The objective of this article is to review the recent adoption, experience, and applications of robot-assisted laparoscopy in gynecologic surgery. The use of robotics in gynecologic surgery is increasing in the United States. Robotic-assisted laparoscopic surgeries in gynecology include benign hysterectomy, myomectomy, tubal reanastomoses, radical hysterectomy, lymph node dissections, and sacrocolpopexies. The majority of the current literature includes case series of various robotic surgeries. Recently, comparative retrospective and prospective studies have demonstrated the feasibility of this particular type of surgery. Although individual studies vary, robot-assisted gynecologic surgery is often associated with longer operating room time but generally similar clinical outcomes, decreased blood loss, and shorter hospital stay. Robot-assisted gynecologic surgery will likely continue to develop as more gynecologic surgeons are trained and more patients seek minimally invasive surgical options. Well-designed, prospective studies with well-defined clinical, long-term outcomes, including complications, cost, pain, return to normal activity, and quality of life, are needed to fully assess the value of this new technology.

(Obstet Gynecol 2008;112:1369–84)
One major obstacle to the more widespread acceptance and application of minimally invasive surgical techniques to gynecologic surgery has been the steep learning curve for surgeons and longer operative times associated with many of these advanced procedures. Other limitations encountered with conventional laparoscopy include countervuitive hand movements, two-dimensional visualization, and limited degrees of instrument motion within the body as well as ergonomic difficulty and tremor amplification. Overall, it is unclear whether the difficulty in training surgeons to feel comfortable with laparoscopic surgery is due to residents or attendings having an inadequate volume of surgical cases to maintain a comfort level with this technology and transcend the learning curve or whether there are inherent limitations of laparoscopy that make gynecologic surgeons choose other routes of surgery.

In an attempt to overcome these obstacles, robotics has been recently incorporated into the gynecologic armamentum. Robotic surgery carries with it the potential to transform laparoscopic surgery by providing, for the first time, instruments with distal ends that mimic the intricate movements of the human hand while at the same time providing the surgeon with a high-definition, three-dimensional view of the operative field. As this technology grows and develops, the hope is that further refinement and improvements will allow for even more precise and even less invasive surgical options beyond laparoscopy and the current forms of surgical robots. This article will review the history of robotics in medicine, its incorporation into gynecologic surgery, and where the future lies.

**MILITARY DEVELOPMENT**

The use of robots in surgery has only come about within the past 25 years. The first application of a robot in surgery was in neurosurgery. The original model, known as the PUMA 560 (Stäubli Corporation, Duncan, SC), was used for neurosurgical stereotactic maneuvers under computed tomography (CT) guidance. Soon, orthopedic surgery was using a device called Aesop (Computer Motion Inc.) instruments that had improved articulating distal ends, and improved ergonomic efficiency. This early device soon evolved into Zeus (Computer Motion Inc.), another predecessor to the current platform of surgical robots. This system comprised three remotely controlled robotic arms that were attached to the surgical table and a workstation called a robotic console. This console possessed the instrument controls, whereas three-dimensional vision was obtained with the aide of special glasses. The robotic arms operated the camera in a manner similar to Aesop but also provided the surgeon with two operating arms that possessed interchangeable “MicroWrist” (Computer Motion Inc.) instruments that had improved dexterity when compared with conventional laparoscopic instruments. Most importantly, for the first time, the surgeon was moved away from the operating room to a remote console.

Early studies reported on its successful application to tubal reanastomosis. Falcone evaluated pregnancy rates in 10 patients with previous tubal ligations who underwent laparoscopic tubal reanastomosis using the identical technique used at laparotomy. A postoperative tubal patency rate of 89% was demonstrated in 17 of the 19 tubes anastomosed, with a pregnancy rate of 50% at one year. There were no complications or ectopic pregnancies. Comparability to traditional gynecologic techniques was demonstrated.

Today there is only one U.S. Food and Drug Administration–approved device for surgical robotics. This current robotic platform is known as the...

The concept of robotic telepresence technology was born through the collaborative efforts of the Stanford Research Institute, the Department of Defense, and the National Aeronautics and Space Administration. Research was directed toward allowing military surgeons to perform surgery on wounded soldiers from a safe and remote location. As the technology further developed, research focused not on telesurgery but on using robotic surgery to further enhance laparoscopic and minimally invasive surgery in civilian operating rooms. Such advances became possible due to improved vision systems, instruments with articulating distal ends, and improved ergonomics. Although robotic telepresence technology was initially created for cardiac surgery, it soon was applied to the fields of urology and gynecology.

**INTRODUCTION OF ROBOTIC SURGERY**

One of the early predecessors and first applications of robotic technology to the civilian operating room was with a voice-activated robotic arm known as Aesop (Computer Motion Inc., Goleta, CA). The primary role of Aesop was to operate the camera during laparoscopic surgery. This early device soon evolved into Zeus (Computer Motion Inc.), another predecessor to the current platform of surgical robots. This system comprised three remotely controlled robotic arms that were attached to the surgical table and a workstation called a robotic console. This console possessed the instrument controls, whereas three-dimensional vision was obtained with the aide of special glasses. The robotic arms operated the camera in a manner similar to Aesop but also provided the surgeon with two operating arms that possessed interchangeable “MicroWrist” (Computer Motion Inc.) instruments that had improved dexterity when compared with conventional laparoscopic instruments. Most importantly, for the first time, the surgeon was moved away from the operating room to a remote console.

Today there is only one U.S. Food and Drug Administration–approved device for surgical robotics. This current robotic platform is known as the...
daVinci surgical system (Intuitive Surgical, Sunnyvale, CA; Fig. 1). The key technologic advancements seen with earlier predecessors are not only incorporated into today’s platform but are further refined.

**BASIC SETUP**

A basic surgical robotic system is composed of three parts: a patient-side robot, a vision cart, and the robotic master console (Fig. 1). The robotic surgeon operates from the remote master console using a combination of hand controls and foot pedals (Fig. 2). One foot pedal controls the camera movement (right/left, up/down, in/out) and horizontal orientation, while a nearby pedal controls the focus. Another pedal provides a clutching mechanism that allows for repositioning of hand controls and provides the instruments a range of motion beyond the physical confines of the console. Another set of pedals controls both monopolar and bipolar energy sources. The patient-side cart is wheeled in between the patient’s legs, and the robotic arms are attached to stainless steel robotic trocars through a process termed “docking.” The hand controls operate either the camera or up to two robotic instruments at one time. There are up to three operative robotic arms, with the option to swap control among any two of the three operative arms. While operating the robotic operative instruments, the surgeon is capable of manipulating, repositioning, grasping, retracting, cutting, dissecting, coagulating, and suturing. The robotic master console also provides the surgeon with three-dimensional imaging through a stereoscopic viewer. Despite all of these technologic advancements that make the surgeon nearly autonomous, a bedside assistant is still required for all robot-assisted cases. Their responsibility is mainly instrument exchanges, suction and irrigation, suture introduction and retrieval, and additional retraction.

Fig. 1. Da Vinci robot system. Copyright Intuitive Surgical, Inc. Reproduced with permission.

**ADVANTAGES**

Robotic surgery offers several advantages over laparoscopy: a three-dimensional vision system, wristed instrumentation, and ergonomic positioning for the surgeon while performing surgical procedures. The only currently available surgical robot employs two magnifying, wide-angle cameras that when aligned provide three-dimensional vision to the console surgeon with an available high-definition vision system. This enhanced visualization gives the gynecologic surgeon an improved ability to identify tissue planes, blood vessels, and nerves while performing the surgical procedure. Decreased blood loss has been reported in comparative studies.14,15

The gynecologic laparoscopic surgeon performs procedures in a confined space, the female pelvis. The limited degrees of freedom associated with a standard laparoscopic instrument compared with the human hand can significantly limit dexterity and a surgeon’s ability to complete particular tasks, such as difficult dissections, lymph node removal, and intracorporeal knot tying. Wristed instrumentation allows the gynecologic surgeon to obtain the exact instrument angle available at laparotomy. This also eliminates the fulcrum effect that is present with laparoscopy, where surgeons need to move their hand in the opposite direction to the intended location of the distal instrument tip (eg, toward the patient’s left if they want the instrument moved to the patient’s right). With robotic surgery, the movements are natural, and surgeons move their hands in whichever direction they want the instruments to move. The “wristed” instrumentation affords greater dexterity and provides seven degrees of freedom, similar to the human hand. Three degrees are provided by the robotic arms attached to the abdominal wall trocars (insertion, pitch, yaw), and four degrees result from the “wristed” instruments (pitch, yaw, roll, and grip). The terms pitch, roll, and yaw are the three characteristics that describe the rotations in three dimensions around the robotic instrument’s coordinate system origin, the center of mass. Pitch is the rotation around the lateral or transverse axis. The yaw is rotation about the vertical axis, and the roll is rotation around the longitudinal axis. The improved dexterity and control allow for finer, more delicate, tremor-free manipulation, dissection, removal, or reconstruction of tissue.

Fatigue and physical discomfort can become limitations during any surgical procedure. During laparoscopy, surgeons are often contorted to successfully complete the surgical procedure because they need to
reach over the patient’s abdomen to manipulate the hand controls on the laparoscopic instruments. With robotic surgery, the surgeon sits comfortably at the surgical console from the vantage point of standing at the patient’s head and manipulates the hand controls and foot pedals while in an ergonomic position. This may serve to reduce fatigue and discomfort during complex surgical procedures.
TELESTRATION

The current version of the daVinci robotic surgical system, the daVinci S (with or without high definition) allows for telestration. This allows the instructing surgeon to write on a touch screen with a finger or an electronic pen that is visible to both the console surgeon and the bedside staff. This feature allows the instructor to help guide the dissection, supervise which direction a particular robotic instrument should be moved, assist with suture tying, and outline vital structures to be avoided. It is important to confirm that proper target alignment of the cameras has been performed to allow the exact location that is highlighted to be appreciated by the console surgeon.

TilePro (Intuitive Surgical, Inc., Sunnyvale, CA) is a feature that allows for image and video input to the console. This can be viewed by the console surgeon for instructional purposes during the early phase of the learning curve or for input of radiologic data from ultrasonography, computed tomography, or magnetic resonance imaging.

DISADVANTAGES

The main disadvantages of robotic surgery across applications are the cost, the large size of the robot and console, limited availability within some health systems, lack of tactile feedback or haptics, and the need to train residents, attending surgeons and operating room personnel on the use of this technology. The costs associated with robotic surgery include the cost of the unit that can range from 1.4–1.6 million dollars, annual maintenance fees, and the cost of instrumentation that has limited (10) patient uses. Health systems need to perform a return on investment analysis. Given the substantial fixed costs associated with the purchase, high robotic surgical volume is required to improve this calculation. Additional costs that need to be considered include the time and cost of training surgeons and operating room personnel, the potential cost of reduced productivity during a surgeon’s learning curve, and increased operative time associated with operating room setup as well as the assembly and disassembly of the robotic system during the early phase of the adoption. There is evidence that with experience, operative time can become shorter than with laparoscopy.

The bedside assistant(s) may experience difficulty manipulating laparoscopic instruments through an assistant port and controlling a uterine or vaginal manipulator. This job is made more challenging for the assistant because the robotic arms are moving over the patient at the same time. Although robotic instrument exchange can become quite efficient, compared with laparoscopy it still requires attachment of the robotic instruments to the instrument arms before insertion.

Another current limitation of robotic surgery is the lack of haptics, or tactile feedback. While this is initially noted to be a limitation for novice robotic surgeons, most quickly adapt and obtain heightened visual feedback from the magnified, three-dimensional vision system. If there are particular structures that the surgeon desires to palpate, they can do so laparoscopically before docking the robot or ask the bedside assistant to palpate and confirm the location, such as palpation of a cervicovaginal colpotomy ring during a hysterectomy or the sacral promontory during a sacrocolpopexy.

Moving the robot to the operating table and docking or attaching the robotic arms to the trocars is often cited as a major disadvantage requiring significant time. With practice and training, this can be performed efficiently but does require time that is not necessary with laparoscopy. Docking time has been shown to decrease with experience to an average of less than 5 minutes. Once docked, the robotic arms are attached and fixed to specialized trocars. Because the operating table and the robot do not communicate and are therefore not synchronized, once the robotic unit is docked, the patient bed cannot be moved in any direction, including Trendelenburg; otherwise, the trocar depth can become incorrectly positioned and abdominal wall as well as visceral trauma could occur. Increased operative time associated with some robotic surgeries may have associated side effects, including anesthetic complications. Prospective studies with large sample sizes will also be necessary to fully assess for differences of rare outcomes such as deep vein thrombosis, dependent edema, and subcutaneous emphysema.

Finally, given the size of both the robotic unit and console, operating room size becomes a major consideration. Depending on current operating room size and availability, relocation to a larger operating room may be necessary. Many of these disadvantages could be improved with further development and technological refinement.

Future research is imperative to address the questions of cost-effectiveness, effect on resident training, and whether this technology is best made available to all surgeons or to a limited number of surgeons with high surgical volume who develop particular robotic expertise and are able to maintain proficiency with this evolving technology. Well-designed randomized trials comparing various routes of surgery with clini-
<table>
<thead>
<tr>
<th>Author</th>
<th>Comparison Group(s)</th>
<th>Cervical Cancer Stage</th>
<th>Endometrial Cancer Stage</th>
<th>Age (y)</th>
<th>Operative Time (min)</th>
<th>Total Lymph Nodes</th>
<th>Estimated Blood Loss (mL)</th>
<th>Length of Hospital Stay (d)</th>
<th>Transfusions</th>
<th>Complications</th>
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<tr>
<td>Kim et al. 2008</td>
<td>10 None</td>
<td>IA2-IB1</td>
<td>—</td>
<td>49.9 (34–75)</td>
<td>207 (120–240)</td>
<td>27.6 (12–52); margins all negative</td>
<td>355</td>
<td>7.9 (5–17)</td>
<td>0</td>
<td>No urinary tract injuries. One postoperative pneumonia</td>
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<td>Fanning et al. 2008</td>
<td>20 None</td>
<td>IB-IIA</td>
<td>—</td>
<td>44</td>
<td>6.5 h</td>
<td>18 (15–35)</td>
<td>300</td>
<td>1</td>
<td>Urerovaginal Fistula</td>
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<td>Magrino et al. 2008</td>
<td>27 Robotic</td>
<td>IA2-IB2 (n=18)</td>
<td>IB-IIIC (n=9)</td>
<td>50.0</td>
<td>189.6±43.5</td>
<td>25.9±6.3</td>
<td>133.1±108.5</td>
<td>1.7±0.9</td>
<td>1</td>
<td>No intraoperative complications. No readmissions. Bilateral pleural effusions (1), spontaneous mild pneumothorax resolved overnight</td>
</tr>
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<td>Kim et al. 2008</td>
<td>31 Laparoscopy</td>
<td>IA2-IB1</td>
<td>IB-IIIC</td>
<td>54.9±14.3</td>
<td>220.4±37.5</td>
<td>25.9±7.8</td>
<td>208.4±105.4</td>
<td>2.4±1.5</td>
<td>0</td>
<td>Femoral nerve (1), lymphocyst (1), vaginal cuff dehiscence (1)</td>
</tr>
<tr>
<td>Boggs et al. 2008</td>
<td>35 Open</td>
<td>IA2-IB2</td>
<td>IB-IIIC</td>
<td>50.9±8.6</td>
<td>166.8±33.2</td>
<td>27.7±6.6</td>
<td>443.6±253.2</td>
<td>3.6±1.2</td>
<td>0</td>
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<td>Boggess et al. 2008</td>
<td>49 Open</td>
<td>IA2-IIA</td>
<td>—</td>
<td>41.9±11.2</td>
<td>247.8±48.8</td>
<td>23.3±12.7</td>
<td>416.8±188.1</td>
<td>3.2±4</td>
<td>4</td>
<td>Bowel (1), bowel obstruction (1), ICU admission-pulmonary (1)</td>
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<td>Veljovich et al. 2008</td>
<td>25 Robotic</td>
<td>—</td>
<td>—</td>
<td>59.5 (&lt;P&lt;.03)</td>
<td>281</td>
<td>17.5 (&lt;P&lt;.11)</td>
<td>66.6 (&lt;P&lt;.001)</td>
<td>1.7 (&lt;P&lt;.001)</td>
<td>0</td>
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</tr>
<tr>
<td>Boggess et al. 2008</td>
<td>103 Open</td>
<td>—</td>
<td>IA-III (ABC)</td>
<td>61.9±10.6</td>
<td>191.2±36.0</td>
<td>32.9±26.2</td>
<td>197.6</td>
<td>5.3</td>
<td>1%</td>
<td>Bowel (1), portal-site hernia (1), pulmonary embolus (1), lymphocyst (1), lymphedema (1)</td>
</tr>
<tr>
<td>Boggess et al. 2008</td>
<td>81 Laparoscopy</td>
<td>—</td>
<td>IA-III (ABC)</td>
<td>62.9±10.8</td>
<td>213.2±34.7</td>
<td>23.1±11.4</td>
<td>145.8±105.6</td>
<td>1.2±0.5</td>
<td>2.5%</td>
<td>Bowel (1), caval injury (1), cystotomy (1), port-site hernia (1), ileus (1), umbilical hernia (1), femoral nerve palsy (1), lymphocyst (1)</td>
</tr>
<tr>
<td>Boggess et al. 2008</td>
<td>138 Open</td>
<td>—</td>
<td>IA-III (ABC)</td>
<td>64.0±12.8</td>
<td>146.5±48.8</td>
<td>14.9±1.3</td>
<td>266.0±185.5</td>
<td>4.4±3.0</td>
<td>1.5%</td>
<td>Bowel (1), stroke (1), ileus (7), deep vein thrombosis (1), pulmonary emboli (2), wound separations (14)</td>
</tr>
</tbody>
</table>

NA, not available; ICU, intensive care unit.
Data are n, mean (range), or mean ± standard deviation unless otherwise specified.
*Laparoscopy compared with robotic or open.
cally meaningful long-term outcomes are needed. These outcomes include effect on quality of life and patient satisfaction associated with hysterectomy, recurrence, and survival rates for oncology procedures, future fertility rates and pregnancy outcomes associated with tubal reanastomosis or myomectomy, and reoperation rates for urinary incontinence or recurrent pelvic organ prolapse for sacrocolpopexy.

INTRODUCTION OF ROBOTIC SURGERY

In 2005, U.S. Food and Drug Administration approval was granted for the use of the daVinci surgical system in gynecologic surgery. Since that time, this technology has been applied to a number of different conditions, with the development of several robotic procedures. Robotic hysterectomy with or without bilateral salpingo-oophorectomy, myomectomy, tubal reanastomoses, pelvic and paraaortic lymph node dissection, and sacrocolpopexy can all be performed robotically. These procedures can also be accomplished laparoscopically, but there has been limited adoption of laparoscopy for these procedures. It is yet to be determined if the adoption curve for gynecologists will be similar to that of urologists. Robotic prostatectomy, first performed in the United States in 2000, has become a standard approach for this surgical procedure.

General Gynecology

Hysterectomy

Hysterectomy, the most common major gynecologic surgery, can be performed a number of ways: vaginally, laparoscopically, and abdominally. A systematic evidence-based review that included 27 randomized controlled trials comparing vaginal, laparoscopic, and abdominal hysterectomy concluded that laparoscopic hysterectomy was preferred over abdominal hysterectomy. Patients undergoing laparoscopic surgery had a quicker return to normal activities, shorter length of hospital stay, and lower mean estimated blood loss. A higher rate of bladder and ureteral injury were observed in the laparoscopic hysterectomy group (odds ratio 2.6 95%, confidence interval [CI] 1.2–5.6).

Technologic advances introduced over the past two decades, such as improved optics, more powerful light sources, and safer electrosurgical generators, have facilitated the transformation of hysterectomy from the abdominal approach to the laparoscopic-assisted vaginal hysterectomy and eventually the laparoscopic supracervical and total laparoscopic hysterectomy. Although a definite trend toward laparoscopic hysterectomy has been seen since the 1990s, hysterectomy performed with laparotomy remains the most common route. It is important to recognize that although laparoscopic hysterectomy is available and performed easily in many situations, the data from a cross-sectional analysis of national discharge data using the 2003 National Inpatient Sample showed that the minority of surgeons use this minimally invasive option. Our study found that of the 538,722 hysterectomies performed for benign disease, 66.1% were performed abdominally, 21.8% were performed vaginally, and only 11.8% were performed laparoscopically. We concluded that despite a shorter hospital stay, vaginal and laparoscopic hysterectomies remain far less common than abdominal hysterectomy for benign disease.

One explanation for this slow acceptance is the learning curve with conventional laparoscopy and its associated complications. Another has often been advanced pathology, such as large uteri or pelvic adhesions, which affect the surgical anatomy field. This in turn is affected by the surgeon’s skill level and the technical limitations of conventional laparoscopic instruments. Contributing to this trend is a decreasing number of gynecologic residents who complete residency with adequate numbers of total vaginal hysterectomies to provide them with the skills and confidence to perform this surgery independently upon graduation.

Dunn et al analyzed whether a concerted effort to increase the number of vaginal hysterectomies performed in a residency training program could be accomplished without an increase in intraoperative or postoperative complications. During a period of 3 years, the rate of vaginal hysterectomy increased from 37% to 60% compared with the previous 3-year period. It is yet to be determined whether such a concerted effort will be made across the country. The current state of residency education in vaginal hysterectomy provides significant challenges to maintaining a cohort of gynecologists with the skills and confidence to perform this minimally invasive procedure. Given the morbidity and recovery associated with laparotomy incisions, the evaluation of alternatives, including laparoscopic hysterectomy and robotic hysterectomy, is prudent. This, of course, can be done while also working to increase the percentage of hysterectomies performed vaginally.

Robotics has been looked upon as a possible way to facilitate the trend toward a less invasive hysterectomy. In the gynecologic literature, several authors have evaluated robot-assisted laparoscopic hysterectomy and patient outcomes. Diaz-Arrastia and colleagues in 2002 reported one of the earliest experiences with robot-assisted laparoscopic hysterectomy. This series included 16 patients ranging in age from...
27 to 77 years. Operative times ranged from 270 to 600 minutes, and blood loss ranged between 50 mL and 1,500 mL, with an average loss of 300 mL. The average hospital stay was 2 days, with a range of 1 to 3 days. Although their approach was labeled a laparoscopic hysterectomy, all cases in that series were Type IIB according to the American Association of Gynecologic Laparoscopists (AAGL) classification system for laparoscopic hysterectomy, meaning that the posterior culdotomy and ligation of the cardinal and uterosacral ligament complexes were performed vaginally to complete the hysterectomy.25

Beste et al26 described their initial hysterectomy experience with 10 robot-assisted AAGL Type IVE cases. The AAGL Type IVE hysterectomy is defined as totally laparoscopic removal of the uterus and cervix, including vaginal cuff closure. They found their operative results were similar to those of conventional laparoscopic hysterectomy.

Recently, Fiorentino and colleagues published a series of AAGL Type IVE hysterectomy.27 Eighteen of 20 women presenting with benign gynecologic conditions underwent a successful robot-assisted total laparoscopic hysterectomy. Two patients were converted to laparotomy with subsequent abdominal hysterectomy because of poor visualization during robot-assisted surgery. Reynolds and Advincula28 reported their initial series of 16 consecutive patients who underwent either an AAGL Type IVE or Type III laparoscopic supracervical hysterectomy. In contrast to the Type IVE, the Type III laparoscopic supracervical hysterectomy is defined as a totally laparoscopic supracervical procedure with removal of the uterine corpus, including division of the uterine arteries. The mean uterine weight was 131.5 g with a range of 30–327 g. There were no conversions to laparotomy in this series. Specifically, they noted the advantage of robotic technology in the patient with scarred or obliterated surgical planes, because 13 of the 16 patients had prior pelvic surgery and required intraoperative management of pelvic adhesions to complete the hysterectomy. This same advantage was also described by Advincula and Reynolds29 in a robotic series of six patients undergoing successful hysterectomy who had a scarred or obliterated anterior cul-de-sac as a result of prior cesarean deliveries.

Despite significant advantages seen with the robotic approach for hysterectomy, Nezhat et al30 recently described disadvantages with their very early robotic experience. They found the absence of haptic (tactile) feedback, bulkiness of the system, lack of vaginal access, and costs to be limiting factors; however, their experience included only three robotic hysterectomies.

Kho et al16 at the Mayo Clinic, Scottsdale, published the largest series to date. Ninety-one patients undergoing robotic hysterectomy were evaluated. Those requiring lymphadenectomy were excluded. A wide range of pathology, including ovarian neoplasms, abnormal uterine bleeding, and moderate-to-severe endometriosis, was addressed. The average uterine weight was 135.5 grams. The mean operative time was 127.8 minutes, with an estimated blood loss of only 78.6 mL and hospital stay of 1.4 days. There were no conversions to conventional laparoscopy or laparotomy and no bladder or ureteral injuries occurred.

The only comparative study to date of robotic hysterectomy to conventional laparoscopy is by Payne and Dauterive15 in 2008. Their experience involved a retrospective review of their last 200 consecutive hysterectomy cases completed before and after implementation of a robotics program. There were no statistically significant differences in patient characteristics or uterine weights between the two groups. The rate of intraoperative conversions to laparotomy was two-fold higher in the laparoscopic cohort of 100 patients as compared with the robotic cohort (9% compared with 4%). The mean blood loss was also significantly reduced in the robotic cohort. However, the incidence of adverse events was similar in the two groups.

**Oncology**

A natural progression of robotic technology in gynecology has been to the area of oncology. In 2005, the first feasibility studies in both Europe and the United States were published. The first, by Marchal et al31 evaluated 12 malignant cases (five endometrial adenocarcinomas and seven cervical carcinomas). The mean number of pelvic lymph nodes removed was 11 (range 4–21). No port-site metastasis or recurrences were found with a mean follow-up of 10 months (range 2–23). A second study involved seven patients (four endometrial, two ovarian, and one fallopian tube cancer).32 The median lymph node count was 15 (range 4–29). Both early experiences clearly demonstrated the feasibility of applying robotic assistance to laparoscopic cancer staging without an increase in complication rates or compromise to surgical technique. Since these early reports, several other case series confirming feasibility have been published (Table 1).33,34

Magrina et al14 published the first comparative study of robotic radical hysterectomy. This study evaluated all three approaches: laparotomy, conven-
tional laparoscopic, and robotic. There were no statistically significant differences between the three groups with respect to mean age, body mass index, or lymph node count. However, the authors did find significantly less estimated blood loss and shorter length of stay associated with the robotic approach. In particular, operative times were comparable to open surgery and better than conventional laparoscopy. There were also no conversions or intraoperative complications in the robotic group.14

Similarly, Boggess et al35 published a study comparing robot-assisted, conventional laparoscopic and open hysterectomy with staging for endometrial cancer. They found the highest lymph node yields with the robotic approach. Robotic hysterectomy with staging was associated with significantly longer operative times compared with open hysterectomy, but shorter operative times when compared with laparoscopy. Conversion rates for robotic and laparoscopic groups were similar. Boggess et al36 later published a comparative study of robotic-assisted radical hysterectomy with pelvic lymph node dissection compared with open radical hysterectomy. The robotic cohort was associated with higher lymph node retrieval, shorter operative time, lower estimated blood loss, and shorter length of stay. Ultimately, 5-year survival rates will need to be evaluated to truly assess the effect of robotics on gynecologic cancer staging.

Reproductive Surgery
Myomectomy
The ability to manage leiomyomas endoscopically is one of the major advances in minimally invasive gynecologic surgery. Despite the fact that two prospective trials have shown postoperative morbidity to be less and recovery faster with laparoscopic myomectomy, the majority of cases are still performed using laparotomy.4,38

Because the various steps of myomectomy can be difficult with conventional laparoscopy, many concerns exist. In particular, the ability to enucleate leiomyomas and perform a multilayer closure requires advanced laparoscopic skills. Although pregnancy rates after myomectomy managed endoscopically are similar to those after laparotomy, a major worry continues to be the risk of uterine rupture. Also, the risk of recurrence seems to be higher after laparoscopic myomectomy compared with laparotomy. These factors and the associated learning curve may contribute to the fact that abdominal myomectomy remains the standard approach.39,40 In a manner similar to hysterectomy, robotics may facilitate the incorporation of a less invasive approach to the surgical management of leiomyomas. Figure 3 shows robot-assisted laparoscopic myomectomy and myometrial suturing after myomectomy.

In a series of 35 cases of robot-assisted laparoscopic myomectomy from Advincula et al41 the mean ± standard deviation myoma weight was 223.2 ± 244.1 g (95% CI 135.8–310.6). The mean number of myomas removed was 1.6 (range 1–5), and the mean diameter was 7.9 ± 3.5 cm (95% CI 6.6–9.1). The average estimated blood loss was 169 ± 198.7 mL (95% CI 99.1–238.4). No blood transfusions were necessary. The mean operating time was 230.8 ± 83 minutes (95% CI 201.6–260.0). Median length of stay for these patients was 1 day. Their conversion rate to laparotomy was 8.6% (two cases), because of an absence of haptic (tactile) feedback, which made enucleation of the leiomyomas difficult.

In 2007, Advincula et al42 published a retrospective case-matched analysis of robot-assisted laparoscopic myomectomy compared with abdominal myo-

Fig. 3. A. Myomectomy. B. Myometrial suturing after myomectomy.
mectomy. Although costs and operative times were higher in the robotic cohort, patients had significantly less blood loss and did not require blood transfusions. Complication rates were higher in the laparotomy group. Length of stay was significantly reduced in the robotic cohort (mean 1.5 days compared with 3.6 days).

Nezhat\textsuperscript{43} compared 15 robot-assisted laparoscopic myomectomies to a matched sample of 35 patients undergoing conventional laparoscopic myomectomy. The groups were matched by age, body mass index, parity, previous abdominopelvic surgery, and size, number, and location of the myomas. They found that the mean surgical time for the robotic myomectomy was longer: 234 minutes (range 140–455) compared with 203 minutes (range 95–330) for laparoscopic myomectomy. The authors found that the blood loss, length of stay, and postoperative complications were not significantly different. Recently, Senapati and Advincula\textsuperscript{44} described their surgical technique with robot-assisted laparoscopic myomectomy as a means to overcome the difficulties encountered with hysterotomy, including enucleation, repair, and extraction, that adheres to the principles of open surgery.

Tubal Reanastomosis

The ability to leverage the advantages of an advanced vision system along with the microsurgical precision of articulating endoscopic instruments is exemplified in gynecologic surgery with tubal reanastomosis. Although much is written by Falcone and colleagues\textsuperscript{13,45} on their early work with the Zeus Surgical System, very little has been published as it pertains to today’s platform of surgical robotics. In 2000, Degueuldre et al\textsuperscript{46} reported their feasibility study on eight patients with prior laparoscopic tubal sterilization who requested tubal reanastomosis. Sixteen tubes were successfully reanastomosed. The mean time that the robotic system was in use was 140 minutes, and mean surgical time was 52 minutes per tube. Five of the eight patients underwent a hysterosalpingogram and demonstrated at least unilateral patency, with two pregnancies reported within 4 months after surgery. The authors noted the absence of tactile feedback to be a disadvantage, but overall found that the operating time compared favorably with the time required to perform open microsurgery.\textsuperscript{46} Similar operating times were noted in a second study that evaluated 28 patients.\textsuperscript{47}

Dharia et al\textsuperscript{48} prospectively compared robotic to open microsurgical tubal anastomosis in women with a history of bilateral tubal ligation who desired reversal. They found that robotic tubal anastomosis was associated with significantly longer operative time (201 minutes compared with 155 minutes with open) but significantly shorter hospital length of stay (4 hours compared with 34.7 hours with open) and faster return to normal activities of daily living (11.1 days compared with 28.1 days with open). Pregnancy rates were comparable between groups (62.5% compared with 50% with open), yet the robotic group had a higher number of ectopic pregnancies (four compared with one with open). The cost per delivery was similar between robotic anastomosis ($92,488) and open tubal anastomosis ($92,206).

Most recently, Rodgers et al\textsuperscript{49} published a retrospective case–control study of tubal anastomosis by robotics compared with outpatient minilaparotomy. Twenty-six cases were performed with the robot, and 41 cases were performed by outpatient minilaparotomy. Although there were no conversions to laparotomy in the robotic group, the authors found significantly prolonged surgical and anesthesia times with the robotic technique. The robotic approach was associated with higher costs but a more rapid return to normal activity.

Urogynecology

Sacrocoldopexy

Improved access to health care, advances in medicine, and healthier lifestyles have contributed to the increased life expectancy observed over the past century. The life expectancy at age 65 years increased from 12 years in 1900 to 20 years in 2004. The life expectancy of a female born in 2004 is 80 years.\textsuperscript{50} As the size of the aging population grows, it is expected that we will see similar increases in the prevalence of conditions associated with age, such as pelvic organ prolapse. Abdominal sacrocolpopexy has a high long-term success rate of 93–99% but has traditionally been primarily performed through a laparotomy incision (Fig. 4).\textsuperscript{51} Vaginal reconstructive surgical options, such as sacrospinous ligament fixation, uterosacral ligament suspension, and vaginally placed mesh procedures, are alternative treatments but have different effectiveness levels and are associated with different risks of complication.\textsuperscript{52–55}

Maher et al\textsuperscript{56} performed a systematic evidence review that included three randomized controlled trials and found that abdominal sacrocolpopexy was better than vaginal sacrospinous fixation in terms of a lower rate of recurrent vault prolapse (relative risk [RR] 0.23, 95% CI 0.07–0.77) and less dyspareunia (RR 0.39, 95% CI 0.18–0.86), but the trend toward a lower reoperation rate for prolapse after abdominal
sacrocolpopexy was not statistically significant (RR 0.46, 95% CI 0.19–1.11). However, compared with sacrocolpopexy performed through a laparotomy, the vaginal sacrospinous fixation was associated with shorter operating room time, less cost, and earlier return to activities of daily living. The data were too few to evaluate other clinical outcomes and adverse events.

Laparoscopic sacrocolpopexy is possible but technically challenging due to the technical difficulties with dissection of both the presacral space and rectovaginal septum, mesh positioning, suturing, and extracorporeal knot tying. It is for these reasons that this technique, while available for more than a decade, has not gained wide popularity. The few data that are available indicate that a laparoscopic sacrocolpopexy is associated with lower blood loss and shorter hospital stay but longer operating room time.

Agarwala et al\textsuperscript{57} reported a series of 74 patients with stage II–IV prolapse who underwent a laparoscopic sacrocolpopexy\textsuperscript{52} or cervicopexy\textsuperscript{23} with polypropylene mesh (Prolene, Ethicon, Inc., Johnson and Johnson, Somerville, NJ). Patients had a median age of 63 years (range 48–76 years) and median BMI of 35 (range 24–41). The median estimated blood loss was less than 25 mL (range 25–150 mL), and median length of hospital stay was 1 day (range 1–2 days). Two subjects (3\%) required conversion, one to laparotomy due to dense rectosigmoid adhesions requiring a partial sigmoid resection because of postdissection trauma to the sigmoid. Another surgery was completed as a vaginal procedure because of finding a prior polyethylene terephthalate (Mersilene, Ethicon, Inc.) mesh that was densely adherent to the pelvic contents. Fifty-two patients underwent a concurrent sling for urinary incontinence. Patients had a subjective and objective cure of 97\% and 100\%, respectively. No mesh erosions were noted with a median follow-up of 24 months (range 9–36 months).\textsuperscript{57}

Paraiso et al\textsuperscript{5} compared 56 laparoscopic with 61 abdominal sacrocolpopexies in a retrospective cohort.
study. The patients were followed for 13.5±12.1 months in the laparoscopic group and 15.7±18.1 months in the open group. Mean operating time was significantly greater in the laparoscopic cohort (269±65 minutes) compared with the open group (218±60 minutes; \(P<.001\)). However, estimated blood loss (172±166 mL compared with 234±149 mL; \(P=.04\)) and hospital stay (1.8±1.0 days compared with 4.0±1.8 days; \(P<.001\)) were significantly less in the laparoscopic group than in the open group. Complication and reoperation rates were similar.

**Robotic Sacrocolpopexy**

Robotic sacrocolpopexy has been developed over the past few years (Fig. 5). Elliott et al\(^5\) reported long-term outcomes in 30 patients who underwent robotic-assisted sacrocolpopexy for posthysterectomy vaginal vault prolapse. They performed the presacral dissection laparoscopically and the suturing robotically. Recurrent grade 3 rectocele developed in one patient and recurrent vaginal vault prolapse in another. Two patients experienced mesh erosion. All patients reported satisfaction with the procedure. The mean operative time was 3.1 hour (range 2.2–4.8 hours). All but one patient left on postoperative day 1.

Daneshgari et al\(^5\) published a series of 15 patients with stage III–IV pelvic organ prolapse who underwent robotic sacrocolpopexy or sacrouteropexy. They experienced a 20% conversion rate (3 of 15), one to laparoscopy, one to open, and one to a transvaginal repair. The patients had a mean age of 64 years (range 50–79 years) and a mean pelvic organ prolapse quantification system (POP-Q) stage of 3.1.\(^3,4\) Preoperatively, the mean POP-Q values for the anterior vaginal wall (Aa, Ba), posterior vaginal wall (Ap, Bp), and apex (C) point were: Aa=–0.9, Ba=+1.0, Ap=–1.0, Bp=+1.3, C=+2.1. Postoperatively, the mean POP-Q Stage was 0 and mean POP-Q measurements were Aa=–2.3, Ba=–2.3, Ap=–2.7, Bp=–2.7, C=–8.3. The mean estimated blood loss during surgery was 81 mL (range 50–150 mL) and the mean length of hospital stay was 2.4 days (range 1–7 days).

We performed a comparative study of 73 robotic sacrocolpopexies performed by a single surgeon (A.V.) compared with 105 open colpopexies performed by four urogynecologists (see p. 1201).\(^6\) These surgeries were performed for vaginal vault prolapse and uterine prolapse. Robotic sacrocolpopexy was associated with similar improvement in POP-Q “C” point (−9 compared with −8, \(P=.008\)) when compared with abdominal sacrocolpopexy and was associated with less blood loss (103±96 mL compared with 255±155 mL, \(P<.001\)), longer total operative time (328±51 minutes compared with 225±61 minutes, \(P<.001\)), shorter length of stay (1.3±0.8 days compared with 2.7±1.4 days, \(P<.001\)), and a higher incidence of postoperative fever (4.1% compared with 0.0%, \(P=.04\)). There were no differences in other secondary outcomes but limited power to fully assess secondary outcomes.

We find dissection of the presacral space, positioning of the mesh, and intracorporeal suturing to be significant advantages to the robotic approach. We concluded, based on our initial experience, that robotic assisted sacrocolpopexy offers a reproducible, minimally invasive technique for vaginal vault and uterine prolapse with similar short-term durability.
compared with open sacrocolpopexies. Follow-up studies are needed to assess factors such as long-term durability, effect on quality of life, and postoperative sexual and urinary function.

TEACHING ROBOTIC SURGICAL SKILLS

Given the recent introduction of robotic assistance in surgery—particularly in gynecologic surgery—little is known about how best to train robotic surgeons. There is a paucity of experienced robotic surgeons. Currently, the training involves practice with the surgical robot in either a pig or human fresh tissue laboratory environment to become familiar with the functions of the robot, the attachment of the robotic arms to the robotic trocars, and the overall functions of the robotic console. Further training allows the surgeon to learn how to perform simple maneuvers such as grasping, cutting, and intracorporeal knot tying, the last task being particularly difficult with conventional laparoscopy. In fact, the vast majority of laparoscopic surgeons perform any knot tying extracorporeally.

Our understanding of the method and process by which a surgeon becomes experienced and proficient at performing robot-assisted laparoscopy is limited. The belief is that robotic surgery will allow for a more rapid development of the necessary skills and allow for a larger number of surgeons to attain those skills and, therefore, provide minimally invasive surgical options to a larger number of patients. One study compared five novices (medical students) to five expert laparoscopists in various operative skills using a robotic surgical system. Before training, the time to task completion for the various inanimate steps chosen was significantly longer for the novices. However, the novices significantly improved their surgical efficiency after only 10 trials. Most interesting was the finding that novice performance after this brief robotic training approached expert performance.61

Residents and fellows exposed to advanced laparoscopy and robotic surgery have several years to learn and become proficient with the technology and the surgical techniques. However, can the gynecologist in practice, whether a generalist or subspecialist, obtain the necessary postgraduate training? Vlaovic et al62 studied the effect of an intensive 1-week open, traditional laparoscopic, and robotic surgery training program for postgraduate urologists. The mean age of the surgeons was 47 years. Using Objective Structured Assessment of Technical Skill scoring, significant improvements were observed after training with laparoscopy (58 compared with 52) and to an even greater degree with robotic surgery (114 compared with 95).

Learning Curve

A paucity of data existed in the area of learning curves for gynecology until recently. Two studies have specifically looked at learning curves. The first by Pitter et al63 compared blood loss and operative time in the first 20 cases of robotic hysterectomies and myomectomies with the second 20 cases. All surgeries were performed by a single surgeon. They found no significant difference between groups in blood loss, with 86 mL in the first group and 63 mL in the second group. However, mean total operative times were significantly shorter in the second group, with 212 minutes for the first group compared with 151 minutes for the second group. There were no conversions to laparotomy.

A second study by Lenihan et al64 evaluated 113 sequential patients over a 22-month period. They found that the learning curve for various benign surgical interventions stabilized in regard to operative times after 50 cases. A similar learning curve was documented for the OR team to be able to set up the robot for surgery in 30 minutes. This break point was 20 cases.

Several other studies allude to learning curves. A major hurdle often encountered early in a surgeon’s robotic experience is “docking time,” or the attachment of the robotic device to the patient. This is often perceived as taking an inordinate amount of time. However, Kho et al65 published a mean docking time of 2.95 minutes in 88 patients, with times decreasing for subsequent groups of 10 patients. Even more significant are the findings by Payne and Dauterive,15 who noted improvements in mean operative times between their first 25 cases compared with last 25 cases in the robotic cohort (133.5 compared with 78.7 minutes). Also, their mean operative time for laparoscopic hysterectomy in the prerobotic cohort of 100 cases was 92.4 minutes compared with 78.7 minutes in the last 25 robotic cases. After progressing through the learning curve, they were able to improve upon their conventional laparoscopic times with the aide of robotics.

Credentialing

With the introduction of robotic surgery, hospitals and departments have been challenged to establish credentialing requirements for this advanced surgical technique. There are no universally established credentialing guidelines. We propose a set of guidelines that require as a prerequisite that the surgeon be fully credentialed in laparoscopic surgery.
Basic System Training
We also recommend that the surgeon show evidence of at least 8 hours of hands-on training in the use of the robotic surgical system. A significant portion of this training must include console time as the primary surgeon performing surgical procedures on either anesthetized pigs or fresh cadavers. For surgeons who are already familiar with the robotic surgical system, usually having completed a residency or fellowship that included training in robotic surgery or having performed robotic surgical procedures at another institution, demonstration of such experience is required. We recommend that the requesting surgeon demonstrate proof of a minimum of 10 robotic surgical procedures of the same type to waive the basic system training.

Preceptorship/Proctoring
The surgeon is required to perform a minimum of two robotic surgical procedures of each type for which privileges are being requested in the presence of an expert preceptor. Some institutions are using four as the minimum number of proctored robotic surgeries necessary for independent robotic privileges. The applicant should also possess privileges to perform a procedure by laparotomy before requesting such privileges robotically. If the applicant is applying for robotic privileges based on a previously documented series of a minimum of 10 cases either as part of an accredited residency or fellowship program or based on performance of such procedures at another institution, the Division Chief or Chair of the appropriate Surgical Division or Department may, at his/her discretion, recommend waiving the requirement of one or all of the proctored surgical robotic procedures.

An expert preceptor is defined as a surgeon who has current Robotic Surgical Privileges and has been approved as an expert preceptor by the Chair of the Department of the individual applying for privileges. Ideally, a preceptor will be from the same institution and will have full privileges at that institution. The ability to sit at the console occasionally during the first several surgical procedures is a valuable educational opportunity that is generally not possible when the preceptor is chosen from another institution or state. Telestration, the ability to write on a touch screen and have the markings visible at the console, is helpful but does not replace the educational guidance a “cosurgeon” training robotic console would afford. Such a “copilot” console is not currently commercially available.

Reappointment/Maintenance of Privileges
We contend that, similar to other surgical procedures, maintenance of competence requires performing procedures on an ongoing basis. We recommend that at reappointment, the applicant must demonstrate maintained competence of a set number of robotic procedures determined by the hospital or institutional credentialing committee. For surgeons who have performed less than the required number of robotic procedures per year and who desire ongoing privileges, a plan by the applicant and Service Chief/Chair that may include potential preceptorship would be submitted for review by the institutional credentialing committee.

SUMMARY
Robotic surgery has seen enormous growth over the past decade in several fields, including gynecology. However, we are likely to see further improvements as the technology continues to develop and further refinements occur. It has been just more than a decade since robotic surgery was first introduced into the operating room. Advances in robotic gynecologic surgery are also likely to continue as more gynecologic surgeons are trained in this technique and more patients seek minimally invasive surgical options. Well-designed, prospective studies with well-defined long-term clinical outcomes, including complications, cost, pain, return to normal activity, and quality of life, are needed to fully assess the value of this new technology.

REFERENCES


