac output, and distal arm neuropraxias and nerve compression injuries [33].

Physiologic change: Hemodynamic changes that occur with pneumoperitoneum include increased Systemic Vascular Resistance (SVR), Mean Arterial Pressures (MAP) and filling pressures as well as a 50% decrease of Cardiac Index (CI). The SVR and CI normalize after 10 minutes [1]. Central venous pressure and wedge pressures may increase. The addition of trendelenberg positioning may decrease cardiac output by 10–30% [1]. These changes, in addition to the risk for embolic events, put the patient at risk for hemodynamic collapse. In the event that intraoperative Advanced Cardiac Life Support (ACLS) measures are required, the robot must first be undocked and trocars removed prior to defibrillation. Critical delay to instituting life saving measures may occur if the surgical team is not adequately prepared to abort a robotic procedure in roughly 1 minute [1,19,26].

The risk of bleeding is greatest during port insertion near the inferior epigastrics and, for prostate surgery, during dissection of the dorsal venous complex. Robotic surgery typically yields less blood loss and consequently fewer transfusions than open procedures that do not have the benefit of pneumoperitoneum pressure gradients tamponading small veins and capillaries [19]. Urine output monitoring might not be available as an aid to the determination of volume status; for example, due to the open bladder in prostate surgery. In order to minimize the amount of urine that is produced into the surgical field, as well as to decrease edema of dependent parts, fluids are typically limited to 1-2 liters until critical portions of the operation requiring optimal visualization are complete [27]; afterwards, a clinically guided management strategy for crystalloid will suffice.

Minimizing ischemic time is an evolving topic for anesthesia providers during robot-assisted partial nephrectomy. Reducing ischemic time from hilar clamping limits renal damage as evidence by Glomerular Filtration Rate (GFR) measurements. Ischemic time greater than 28 minutes has been shown to reduce renal function for up to a year [46]. Substituting hilar clamping for deliberate hypotension prior to incision of the renal parenchyma is an alternative that is gaining popularity. Hypotension may be induced with a combination of volatile anesthetic with nitroglycerine and esmolol infusions or boluses to maintain a Mean Arterial Pressure (MAP) of 60. Gill et al. report giving 1-2L crystalloid bolus preoperatively and beginning a 20% mannitol infusion at 20 mL per hour 1 hour prior to inducing hypotension. They measured Mixed Venous Oxygen (MVO₂) saturation throughout the hypotensive period and adjusted pressures to maintain MVO₂ greater than 40 [32].

Pulmonary physiologic changes that occur with robotic surgery include decreased compliance from restrictive forces induced by chest padding as well as the cephalad displacement of the diaphragm from pneumoperitoneum and trendelenberg positioning. Functional residual capacity is decreased and peak airway pressures are increased [1,41]. Hypercarbia induced by pneumoperitoneum results in respiratory acidosis. Acidosis may be exacerbated by CO₂ embolism or preexisting pulmonary disease [1]. Either pressure or volume-controlled ventilation strategies are acceptable, but the ventilation strategy must account for peak pressures that are often increased by 50% [35]. To compensate for high pressures, hypercapnia, and the desire to lower tidal volumes for improved surgical view, anesthesia providers should alter minute ventilation by titrating respiratory rate. Atelectasis that results in shunting of blood often occurs, resulting in hypoxia [33]. Peak End-Expiratory Pressures (PEEP) can improve gas exchange and should therefore be considered if peak pressures remain below safe limits.

Steep Trendelenberg positioning leads to increases cerebral

blood flow and pressure, and decreased venous outflow; therefore, patients with preexisting intracranial or ocular pathology may be at increased risk that requires careful consideration [1,41]. Blood flow to intraabdominal organs such as intestines, kidneys and liver is decreased due to decreased flow to systemic and portal circulations that accompany pneumoperitoneum.

Surgical injury: Intraoperative surgical risk has been reported at 0.8-2% bleeding requiring transfusion, 1.3% urinary leak, 0.5% wound infection, 0.2% bowel injury, and 0.2% femoral nerve palsy [27]. Other concerns should include: port-site hernia, anastomotic leak, and other peripheral nerve injuries [1]. The robot light source produces more heat than typical laparoscopy and therefore demands greater vigilance to prevent burns or fire [47].

Robot malfunction: Robotic malfunction is a concern. 2.6% failure rates have been reported due to joint, camera or arm failure, power errors, and monocular power loss or software incompatibility. One institution reported a non-recoverable robot malfunction of critical equipment of 0.4% [19]. Checklists can be instituted to further prevent equipment malfunction [45].

Emergence: Positioning, pneumoperitoneum and fluids combine to put the patient at risk for airway edema and failed extubation [26]. Several reviews have suggested conducting an airway cuff leak test prior to extubation as an indicator of risk for post-extubation stridor [19,26,44]. Patients who do not meet strict extubation criteria should remain intubated in the Post-Anesthesia Care Unit (PACU) until criteria are met. Often, allowing several hours for excretion of anesthetics and redistribution of fluids permits a safe extubation in the PACU.

Postoperative Management

Airway complications such as stridor, laryngeal edema, obstruction, and tracheal deviation result in postoperative respiratory distress in roughly 0.7% of robotic surgeries, requiring postoperative re-intubation [30,44,48]. Postoperative ileus leading to abdominal distension and nausea can occur and should be monitored, advancing diet beyond clears when clinically indicated [35]. Pain management is often accomplished with intravenous, multimodal therapy including narcotic, non-steroidal, neuropathic and acetaminophen analgesics [15,49]. Epidurals are typically not required for robotic incision pain [35].

Referred shoulder pain as a result of pneumoperitoneum's effect on the phrenic nerve, and a variety of neuropathies may present in the postoperative period [30,38]. Postoperatively, kidney function should be monitored as pneumoperitoneum may inhibit urinary excretion, decrease creatinine clearance, glomerular filtration rate and renal blood flow for up to 3 days postoperatively [30]. If urine output is less than 0.5 mg per mL per hour, a bolus of crystalloid should be considered. Encouraging early ambulation mitigates the risk of postoperative deep vein thrombosis [35].

Future Considerations

Comparable cancer-free outcomes with improved functional outcomes will continue the growth of robotic surgery for gynecologic and urologic surgery in spite of cost concerns. Invariably, competition for the da Vinci Surgical System, such as Titan Medical Inc's Amadeus System (Toronto, ON, CA), and The University of Santa Cruz's Raven Project, will enter the robotic surgery space, bringing down costs and driving quality and innovation. One area in need of innovation

is patient positioning where most institutions currently rely on self-created padding held together with tape to ensure safety with extreme positioning [20]. Practitioner proficiency and competency will need to be ensured by standardization of practice and credentialing on a national level [18,20]. The future of minimally invasive surgery with robotic technology holds great potential. Laproendoscopic Single Site Surgery (LESS) with robot-assistance [34], and Natural Orifice Transluminal Endoscopic Surgery (NOTES) are in development [2] as are robotics with haptic sensation. In vivo mini-robots that deploy intracorporeally for imaging and retracting are in development as well. Anesthesiologists would do well to prepare themselves for the robotic surgery revolution.

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