Robotics in reproductive medicine

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1. ABSTRACT

In the past decade, robotic technology has been increasingly incorporated into various industries, including surgery and medicine. This chapter will review the history, development, current applications, and future of robotic technology in reproductive medicine. A literature search was performed for all publications regarding robotic technology in medicine, surgery, reproductive endocrinology, and its role in both surgical education and telepresence surgery. As robotic assisted surgery has emerged, this technology provides a feasible option for minimally invasive surgery, impacts surgical education, and plays a role in telepresence surgery.

2. INTRODUCTION

Surgery has evolved from the 19th century with introduction and improvements of anesthesia, sterile technique and antisepsis, and formalization of surgical training (1). In the late 20th century, video laparoscopy was introduced which provided benefits including smaller abdominal incisions, improved patient comfort, shortened recovery period, and improved cosmesis (2). Although laparoscopic surgery has many benefits over traditional laparotomy, it also carries some disadvantages such as limited range of motion intraabdominally and two-dimensional vision (3). The introduction of robotic surgery has addressed many of these limitations. In this chapter, we

will review the history and development of robotics, its current applications in surgery and reproductive medicine, the role of robotics in surgical training, and the future of this technology.

3. THE DEVELOPMENT AND HISTORY OF ROBOTICS

Derived from the Czech word robota (meaning compulsory labor) a robot was defined by the Robotic Institute of America as "a machine in the form of a human being that performs the mechanical functions of a human being but lacks sensitivity…(4). Leonardo da Vinci developed one of the first robots in 1495; a mechanical armored knight whose purpose was to amuse royalty. This was followed by the creation of the first operational robot in 1801 by Joseph Marie Jacquard, in which an automated loom, controlled by punch cards, created a reproducible pattern woven into cloth. This robot demonstrated both precision and accuracy, a continuing theme in today's robotic technology.

In other fields separate from medicine and surgery, the first applications of robots were in computers, industry, and mathematics. Joseph Engelberger and George C. Devol developed the first industrial robot, The Unimate robot, which was used as an automated die-casting mold robot at General Motors Factory in 1962. Robotic technology is currently being used in space and ocean explorations (taking images and collecting information), industrial tasks (welding), military and police tasks (spying, destroying mines, or information collection), and entertainment (from toys to television). Across various fields and industries, robots utilize three important characteristics; 1) programmability (computational and symbol-manipulative capabilities controlled by a designer 2) mechanical capability (ability to interact within its environment not just function as a data processing machine and 3) flexibility (function and process a variety of differing programs and materials) (5).

4. APPLICATIONS IN MEDICINE

Robotics has been integrated into many aspects in the field of medicine. Robots can function in supportive, rehabilitation, and surgical roles. Supportive robots are used in various tasks such as transporting pharmaceuticals, equipment and supplies, medical records, and radiology films around the hospital. A robot, known as RAID, has been used in physical medicine as therapy aids in joint movement by assisting in activities of daily living (6). Also, there is continued interest in the use of mobile robot with a video screen capable of rounding on the hospital wards (e.g. telerounding) (7).

5. APPLICATION IN SURGERY

Early surgical applications were in the fields of neurosurgery, urology, and orthopedics. These applications ranged from supervisory robots (which use computer guidance to assist the surgeon) to autonomous robots (where movement is determined by a pre-operative plan).

Simultaneously, the birth of robotic telepresence technology (which would allow the surgeon to operate at a distance from the operating room) was occurring at Stanford Research Institute in conjunction with National Aeronautics and Space Administration (NASA) and the Department of Defense (8). Originally, the prototype was intended to suit the needs of the military, and the robotic arms were designed to be mounted on an armored vehicle to provide immediate operative care in the battle field. Soon, thereafter, the system (da Vinci) became commercially available. The da Vinci system focused on the immersive telepresence concept (where the surgeon operates from a distance from the patient, yet feels as if in the operating room). Also at this time, AESOP (Automated Endoscopic System for Optimal Positioning) was developed as the first laparoscopic camera holder. Computer motion later created Zeus surgical system, which is an integrated robotic system (surgeon operates at a distance from the patient and is aware of that distance) (8).

5.2. Application is surgical subspecialties
5.2.1.Urology

The first use of robotics in urology was the PROBOT in 1989 utilized for transurethral resection of the prostate (9). In the past decade, robotic assisted surgery has been most successfully used in prostatectomy. Patel *et al.* demonstrated that the da Vinci system in radical prostatectomy has similar oncogenic results as well as reduced blood loss, shortened hospitalization, and early continence (10). Robotic surgery has also proven to be beneficial in pyeloplasty, with several studies reporting 94-96% success rate with the procedure (11,12). Moreover, robotic technology has been implemented in various other urologic procedures including renal transplant (13,14), donor nephrectomy (15), adrenalectomy (16), cystectomy (17,18), vasovasostomy (19), and pediatric urologic surgeries (20).

5.2.2. Orthopedics

Proper alignment of the limb and prosthesis are critical for success in total knee replacement. The ROBODOC system, utilizes CT guidance for both precise pre-operative implant selection and intraoperative precision to mill a hole into the femoral cavity (21,22). A second integrated robotic system, the ACROBOT has been shown to have improved accuracy in clinical trials (23,24). This system is utilized in unicompartmental knee replacement to allow for motion in pre-programmed regions, while avoiding motion in prohibited areas (9). In addition, for patients with low back pain who undergo minimally invasive procedures such as nerve blocks, a robot has been developed by three different groups to assist the physician in needle placement (24).

5.2.3. Gastrointestinal surgery

In the past few years, telerobotic surgical systems have been applied for use in a variety of laparoscopic gastrointestinal surgeries. Feasibility of robotic assisted procedures was early on described by the Academic Robotic Group at the Society of American Gastrointestinal Endoscopic Surgeons. The society presented case reports involving robotic technology in various gastrointestinal

procedures such as Heller myotomy, gastric banding bypass, and Roux-Y gastric bypass (25,26). Additional case reports describe a role for robotics in total splenectomy, cholecystectomy, bilateral inguinal hernia repair, biliary pancreatic diversion, wedge resection, distal gastrectomy, anterior resection, and abdominalperineal resection (27-30).

5.2.4. Cardiac surgery

The telerobotic surgical systems were designed are for optimizing minimally invasive procedures for cardiac surgeries. These systems were first used to assist in coronary artery bypass grafting (CABG) (31). The extent of robotic involvement in the cardiac surgery increased with experience until robotic assisted endoscopic coronary artery bypass grafting were performed without cardiopulmonary bypass on a beating heart (32). Robotics has been successfully adopted by both simple and complex mitral valve procedures. A number of surgeons have reported their experience with robotics in atrial septal defect (33), patent foramen ovale closure (33), repair of patent ductus arteriosus (34), atrial fibrillation surgeries (34), and left ventricular lead placement (34).

5.2.1. Other surgical subspecialties

Robotization of neurosurgical procedures advanced significantly with modification of industrial robots to perform stereotactic tasks. The initial model was the PUMA 560 using computer tomographic guidance for stereotactic brain biopsy which was then followed by Minerva and Neuromate. In addition to brain biopsy, robots been successfully implemented in both brain and spinal cord surgeries. These include the Spine Assist for pedicle screws in spinal surgery, Evolution 1 for endoscopic third ventriculostomy, and both the CyberKnife and NeuRobot for tumor resection both in the spinal cord and brain (35).

For use in maxillofacial surgery, a robot (RX90) was developed to perform craniofacial osteotomies with a surgical cutting saw using computer tomographic scanning. Robots using computer tomographic and computer assisted navigation appear optimistic in early case reports for surgical repair of orbitozygomatic fractures (36,37). Also, a study has shown the feasibility of robots in performance of thyroidectomy in the infant neck using a porcine model (38).

In the field of ophthalmology, many surgical operations on the eye require precise microsuturing skills. A robot (Steady Hand) has been developed for microsurgical augmentation. The robotic instrument requires the physician to actually hold and manipulate the tool with the aid of the robot. Inanimate studies evaluating the precision of suture placement have demonstrated an advantage with robotic assistance (24)

6. ROLE OF ROBOTICS IN GYNECOLOGY AND ITS SUBSPECIALTIES

Traditionally, gynecologic surgery has been performed through either laparotomy or a vaginal approach.

These methods provide the benefit three-dimensional vision of the operative field as well as tactile feedback from resistance of the tissues. Additionally, the 6 degrees of freedom of the human wrist allow for ease of dissection and suturing. However advantageous the shortcomings of laparotomy include a large abdominal incision, prolonged hospitalizations, increased need for postoperative analgesia, and increased morbidity (3, 39). This has led to development and increased use of minimally invasive surgical techniques. In 1901, Ott from Petrograd described "ventroscopy" using a head mirror and abdominal speculum to inspect the abdominal cavity (40). In the last four decades, the use of operative laparoscopy has been utilized to perform nearly all types of gynecologic surgeries including tubal sterilization (41) and gamete intrafallopian tubal transfer (42). Advantages of laparoscopy include: improved cosmetic appearance, quicker recovery time, decreased hospital stay, and reduced post-operative morbidity. In addition, laparoscopic surgery is thought to reduce de novo adhesion formation by eliminating the use of sponges and retractors as used in a laparotomy incision (43). However, the usefulness of laparoscopy is compromised by the steep learning curve for surgeons. Both reduced depth perception affronted by the two-dimensional (2D) video monitor as well as restricted dexterity and counterintuitive movements limit the efficacy of laparoscopic surgery. The length and rigidity of laparoscopic instruments produces amplification of tremor during prolonged surgeries (44). The fulcrum point, the insertion point of the trocars in the abdominal cavity, affords only four degrees freedom reducing surgical range of motion. Furthermore, the working end of laparoscopic instruments move in the opposite direction of the surgeon's hands, often times making movements counterintuitive (44). Ergonomics is also impacted by minimally invasive surgery. The society of Gastrointestinal Endoscopic Surgeons reported 8-12% incidence of pain or numbness in arms, wrist, or shoulders after performing laparoscopic surgery (45). Thenar neuropathies have also been reported in association with laparoscopic surgeries (46, 47). Many of the limitations can be reduced by efficient and facile surgeries.

Simple gynecological procedures such as tubal ligation, management of ectopic pregnancy, lysis of adhesions, and cautery of endometriosis can all be performed by many gynecologists using laparoscopic technique. However, few gynecologists possess the skill to perform the more complex procedures such as; tubal anastomosis, radical hysterectomy, lymphadnectomy, and abdominal sacrocolpopexy, laparoscopically, and therefore these surgeries are typically managed through laparotomy.

Many of these limitations have been reduced by robotic assistance, without sacrificing the benefits of laparoscopy. Robotic surgery, specifically the telerobotic system, allow for improved ergonomics, by allowing the surgeon to be seated during the surgery, as well as offering three-dimensional imaging and intra-abdominal dexterity with laparoscopic instruments.
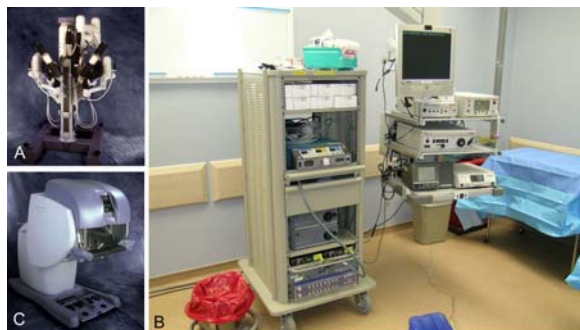
Figure 1. The three components of the da Vinci surgical system. (A) The surgeon's console with the "masters" and foot pedal control, (B) the vision cart with two light sources and two 5-mm cameras, and (C) the surgical cart with either three or four arms (three arms are shown in this figure). Printed with permission from Intuitive Inc.

7. TYPES OF ROBOTIC ASSISTANCE IN GYNECOLOGIC SURGERY

In gynecology and its subspecialty, three active functional robots are used to assist in minimally invasive surgery.

7.1.1. Laparoscopic camera holder

The automated endoscope system for optimal positioning (AESOP) was the first robot that was approved for clinical use in intra-abdominal surgery. This robotic system is designed to hold and control the laparoscopic camera. When initially introduced, AESOP operated under the control of the surgeon by manipulating either a foot switch or hand control (48, 49); later the system was modified to respond to voice commands using a vocabulary of 23 words (50). Since its introduction, AESOP has facilitated several thousand surgeries, by providing a stable, hands free image, while eliminating the need for human camera holder.

AESOP was compared to traditional camera holder in several urologic procedures, demonstrating similar operating times with a considerable steadier camera platform (51, 52). Results of AESOP use in gynecology by Mettler *et al*, also exhibited similar operative times as compared to a human camera holder (53).

A disadvantage of AESOP is the constant conversation by the surgeon with voice control, which may be distracting to other team members. In addition, the cost benefit of AESOP is based on the replacement of the surgical assistant. This is not always beneficial since often times an assistant is needed to operate fourth port, or in academia where residents or students often act as the assistant.

7.1.2. Robotic integrated surgical system

One of two available surgical systems is Zeus developed by Computer Motion in the early 1990's now with few remaining operational systems. This system modified AESOP to produce a robot functional in teleroboic surgery. The Zeus system is composed of two separate subsystems, the "surgeon-side" and "patient-side". Later versions of the surgical system were modified to include both three-dimensional vision and improved intra-abdominal articulation (e.g. MicroWrist) (54). Although, the efficacy and benefits were demonstrated in various animal and human studies, the Zeus surgical system has been phased out.

7.1.3. Immersive telerobotic surgical system

The initial purpose of this type of surgical system was designed for remote telemanipulation designed for use on the battlefield. This system was modified to function as a possible solution to the limits of laparoscopy. The functionality of this system was based on three main components: "1) a master/slave, software-driven system that provided intuitive control of laparoscopic instruments offering seven-degree-of freedom 2) a stereoscopic vision system displayed in an immersive format 3) a system architecture composed of redundant sensors to provide maximum safety in operation" (55). Early human studies demonstrated the limits of traditional endoscopes used in the initial prototype. Therefore, the system was enhanced by the development of binocular endoscopic technology which could attain resolution and stereo separation essential for complex surgery. After completion of preliminary human trials and review of the date, the FDA approved the da Vinci robot in July 2000 (55). This system encompasses three main components (Figure 1).

7.1.3.1. Surgeon's console

The surgeon is seated at a computer console, placed anywhere within the operating room. The console is connected through a cable to the robotic tower which allows the surgeon to directly control the movement of the da Vinci robot. The console houses binoculars through which the surgeon observes the operation in 3D vision. Infrared safety controls deactivate the robotic tower when the surgeon is not viewing through the binoculars. Additionally, the console contains hand controls, called "masters" that translate the 3D motion of the surgeon's hands into electric signals that directly control the activity of the robotic arms. The "masters" can be modified to adjust the ratio of motion of surgeon's hand to that of the robotic arms (e.g. motion scaling). For example, a 5:1 ratio allows for every 5 inches of movement by the surgeon, only 1 inch movement by the robotic arm. Furthermore, the da Vinci hand controls provide an improvement of tremor filtration that is beneficial in suturing and dissection. Foot pedals within the console are used for activation of electrocautery. There is an ability to control the camera, energy devices, and the "masters" with foot pedals (Figure 1A).

7.1.3.2. Video cart

The video cart has two video camera control boxes and two light sources, in addition to a synchronizer (Figure 1B).

7.1.3.3. Surgical cart

The surgical cart houses four robotic arms, which are attached to surgical instruments through robotic-arm
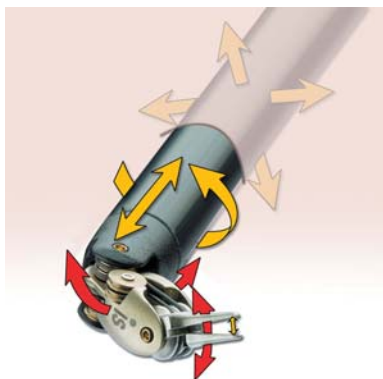
Figure 2. The seven degrees of freedom include four movements found in traditional laparoscopy (shown in large yellow arrows), plus two endocorporeal movements afforded by Endowrist technology (shown in large red arrows) in addition to "grip" (shown by a small yellow arrow). Printed with permission from Intuitive Inc.

Table 1. Gynecologic procedures performed with a robot

Reproductive surgery
• Tubal reanastomosis
• Myomectomy
• Ovarian transposition
Reconstructive pelvic surgery
• Burch procedure
• Colpopexy
General gynecology
• Hysterectomy
• Dermoid cystectomy, oophorectomy, salpingo-oophorectomy
Salpingectomy, tubal ligation
Gynecologic oncology
• Hysterectomy
• Lymphadenectomy

Table 2. Seven degrees of intra-abdominal articulation for surgical instruments[1]

• In and out
• Elbow up and down
• Elbow left and right
• Wrist up and down
• Wrist left and right
• Open and shut
• Axial rotation

1. Some instruments such as ultrasonic instruments and electrocautery hooks have limited articulation.

instrument adapter. Each instrument passes through a reusable 8-mm da Vinci-specific port. A 12-mm telescope is connected to the central robotic arm and contains two 5-mm telescopes producing three-dimensional vision. The instruments possess the ability to articulate the seven degrees of freedom of the human wrist (Figure 2 and Table 1) (56). The robotic instruments are responsible and can be used for a maximum of 10 surgical procedures and then must be replaced (Figure 1C).

The advantages of the da Vinci systems include three-dimensional vision, the immersive environment, tremor stabilization, seven degrees of intra-abdominal articulation, and motion scaling which makes it ideal for complex laparoscopic movements such as intracorporeal

suturing and microsurgical movements in an anatomically confined space. Disadvantages of the system include the lack tactile feedback, the bulkiness of the machine with large robotic arms often leading to frequent collisions, positional changes for abdominal procedures are often cumbersome, and limited instrumentation. Also, the cost of a da Vinci system can also be a hindrance to its benefits. A da Vinci surgical system costs approximately 1 million dollar and each instrument costs $2,000 every 10 uses.

Since original production of the da Vinci, two additional systems are now commercially available. The *da Vinci S-series*, is a slimmer version of the original prototype, decreasing the bulkiness of the robot. The *da Vinci S HD* includes an integrated touchscreen monitor, telestration for improved proctoring and team communication, and a TilePro multi-input display that allows an integrated view of patient critical information (e.g. radiographic images superimposed on the operative field).

8. CURRENT APPLICATIONS IN GYNECOLOGY

Operative laparoscopy has gained wide acceptance in field of surgical gynecology over the past four decades. Robots have only recently been employed to assistance in more routine and complex gynecologic procedures. One of the first uses of robots occurred in 1998, when Mettler *et al.* compared the use of AESOP versus traditional camera holder in 50 patients undergoing routine gynecological procedures. The studied demonstrated comparative operative times, a steady platform for the camera, as well as allowing for more complex procedures faster by freeing two surgeons to use both hands during the operation (53). Since then, robotic assistance in gynecological procedures has increased both in general gynecology as well as its subspecialties.

8.1. General and Subspecialty c applications
Most gynecologic procedures have been attempted robotically (Table 2). However there are no randomized clinical trials only case series.

8.1.1. Robotic application in reproductive endocrinology
In 1998, using the Zeus surgical system, Margossian et al, demonstrated in animal models that robotic technology could safely be used in microsurgical anastomosis (57). Falcone et al, in 1999, performed the first robotic assisted tubal anastomosis using the Zeus system in 10 patients (58). The surgical procedure was successfully completed in all 10 patients without complications. The mean operative time to complete anastomosis of both tubes was 159+/- 33.8 minutes. At the completion of the procedure chromopertubation demonstrated patency in all tubes. Follow up from the procedure showed at 6 weeks 89% patency rate demonstrated by hysterosalpingogram and at 12 month a 50% pregnancy rate. A further study, reviewed laparoscopic tubal anastomosis with and without the assistance of the Zeus robot (59). The anastomotic technique was performed by placing four 8-0 polygalactin sutures at 3, 6, 9, and 12 o'clock, with the initial suture

placed at 6 o'clock. The study showed that robotic assistance resulted in >2 hour increased in operative time in addition to increased estimated blood loss (although not clinically significant) without substantial improvement in patient recovery or clinical outcomes. In 2000, Degueldre et al, (60)using the da Vinci robot found similar operating times in 8 patients as compared to open microsurgery, and although follow-up was limited to 4 months, pregnancy did occur in 2/8 patients. A common limitation was the lack of tensile feedback associated with suturing resulting in 11% broken suture material (60). A subsequent study by Patel et al., (61) performed a feasibility study in a fellowship training program comparing open microsurgical technique versus the da Vinci surgical system in tubal anastomosis on 18 patients who desired tubal sterilization reversal. For the preoperative setup, the da Vinci surgical tower was placed between the patient's lower extremities with the patient in lithotomy position. Port placement, as described in figure 3, was relatively consistent among the patients. Operative times were significantly greater in the robotic assisted procedures, however length of hospital stay, time to recovery, time to return to independent activities of daily living were significantly shorted in the robotic group.

A recent study compared tubal anastomosis by robotic compared with outpatient laparotomy (62). Surgical times for the robot and the "minilaparotomy" were 229 minutes and 181 minutes respectively. Hospitalization times, pregnancy and ectopic pregnancy rates were not significantly different. The robotic technique was more costly by about $1446 USD. However if you compare robotic with inpatient tubal reversal by laparotomy the cost analysis would show no difference. The time to return to work was significantly shorter in the robotic system group by approximately 1 week.

Also in reproductive gynecology, several case reports using robotic assisted laproscopy have shown promise for furthering this technology in this field. In 2003, a case by Molpus *et al*, was reported revealing success use of the da Vinci robot in ovarian transposition which is beneficial to women undergoing pelvic radiation in preserving ovarian function and reproductive capacity (63). In 2007, a case report described an uncomplicated term pregnancy following a da Vinci assisted myomectomy (64). Further larger comparative trials are necessary for validating the continued use of robotic assisted laparoscopy within reproductive endocrinology.

8.1.2. Robotic application in benign gynecology

Hysterectomy is one of the most common surgeries performed today. Greater than 90% are still performed using traditional laparotomy and vaginal approaches, which may be linked to the limits of laproscopy. Robotic surgery was first studied in benign gynecological procedures using the Zeus robotic device in 10 female pigs undergoing adnexal surgery and hysterectomy with promising results (65). These studies were then translated in the use of robotic technology in human patients undergoing hysterectomy as a feasible option. A study in 2005, demonstrated effective use of the da Vinci robot 10 patients undergoing total laparoscopic hysterectomy. Operative times ranged from 2.5 to 4.5 hours and estimated blood loss varied from 25 to 350ml. The study concluded that tasks such as lysis of adhesions, suturing, and knot tying were enhanced by the assistance of the robot (66). Subsequently, Advincula and Reynolds described in two studies the feasibility of performing robotic assisted total laparoscopic hysterectomy in patients with previous abdominal surgery or with suspected presence of a scarred or obliterated anterior cul-de-sac (67,68). Mean operative times were reported to range from 244-254 minutes, as suspected prolonged surgeries occurred in patients with dense adhesive disease or obesity. These studies show that even in experienced hands there is a learning curve that will prolong the surgical time. However the studies both stated that operative time was inversely proportional to surgical experience. The surgeon should not expect that operative times will immediately reach thse of conventional laparoscopy. Complication rates were shown to be comparable to those of laparoscopy in the literature. One report of bowel injury, with subsequent intervention and colostomy was reported (67).

In a retrospective case review, the da Vinci robot was assessed in 35 patients undergoing myomectomy. Mean weight of the myomas ranged from 223 +/- 244 g, with an average of 1.6 myomas removed per patient, and average myoma diameter being 7.9 +/- 3 cm. Conversion rate from robotic to laparotomy was 8.6%. An average estimated blood loss of 169 +/- 198 and mean operative times of 230 +/- 83 minutes were described by the study. Again, operative times decreased with experience (69).

A recent study in 2007, evaluated conventional laparoscopy and robotic technology is various gynecologic procedures (70). The study assessed 15 patients undergoing combined laparoscopic and robotic assisted laparoscopic procedures including myomectomy, sacral colpopexy, treatment of endometriosis, total laparoscopic hysterectomy, or supracervical hysterectomy. The study reported average robotic assembly time of 18.9 minutes and disassembly time of 2.1 minutes. Furthermore, the authors reported easier exchange of instruments with conventional laparoscopy, awkward exchange of instruments around the bulkiness of the robot, and increased operative time for both assembly and disassembly of the machine. Then again, a shorter disassembly time is particularly important in a situation for emergent conversion to laparotomy.

Currently, there are no large comparative published trials, evaluating robotic surgery versus laparoscopic myomectomy or hysterectomy. However, when published laparoscopic articles were reviewed, similar complication rates were noted in the robotic procedures. An average additional operative time of 60 minutes was reported in those patients undergoing robotic surgery versus laparoscopy (67). Additional studies will need to examine both clinical outcomes and cost effectiveness of this new technology to determine if robotics is truly beneficial in gynecology.

Table 3. Stepwise model for building advanced skills on a foundation of basic skills

Task performance → Visuospatial training → Setup and exposure → Virtual operation → Operating room

Reference -83.

8.1.3. Robotic advances in other gynecological subspecialties

In urogynecology, robotic technology has been used in repair of vesicovaginal fistula and abdominal sacrocolpopexy, with the latter being the focus of recent studies. Di Marco *et al*, utilized the da Vinci robot in sacrocolpopexy for treatment of posthysterectomy vaginal vault prolapse in 5 women. All patients were discharged within 24 hours and no recurrent anterior, posterior, or apical prolapse was reported by four months post-surgery (71). In 2006, Elliot *et al.* used the da Vinci robot in 31 women undergoing laparoscopic sacrocolpopexy. Operative times were noted to range from 2.25 - 4.75 hours. The authors reported robotic assisted laparoscopic sacrocolpopexy accomplished the equivalent repair as compared to open abdominal technique. In addition, only minor complications were reported and 96% of patients stated they would recommend the robotic procedure (72).

Robotic assisted technology has been increasing in use in the subspecialty of gynecology oncology. In 2005, 7 patients underwent robotic-assisted laparoscopic staging procedures for various gynecologic malignancies without conversion to laparotomy. The average lymph node count was 15 for lymphadnectomy (ranging from 4-29) which was similar to conventional laparoscopy (73). Operative time ranged from 174 to 345 minutes and estimated blood loss averaging 50 ml. Patients remained in the hospital for an average of two day post-operative, and early cost analysis showed decreased overall cost for robotic assisted procedures (73). There is a case report from 2006, describing the feasibility of the da Vinci robotic system in a Piver type III laparoscopic radical hysterectomy. The authors report radical dissection is more accurate than with conventional laparoscopy (74).

An *in utero* sheep model demonstrated the ability of the da Vinci robot in full thickness skin lesion for intrauterine repair of myelomeningocele. Four of six lambs survived until sacrifice, asserting a role for risk reduction by robotic assistance in intrauterine fetal surgery (75).

9. THE ROLE OF TELEROBOTICS IN TEACHING/EDUCATION/SIMULATION

Although clinically robotic surgery is increasing, few residency programs have incorporated robotic training into their curriculum. A survey of urology residents/program directors reported that greater that 30 percent felt that robotics will be important in the future of surgery, yet only 22 percent of residents are being trained in this technology (76). De Ugarte *et al.* determined that training skills used in laparoscopy could be applied to robotic surgery. Furthermore, the study proved that lack of laparoscopic training did not affect robotic training in the same skills (77). Several studies comparing speed and precision of training skills between the robot and traditional laparoscopy reported that tasks performed with the robot were more precise but the data is conflicting as to which method is faster (78-81). In 2005, two urology chief surgeons were followed during robotic training. Following da Vinci training certification, the residents progressively increased their participation in the various steps of the surgical procedure, until operating at the console alone. The study emphasized improvement in performance with time and experience, but also stated that improved computer-based simulators may play an important role in resident training on surgical robots (82).

Laparoscopic and robotic surgical training outside the operating room has tremendous advantages to improving surgical education. Learning for novice trainees can progress through a step-wise fashion to ensure safety and competence once in the operating room (Table 3) (83). The continued development and improvement of virtual reality technology offer the promise of advanced training and preparation in robotic and laparoscopic surgery.

10. TELEMENTORING

The introduction of cost-effective teleconferencing in the 1990 led to the interest in telementoring, which allows expert surgeons to mentor novice surgeons from remote sites. In 1997, Rosser was the first to telementor the performance of laparoscopic colectomies by inexperienced surgeons from across campus (84). Later, he went on to telementor performance of Nissen fundoplications at a hospital 5 miles distance. At Johns Hopkins, surgeons initially were successful in telementoring between hospitals 3.5 miles apart (85). These surgeons then went on to effectively telementor a laparoscopic adrenalectomy in Innsbruck, Austria, a laparoscopic faricocelectomy in Bangkok, Thailand, a laparoscopic radical nephrectomy in Singapore (86,87), and five various urological procedures in Rome, Italy (88). On the USS Abraham Lincoln, the US Navy developed Battlegroup Telemedicine system used to telementor five laparoscopic inguinal hernia repairs. Robot technology may also be beneficial in telementoring surgery. AESOP could permit the expert surgeon to guide the camera, to mentor the novice surgeon stepwise through the procedure. In addition, Panait *et al*, recently described the beneficial use of telementoring in laparoscopic skills and surgical education (89).

11. TELEPRESENCE SURGERY

Telepresence surgery enables a surgeon to operate on patients from a remote distance. Initially, this telerobotic technology was developed to allow surgeons to perform life-saving operations on the battlefield. More recent, Marescaux showed the feasibility of telerobotics by performing a telerobotic cholecystectomy on a patient in France while seated at a Zeus console in New York City (90). Currently, ISDN and Internet methods are utilized for long distance surgeries, which raise concerns over consistency and dependability. Furthermore, an additional concern is the speed of transfer of information from the

operator to the patient. At first, the maximum time delay was 300 milliseconds, but subsequently this lag times was improved to an average of 155 milliseconds in transoceanic experiments (54).

Telepresence surgery, however promising for development of improved surgical care in remote locations, is also surrounded by ethical and legal concerns. In the future, the role of direct patient contact will need to be balanced against the advantages of this technology.

12. CONCLUSIONS

Since its invention, robotic technology has impacted many fields including both medicine and surgery. Robotic surgery has emerged as an alternative in minimally invasive surgery, with many of the advantages of open procedures. Robotic technology also has a role in surgical education, which is only beginning to be incorporated into surgical residency programs. Finally, robotic technology has the potential to be utilized in both telementoring and telepresence surgery, enabling global access to health care.

However, robotic technology involves significant cost and increased learning curve. In the past decade, robotic surgery has shown to be safe and feasible in many surgical fields, but the absolute benefit of this technology is still in question. Larger clinical trials comparing robotic-assisted surgery to conventional laparoscopy and laparotomy, evaluating both efficacy and cost, are necessary to the future of robotic surgery.

13. REFERENCES

1. Halsted W. S: The training of the surgeon. *Johns Hopkins Hosp Bull* 15, 267-275 (1904)

2. Taylor G. W & D. G. Jayne: Robotic applications in abdominal surgery: their limitations and future developments. *Int J Med Robot* 3, 3-9 (2007)

3. Yuen P. M, K. M. Yu, S. K. Yip, W. C. Lau, M. S. Rogers & A. Change: A randomized prospective study of laparoscopy and laparotomy in the management of benign ovarian masses. *Am J Obstet Gynecol* 177, 109-114 (1997)

4. http://www.robotics.utexas.edu/rrg/learn_more/history. Accessed on 05/25/2007. Robotics Research Group. The University of Texas at Austin.

5. Lipson H. & J. B. Pollack: Automatic design and manufacture of robotic lifeforms. *Nature* 406, 974-978 (2000)

6. Busnel M, R. Cammoun, F. Loulon-Latuture, J. M. Detriche, G. Le Claire & B. Lesigne. The robotized workstation "MASTER" for users with tetraplegia: description and evaluation. *J Rehabil Res Dev* 36, 217-229 (1999)

7. Ellison L. M, P. A. Pinto, F. Kim, A. M. Ong, A. Patriciu, D. Stoianovici, H. Rubin, T. Jarrett & L. R. Kavoussi: Telerounding and patient satisfaction after surgery. *J Am Col Surg* 199, 523-530 (2004)

8. Satava R. M: Robotic surgery: from past to future – a personal journey. *Surg Clin N Am* 83, 1-6 (2003)

9. Challacombe B. J, M. S. Khan, D. Murphy & P. Dasgupta: The history of robotics in urology. *World J Urol* 24, 120-127 (2006)

10. Patel V. R, A. S. Tully, R. Holmes & J. Lindsay: Robotic radical prostatectomy in the community setting – the learning curve and beyond; initial 200 cases. *J Urol* 174, 269-272 (2005)

11. Patel V: Robotic-assisted laparoscopic dismembered pyeloplasty. *Urology* 66, 45-49 (2005)

12. Gettman M. T, R. Peschel, R. Neururer & G. Bartsch: A comparison of laparoscopic pyeloplasty: performed with the da Vinci robotic system versus standard techniques. *Eur Urol* 42, 453-458 (2002)

13. Sung G. T. & J. S. Gill: Robotic renal and adrenal surgery. *Surg Clin N Am* 83, 1-11 (2001)

14. Hoznek A, S. K. Zaki, D. B. Samadi, L. Salomon, A. Lobontiu A & P. Lang & C. C. Abbou: Robotic assisted for kidney transplantation: an initial experience. *J Urol* 167, 1604-1606 (2002)

15. Horgan S, D. Vanuno, P. Sileri, L. Cicalese & E. Benedetti: Robotic assisted laparoscopic donor nephrectomy for kidney transplantation. *Transplantation* 73, 1474-1479 (2002)

16. Winter J. M, M. A. Talamini, C. L. Standfield, D. C. Chang, J. D. Hundt, A. P. Dackiw, K. A. Campbell & R. D. Schulick: Thirty robotic adrenalectomies: a single institution's experience. *Surg Endosc* 20, 119-124 (2006)

17. Menon M, A. K. Hemal, A. Tewari, A. Shrivastava, A. M. Shoma, N. A. El-Tabey, A. Shaaban, A. Abol-Enein & M. A. Ghoneim: Nerve-sparing robot-assisted radical cystoprostatectomy and urinary diversion. *BJU Int* 92, 232-236 (2003)

18. Menon M, A. K. Hemal, A. Tewari, A. Shrivastava, A. M. Shoma, H. Abol-Ein & M. A. Ghoneim: Robot-assisted radical cystectomy and urinary diversion in female patients: technique with preservation of the uterus and vagina. *J Am Coll Surg* 198, 386-393 (2004)

19. Kuang W, P. R. Shin, S. Matin & A. J. Thomas Jr: Initial evaluation of robotic technology for microsurgical vasovasostomy. *J Urology* 171, 300-303 (2004)

20. Thaly R, K. Shah & V. P. Patel: Applications of robots in urology. *J Robotic Surg* 1, 3-17 (2007)

21. Bann S, M. Khan, J. Hernandez, Y. Munz, K. Moorthy, V. Datta, T. Rockall & A. Darzi: Robotics in surgery. *J Am Coll Surg* 196, 784-795 (2003)

22. Bauer A, M. Borner & A. Lahmer: Clinical experience with a medical robotic system for total hip replacement. In: Computer assisted orthopedic surgery. Eds: Notle LP, Ganz R, Bern: Hogrefe & Huber, 128-133 (1999)

23. Jakopec M, S. J. Harris, Y. Rodriguex, F. Baena, P. Gomes, J. Cobb & B. L. Davies: The first clinical application of a "hands-on" robotic knee surgery system. *Comp Aid Surg* 6, 329-339 (2001)

24. Cleary K. & C. Nguyen: State of the art in surgical robotics: clinical applications and technology challenges. *Comp Aid Surg* 6, 312-328 (2001)

25. Gould J. C. & W. S. Melvin: Telerobotic foregut and esophageal surgery. *Surg Clin N Am* 83, 1-6 (2003)

26. Talamini M. A, W. Chapman, S. Horgan & W. S. Melvin: A prospective analysis of 211 robotic assisted surgical procedures. *Surg Endosc* 17, 1521-1524 (2002)

27. Hashizume M. & K. Sugimachi: Robot-assisted gastric surgery. *Surg Clin N Am* 83, 1-11 (2003)

28. Rockall T. A. & A. Darzi: Robotic-assisted laparoscopic colorectal surgery. *Surg Clin N Am* 83, 1-4 (2003)

29. Nguyen N. T, W. H. Marcelo, D. Finley, M. Stevens & M. Paya: Applications of robotics in general surgery: initial experience. *Am Surg* 70, 914-917 (2004)

30. Mohr C. J, G. S. Madzam, R. S. Alamim, B. R. Sanchez & M. J. Curet: Totally robotic laparoscopic Roux-en-Y Gastric bypass: results from 75 patients. *Obes Surg* 16, 690-696 (2006)

31. Detter C, D. H. Boehm, H. Reichenspurner, T. Deuse, M. Arnold & B. Reichart: Robotically assisted coronary artery surgery with and without cardiopulmonary bypass – from first clinical use to endoscopic operation. *Med Sci Monit* 8, MT 118-123 (2002)

32. Diodato M. D. Jr. & R. J. Damiano Jr: Robotic cardiac surgery: overview. *Surg Clin N Am* 83, 1351-1367 (2003)

33. Morgan J. A, J. C. Peacock, T. Kohmoto, M. J. Garrido, B. M. Schanzer, A. R. Kherani, D. W. Vigilance, F. H. Cheema, S. Kaplan, C. R. Smith, M. C. Oz & M. Argenziano: Robotic techniques improve quality of life in patients undergoing atrial septal defect repair. *Ann Thorac Surg* 77, 1328-1333 (2004)

34. Rodriguez E. & W. R. Chitwood Jr: Outcomes of robotic cardiac surgery. *J Robotic Surg* 1, 19-23 (2007)

35. Karas C. S. & A. Chiocca: Neurosurgical robotics: a review of brain and spine applications. *J Robotic Surg* 1, 39-43 (2007)

36. Klug C, K. Schicho, O. Ploder, K. Yerit, F. Watzinger, R. Ewers, A. Baumann & A. Wagner: Point-to-point computer-assisted navigation for precise transfer of planned zygoma osteotomies from the stererolithographic model into reality. *J Oral Maxillofac Surg* 64, 550-559 (2006)

37. Westendorff C, D. Gulicher, F. Dammann, S. Reinert & J. Hoffman: Computer-assisted surgical treatment of orbitozygomatic fractures. *J Craniofac Surg* 17, 837-842 (2006)

38. Faust R. A, A. J. Kant, A. Lorinez, A. Younes, E. Dawe & M. D. Klein: Robotic endoscopic surgery in a porcine model of the infant neck. *J Robotic Surg* 1, 75-83 (2007)

39. Lo L, T. C. Pun & S. Chan: Tubal ectopic pregnancy: an evaluation of laparoscopic surgery versus laparotomy in 614 patients. *Aust New Zeal J Obstet Gynecol* 39, 185-187(1999)

40. Gunning J. E: The history of laparoscopy. *J Reprod Med* 12, 222-226 (1974)

41. Siegler A. M. & K. J. Berenyi: Laparoscopy in gynecology. *Obstet Gynecol* 34, 572-577 (1969)

42. Steptoe P. C: Laparoscopy in gynecology. E & S Livingston Ltd., Edinburg and London: 1-3 (1967)

43. Falcone T. & J. M. Goldberg: Robotics in gynecology. *Surg Clin N Am* 83, 1483-1489 (2003)

44. Stylopoulos N. & D. Rattner: Robotics and ergonomics. *Surg Clin N Am* 83, 1-12 (2003)

45. Berguer R, D. L. Forkey & W.D. Smith: Ergonomic problems associated with laparoscopic surgery. *Surg Endosc* 13, 466-468 (1999)

46. Kano N, T. Yamakawa & H. Kasugai: Laparoscopic surgeon's thumb. *Arch Surg* 128, 1172 (1993)

47. Majeed A. W, G. Jacob, M. W. Reed & A. G. Johnson: Laparoscopist's thumb: an occupational hazard. *Arch Surg* 128, 357 (1997)

48. Sackier J. M. & Y. Wang: Robotically assisted laparoscopic surgery: from concept to development. *Surg Endosc* 8, 63-66 (1994)

49. Jacobs L. K, V. Shayani & J. M. Sackier: Determination of the learning curve of the AESOP robot. *Surg Endosc* 11, 54-58 (1997)

50. Ballantyne G. H: Robotic surgery, telerobotic surgery, telepresence, and telementoring: review of early clinical results. *Surg Endosc* 16, 1389-1402 (2002)

51. Partin A. W, J. B. Adams, R. G. Moore & L. R. Kavoussi: Complete robot-assisted laparoscopic urologic surgery: a preliminary report. *J Am Coll Surg* 181, 552-557 (1995)

52. Kavoussi L. R, R. G. Moore, J. B. Adams & A. W. Partin: Comparison of robotic versus human laparoscopic camera control. *J Urol* 154, 2134-2146 (1995)

53. Mettler L, Ibrahim M. & W. Jonat: One year experience working with the aid of a robotic assistant (the voice-controlled optic holder AESOP*) in gynaecological endoscopic surgery. *Hum Reprod* 13, 2748-2750 (1998)

54. Marescaux J. & F. Rubino: The Zeus robotic system: experimental and clinical applications. *Surg Clin N Am* 83, 1305-1315 (2003)

55. Ballantyne G.H. & F. Moll: The da Vinci telerobotic surgical system: the virtual operative field and telepresence surgery. *Surg Clin N AM* 83, 1293-1304 (2003)

56. Patel S. P. & T. Falcone: Robotics in reproductive medicine. *Fertil Steril* 84, 1-11 (2005)

57. Margossian H, A. Garcia-Ruiz, T. Falcone, J. M. Goldberg, M. Attaran & M. Gagner: Robotically assisted laparoscopic microsurgical uterine horn anastomosis. *Fertil Steril* 70, 530-534 (1998)

58. Falcone T, J. M. Goldberg, H. Margossian & L. Stevens: Robotic-assisted laparoscopic microsurgical tubal anastomosis: a human pilot study. *Fertil Steril* 73, 1040-1042 (2000)

59. Goldberg J. M. & T. Falcone: Laparoscopic microsurgical tubal anastomosis with and without robotic assistance. *Hum Reprod* 18, 145-147 (2003)

60. Degueldre M, J. Vandromme, P. T. Huong & G. B. Cadiere: Robotically assisted laparoscopic microsurgical tubal reanastomosis: a feasibility study. *Fertil Steril* 74, 1020-1023 (2000)

61. Patel S. D, M. Steinkampf, S. J. Whitten & B. A. Malizia: Robotically assisted tubal reanastomosis in a Fellowship Training program [abstract]. ESHRE Annual Meeting; Berlin, Germany June (2004)

62. Rodgers A. K, J. M. Goldberg, J. P. Hammel & T. Falcone: Tubal anastomosis by robotic compared with outpatient minilaparotomy. *Obstet Gynecol* 109, 1375-1380 (2007)

63. Molpus K. L, J. S. Wedergran & M. A. Carlson: Robotically Assisted Endoscopic Ovarian Transposition. *J Soc Laparoendosc Surg* 7, 59-62 (2003)

64. Bocca S, L. Stadtmauet & S. Oehninger: Uncomplicated full term pregnancy after da Vinci-assisted laparoscopic myomectomy: case report. *Reprod Biomed Online* 14, 246-249 (2007)

65. Margossian H. & T. Falcone: Robotically assisted laparoscopic hysterectomy and adnexal surgery. *J Laparoendosc Adv Surg Tech A* 11, 161-165 (2001)

66. Beste T. M, K. H. Nelson & J. A. Daucher: Total laparoscopic hysterectomy utilizing a robotic surgical system. *JSLS* 9, 13-15 (2005)

67. Reynolds R. K. & A. P. Advincula: Robot-assisted laparoscopic hysterectomy: technique and initial experience. *Am J Surg* 191, 555-560 (2006)

68. Advincula A. P. & R. K. Reynolds. The use of robot-assisted laparoscopic hysterectomy in the patient with a scarred or obliterated anterior cul-de-sac. *JSLS* 9, 287-291 (2005)

69. Advincula A. P, A. Song, W. Burke & R. K. Reynolds: Preliminary experience with robot-assisted laparoscopic myomectomy. *J Am Assoc Gynecol Laparosc* 11, 511-518 (2004)

70. Nezhat C, N. S. Saberi, B. Shahmohamady & F. Nezhat: Robotic-assisted laparoscopy in gynecological surgery. *JSLS* 10, 317-320 (2006)

71. Di Marco D. S, G. K. Chow, M. T. Gettman & D. S. Elliott: Robotic-assisted laparoscopic sacrocolpopexy for treatment of vaginal vault prolapse. *Urology* 63, 373-376 (2004)

72. Elliot D. S, G. K. Chow & M. Gettman: Current status of robotic in female urology and gynecology. *World J Urol* 24, 188-192 (2006)

73. Reynolds R. K, W. M. Burke, A. P. Advinula: Preliminary experience with robot-assisted laparoscopic staging of gynecologic malignancies. *JSLS* 9, 149-158 (2005)

74. Sert B. M. & V. M. Abeler: Robotic-assisted laparoscopic radical hysterectomy (Piver type III) with pelvic node dissection – case report. *Eur J Gynaecol Oncol* 27, 531-533 (2006)

75. Aaronson O. S, N. B. Tulipan, R. Cywes, H. W. Sundell, G. H. Davis, J. P. Bruner & W. O. Richards: Robot-assisted endoscopic intrauterine myelomeningocele repair; a feasibility study. *Pediatr Neurosurg* 36, 85-89 (2002)

76. Duchene D. A, A. Moinzadeh, I. S. Gill, R. V. Clayman & H. N. Winfield: Survey of residency training in laparoscopic and robotic surgery. *J Urol* 176, 2158-2167 (2006)

77. De Ugarte D. A, D. A. Etzioni, C. Garcia & J. B. Atkinson : Robotic surgery and resident training. *Surg Endosc* 17, 960-963 (2003)

78. Hubens G, H. Coveliers, L. Balliu, M. Ruppert & W. Vaneerdeweg: A performance study comparing manual and robotically assisted laparoscopic surgery using the da Vinci system. *Surg Endosc* 17, 1595-1599 (2003)

79. Dakin G. F. & M. Gagner: Comparison of laparoscopic skills performance between standard instruments and two surgical robots. *Surg Endosc* 17, 574-579 (2003)

80. Nio D, A. Bemelman, K. T. den Boer, M. S. Dunker, D. J. Gouman & R. M. van Gulik: Efficacy of manual vs. robotical (Zeus) assisted laparoscopic surgery in performance of standardized tasks. *Surg Endosc* 16, 412-415 (2002)

81. Sarle R, A. Tewari, A. Shrivastava, J. Peabody & M. Menon: Surgical robotics and laparoscopic training drills. *J Endourol* 18, 63-67 (2004)

82. Rashid H. H, Y. Y. Leung, M. J. Rashid, G. Oleyourryk, J. R. Valvo & L. Eichel: Robotic surgical education: a systematic approach to training urology redients to perform robotic-assisted laparoscopic radical prostatectomy. *Urology* 68, 75-79 (2006)

83. Haluck R. S. & T. M. Krummel: Computers and virtual reality for surgical education in the 21st century. *Arch Surg* 135, 786-792 (2000)

84. Rosser J. C, M. Wood, J. H. Payne, T. M. Fullum, G. B. Lisehorn, L. E. Rosser, P. J. Barcia & R. S. Savalgi: Telementoring: a practical option in surgical training. *Surg Endosc* 11, 852-855 (1997)

85. Lee B. R, J. A. Caddedu, G. Janetschek, P. Schulman, S. G. Docimo, R. G. Moore, A. W. Partin & L. R. Kavoussi: International surgical telementoring: our initial experience. *Stud Health Technol Inform* 50, 41-47 (1998)

86. Lee B. R, D. J. Png, L. Liew, M. Fabrizio, M. K. Li, J. W. Jarrett, L. R. Kavoussi: Laparoscopic telesurg between the United States and Singapore. *Ane Acad Med Singapore* 29, 665-668 (2000)

87. Lee B. R, J. T. Bishoff, G. Janetschek, P. Bunyaratevej, W. Kamolpronwijit, J. A. Cadeddu, S. Ratchanon, S. O'Kelley & L. R. Kavoussi: A novel method of surgical instruction: international telementoring. *World J Urol* 16, 367-670 (1998)

88. Micali S, G. Virgili, E. Vannozzi, N. Grassi, T. W. Jarrett, J. J. Bauer, G. Vespansiani & L. R. Kavoussi: Feasibility of telementoring between Baltimore (USA) and Rome, Italy. *J Endouro* 14, 493-496 (2000)

89. Panait L, A. Rafiq, V. Tomulescu, C. Boanca, I. Popescu, A. Carbonell & R. C. Merrell: Telementoring versus on-site mentoring in virtual reality-based surgical training. *Surg Endosc* 20, 113-118 (2006)

90. Marescaux J, J. Leroy, M. Gagner, F. Rubino, D. Mutter, M. Vix, S. E. Butner & M. K. Smith: Transatlantic robot-assisted telesurgery. *Nature* 413, 379-380 (2001)

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