MODERN TRENDS

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Robotics in reproductive medicine

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Objective: To review the history, development, current applications, and future of robotic technology.
Design: The MEDLINE database was reviewed for all publications on robotic technology in medicine, surgery, reproductive endocrinology, its role in surgical education, and telepresence surgery.
Setting: University medical center.
Conclusion(s): Robotic-assisted surgery is an emerging technology, which provides an alternative to traditional surgical techniques in reproductive medicine and may have a role in surgical education and telepresence surgery. (Fertil Steril® 2005;84:1–11. ©2005 by American Society for Reproductive Medicine.)

Key Words: Robotics, reproductive surgery, telepresence surgery, minimally invasive surgery

Surgery has evolved from the 19th century through the introduction of ether anesthesia, principles of antisepsis, and the formalization of surgical training (1). In the late 20th century, the introduction of video laparoscopy and robotics has continued to evolve the practice of surgery. In this review article, we will review the development of robotics, its current applications in surgery, the role of robotics in surgical training, and the future of this technology.

HISTORY OF ROBOTICS

The word robot (from the Czech word robota meaning compulsory labor) 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 . . . (2)." One of the first robots developed was by Leonardo da Vinci in 1495; a mechanical armored knight that was used to amuse royalty. This was then followed by creation of the first operational robot by Joseph Marie Jacquard in 1801, in which an automated loom, controlled by punch cards, created a reproducible pattern woven into cloth. This allowed for both precision and accuracy, a recurring theme with robotic technology.

The Czech writer Karel Capek in his play R.U.R. (*Rossum's Universal Robots*) describes a plot in which man creates a robot, which initially provides benefits, but in the end produces despair in the form of unemployment and social unrest (3). Issac Asimov further elucidated the role of robotics in 1940 through short stories; however, it was his three laws of robotics that received popular acclaim. The three laws state "1) A robot may not injure a human being, or through inaction allow a human being to come to harm 2) A robot must obey the orders given it by human beings except where such orders would conflict with First Law and 3) A robot must protect its own existence as long as such protection does not conflict with the First or Second Law (4)." These laws have pervaded into current robotic surgical systems as evidenced by their safety features.

APPLICATION IN OTHER FIELDS

In fields apart from medicine, the first applications of robotics were in mathematics, computers, and industry. The first industrial robot was the "Unimate" developed by George C. Devol and Joseph F. Engelberger, which was used to extract die castings from machines and perform spot welding on automobile bodies. Currently, robotic technology is used in space and ocean exploration (taking images and collecting information), industrial tasks (welding), military and police tasks (destroying mines, collecting information, or spying), and entertainment (from toys to television).

APPLICATION IN MEDICINE

Robotics have recently been applied to the field of medicine, initially with rehabilitation devices and assistance for those with disabilities. Dr. David Gow created the first bionic arm in 1998 called the EMAS (Edinburgh Modular Arm System). Robotic technology can also be used to help individuals with severe disabilities perform independent activities of daily

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living (The Winsford feeder) or integrate them into the workplace (RAID: Robot for Assisting the Integration of the Disabled). Used in hospitals indirectly for patient care, robots such as the HelpMate operate semi- or fully autonomously as porter or couriers since 1993. Recently a new concept of "telerounding" has been introduced with a mobile robot system (InTouch Health, Santa Barbara, CA) that enables physicians to remotely interact with patients. Through a 5-ft robot, a remotely located physician can see, hear, and talk with a patient that is located on a hospital ward.

APPLICATION IN SURGERY

In 1985, the first surgical application of the robot was in a neurosurgical procedure (5). The PUMA 560 was used to orient a needle for a brain biopsy under computerized tomography (CT) guidance. However, its use was discontinued due to safety issues. Meanwhile, at the Imperial College in England in 1988, a robotic system called the PROBOT was created to aid in transurethral resection of the prostate. This was the first autonomous surgical procedure performed by a robot, where a three-dimensional model of the prostate is built, the area of resection outlined by the surgeon, the trajectories of cutting are calculated by the robot, and finally, the procedure is executed (6, 7).

A few years later in 1992, International Business Machines (IBM) and associates developed a prototype for orthopedic surgery. The ROBODOC was used to assist surgeons in milling out a hole in the femur for total hip replacements (8, 9).

Simultaneously, the birth of robotic telepresence technology (which would allow the surgeon to operate at a distance from the operating room) was occurring at the Stanford Research Institute, National Aeronautics and Space Administration (NASA), and the Department of Defense (10). Originally, the prototype was created 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 battlefield. Soon thereafter, Intuitive Surgical acquired the prototype and commercialized the system called da Vinci, which focused on the immersive telepresence concept (where the surgeon operates at a distance from the patient, but feels as if in the operating room). At the same time, Computer Motion unveiled the first laparoscopic camera holder, AESOP (Automated Endoscopic System for Optimal Positioning). Computer Motion later created the Zeus surgical system, which is an integrated robotic system (the surgeon operates at a distance from the patient and is aware that he is at a distance) (10).

OTHER SURGICAL SUBSPECIALITIES

Neurosurgery

The first clinical application for robotics was in neurosurgical stereotactic maneuvers. The original model was the PUMA 560. This was then followed by Minerva, Neuromate, and others. More recently, robotics have been used for stereotactic radiosurgery; a robot delivery system (e.g., CyberKnife) is used to manipulate a linear accelerator as it delivers closed-cranium radiation to an area identified on preoperative imaging (11).

Orthopedics

Total knee replacement is a common orthopedic procedure whose success is reliant on the alignment of the limb and the prosthesis. The prototype ROBODOC system uses CT guidance to mill a precise hole into the femoral cavity (8, 9). A second integrated robotic system, the ACROBOT appears promising in preliminary trials (12). 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 (13–15).

Maxillofacial

A surgical robot (RX90) developed in Germany uses CT scanning to perform craniofacial osteotomies with a surgical cutting saw. Preliminary studies in animals appear optimistic (13).

Ophthalmology

Many surgical operations on the eye require precise microsuturing skills. A robot developed by John Hopkins University is the "Steady Hand" robot for microsurgical augmentation. This 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 (13).

Urology

The urologic applications for robotic technology have ranged from transurethral prostate resections with the prototype PROBOT, to percutaneous access of the kidney for minimally invasive kidney procedures. Su et al. (14) recently evaluated the efficacy of robotic percutaneous access of the kidney for nephrolithotomy, and found that the number of attempts and access rates were comparable to standard techniques. The role of telerobotic surgery in urology has been evaluated in a number of procedures with variable results. Sung and Gill and colleagues evaluated the role of the Zeus surgical system for pyeloplasty and ablative urologic procedures in the animal model and found increased operative times as compared to traditional laparoscopic techniques (15, 16). However, comparison of the da Vinci surgical system when used to perform robotic-assisted pyeloplasty has been shown to have comparable times to the open approach with the additional benefits of minimally invasive surgery (17; Patel V, unpublished observations). For radical prostatectomy in humans there appears to be comparable oncologic control with the benefits of minimal blood loss, shorter hospitalization, quicker recovery, and early continence (Patel V, unpublished observations). Robotic surgery has also been used for laparoscopic donor nephrectomy and cystectomy (18), renal transplant (19, 20), and recently, robotic vasovasostomy (21).

Gastrointestinal Surgery

The diversity of robotic cases used by gastrointestinal surgery was originally reported by Cadiere et al. (22), and recently by the Academic Robotics Group at the Society of American Gastrointestinal Endoscopic Surgeons annual meeting. They presented their combined experience with 211 cases (23, 24). These cases encompassed Heller myotomy, gastric bypass, pyloroplasty, gastrojejunostomy, esophagectomy, duodenal polyp excision, and gastric mass excision. Other procedures performed robotically include intragastric resection, distal gastrectomy, wedge resection, Roux-en Y gastric bypass, gastric banding, biliary pancreatic diversion, rectopexy, anterior resection, and abdominoperineal resection (25–27).

Cardiac Surgery

Telepresence robotic technology was originally created for cardiac surgery. The advantages of three-dimensional visualization and miniaturized multiarticulated instruments have allowed cardiac surgeons to perform minimally invasive endoscopic coronary artery bypass grafting and valve procedures (28). Currently, coronary artery bypass grafting and valvular surgery have been performed using either the Zeus or da Vinci surgical system (29, 30). Results have been optimistic for both mitral valve repair in 38 patients and closure of atrial septal defects in 10 patients using the da Vinci surgical system (30–32).

ROLE OF ROBOTIC SURGERY IN GYNECOLOGY AND ITS SUBSPECIALITIES

Surgery in obstetrics and gynecology has traditionally been taught through a laparotomy or vaginal approach. The advantages of the laparotomy approach include depth perception and tactile feedback from the resistance of tissue/organ dynamics. In addition there is an ease of intra-abdominal suturing from the 6 degrees of freedom afforded from the human wrist. Although a laparotomy is advantageous for the surgeon compared to other surgical techniques, there are disadvantages for the patient including a large abdominal incision, prolonged hospitalization, increased postoperative analgesic requirements, and increased morbidity (33, 34). This has led some surgeons to seek out minimally invasive approaches. The first gynecologic laparoscopy was described by Ott from Petrograd who inspected the abdominal cavity using a head mirror and a abdominal wall speculum in 1901, calling the procedure “ventroscopy” (35). However, it was the first International Symposium of Gynecologic Endoscopy in 1964 that initiated interest in laparoscopic tubal sterilization (36), gamete intrafallopian tubal transfer (37), and other laparoscopic gynecologic procedures in the ensuing four decades (38). Laparoscopy offers advantages to the patient: improved cosmesis, decreased blood loss, less postoperative analgesic requirements, shorter hospitalization time, and quicker recovery (33, 34). However, its usefulness is limited due to the steep learning curve for surgeons. Other obstacles include: limited dexterity, counterintuitive motion, two-dimensional vision, and ergonomic difficulty. Tremor amplification can also occur from the use of long rigid instruments for prolonged periods of time in a fixed position (39). In laparoscopic surgery, the fulcrum point created by the trocars limits the surgeon to 4 degrees of freedom, reducing dexterity (40). In addition, because of the fulcrum at the trocars, the movements of the surgeon’s hands results in movements in the opposite direction at the working end of the laparoscope, making movements counterintuitive (39). The laparoscopic surgeon must also accommodate to a two-dimensional screen, which limits depth perception as compared to the three-dimensional vision afforded by open surgery (39). Ergonomics is also impacted by traditional minimally invasive surgery. In a survey by Society of American Gastrointestinal Endoscopic Surgeons, 8%–12% reported pain or numbness in the arms, wrists, hands, or shoulders after performing laparoscopic surgery (41), which has been confirmed by electromyographic data (42). These limitations can be overcome if the surgical procedure is facile and efficient.

Simple gynecologic procedures, such as tubal sterilization, ovarian cystectomy, and cauterization of endometriosis, are examples of procedures that can be effectively performed through laparoscopy and have obtained popular acceptance since its first description in the 1970s (38). It is the more complex, advanced laparoscopic cases, that present a challenging learning curve including microsurgical tubal reanastomosis, abdominal sacrocolpopexy, myomectomy, and radical hysterectomy.

Robotic technology, more specifically telerobotic surgical systems, offers the opportunity to bridge this gap between laparotomy and laparoscopy by enabling minimally invasive surgery with three-dimensional vision, ergonomically optimal positioning, tremor filtration, and laparoscopic instruments with intra-abdominal articulation (43).

TYPES OF ROBOT ASSISTANCE AVAILABLE IN GYNECOLOGY

Robotic technology can be categorized according to their technological or functional classification. Robots can be autonomous where the preoperative plan controls the manipulator (such as with the Probot) (8). In addition, robots can be supervisory where a computer accurately guides the surgeon (such as with the Robodoc) or teleoperated where the robot is manipulated by input devices under the surgeon’s control (such as with the AESOP, da Vinci, or Zeus surgical system) (8). Functionally, robots are classified as either active or passive (8). A passive robot could be used as a navigational aid or a precise positioning system (such as with the Minerva). It is turned on for positioning and then turned off. An active robot performs the surgery by actually moving the tools (such as the AESOP, Zeus, or da Vinci system). In gynecology and its related subspecialties, there are three forms of robotic technology available to assist surgeons in performing minimally invasive procedures, all of which are examples of active robotic technology that are teleoperated.

Laparoscopic Holder

One of the first, active teleoperated robots introduced into clinical practice was the AESOP 300, approved by the Federal Drug Administration (FDA) in 1994. This robotic arm has direct control over the laparoscope and can be manipulated by the surgeon using voice control. The robot is attached to the side of the surgical table and can grasp any rigid laparoscope. The advantage of AESOP was demonstrated by Kavoussi et al. (44) in a comparison of robotic vs. human laparoscopic camera control. In 11 patients requiring bilateral procedures, robotically controlled camera positioning was used on one side and compared to traditional hand control on the contralateral side. They found robotically controlled positioning was significantly steadier with similar operative times. Operative times were also similar in animal studies (45). In gynecology, Mettler et al. (46) used AESOP in 50 gynecologic procedures and found that the operative times using AESOP was similar to those operations using traditional hand control. Disadvantages for AESOP include the constant voice commands, which may be distracting. In addition, the voice control is slower compared to the rapid camera movements achieved by an experienced assistant. AESOP is intended to facilitate solo-surgeon laparoscopic procedures; however, the surgeon may still need an assistant for control of the fourth laparoscopic port.

Robotic Integrated Surgical System

One of two available surgical systems is Zeus developed by Computer Motion in the early 1990s. Initially, it was specifically designed for cardiac operations (e.g., coronary artery bypass grafting), and later the human applicability was diversified for multiple surgical specialties such as general surgery, urology, and gynecology (47). The basic difference between the Zeus and other telerobotic surgical systems was that it was not developed to create an immersive intuitive interface, but an integrated robotic surgical environment, as evidenced by the original system in which instruments lacked intra-abdominal articulation and the console contained a two-dimensional viewing monitor (10). The Zeus system has two subsystems “the surgeon-side” and the “patient-side.” The surgeon’s subsystem consists of a console that can be positioned anywhere in the operating room. The console consists of a video monitor and two handles that control the robotic arms holding the surgical instruments. The patient-side subsystem consists of three robotic arms attached to the table. Three-dimensional vision and instruments with intra-abdominal articulation capabilities were added to later versions of the surgical system. All original animal and human studies evaluating the efficacy of robotic surgery used the Zeus surgical system. However, in late 2003, Intuitive Surgical (Sunnyvale, CA) purchased Computer Motion and the Zeus surgical system. No further production of the Zeus system has been pursued (10).

Immersive Telerobotic Surgical System

The focus of this system was based on three components: “1) A master/slave, software-driven system that provided intuitive control of laparoscopic instruments with six degrees of freedom, 2) a stereoscopic vision system displayed in an immersive format, and 3) a system architecture composed of redundant sensors to provide maximum safety in operation” (48). The first prototype used a traditional stereo endoscope and was tested in humans. Subsequently, binocular endoscopic vision was developed and the safety features were completed in 1999 with FDA approval obtained for the da Vinci in 2000. This system consists of three components as shown in Figure 1.

Console. The surgeon’s computer console is positioned remotely from the patient. Currently, the console is connected by a cable to the video cart and robotic tower. The FDA requires that in the United States, all operations using the da Vinci surgical system are performed in the same room as the patient, although the potential exists for remote surgery. The console houses a stereoviewer, which has an infrared beam to deactivate the robotic arms whenever the surgeon moves his head out of the console. The surgeon’s hands are inserted into free-moving “masters” or finger controls, which convert the movements of the surgeon’s wrist and fingertips into electric signals. These are then translated to computer commands to direct the robotic instruments to perform the same movements in the operative field. The console has controls for three-dimensional viewing, the height of the console, the ability to choose a 0-degree or 30-degree laparoscope, motion scaling (5 to 1 means that 5 units of motion of the surgeons hands are reduced to one unit of motion for the instruments), and tremor filtration. There is an ability to control the camera, energy devices, and the “masters” with foot pedals (Fig. 1A).

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

Surgical Cart. The surgical cart supports either three or four robotic arms. Surgical instruments are attached to the robotic arms through an adapter, which uses an 8-mm da Vinci-specific port. The central robotic arm houses a 12-mm telescope, which contains two separate 5-mm telescopes for three-dimensional vision. The robotic surgical instruments are capable of intra-abdominal articulations with 7 degrees of freedom. The robotic instruments are responsible and can be used for up to 10 cases after which they have to be replaced (Fig. 1C).

The advantages of the da Vinci surgical system include three-dimensional vision, the immersive environment, tremor

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). Permission from Intuitive Inc.

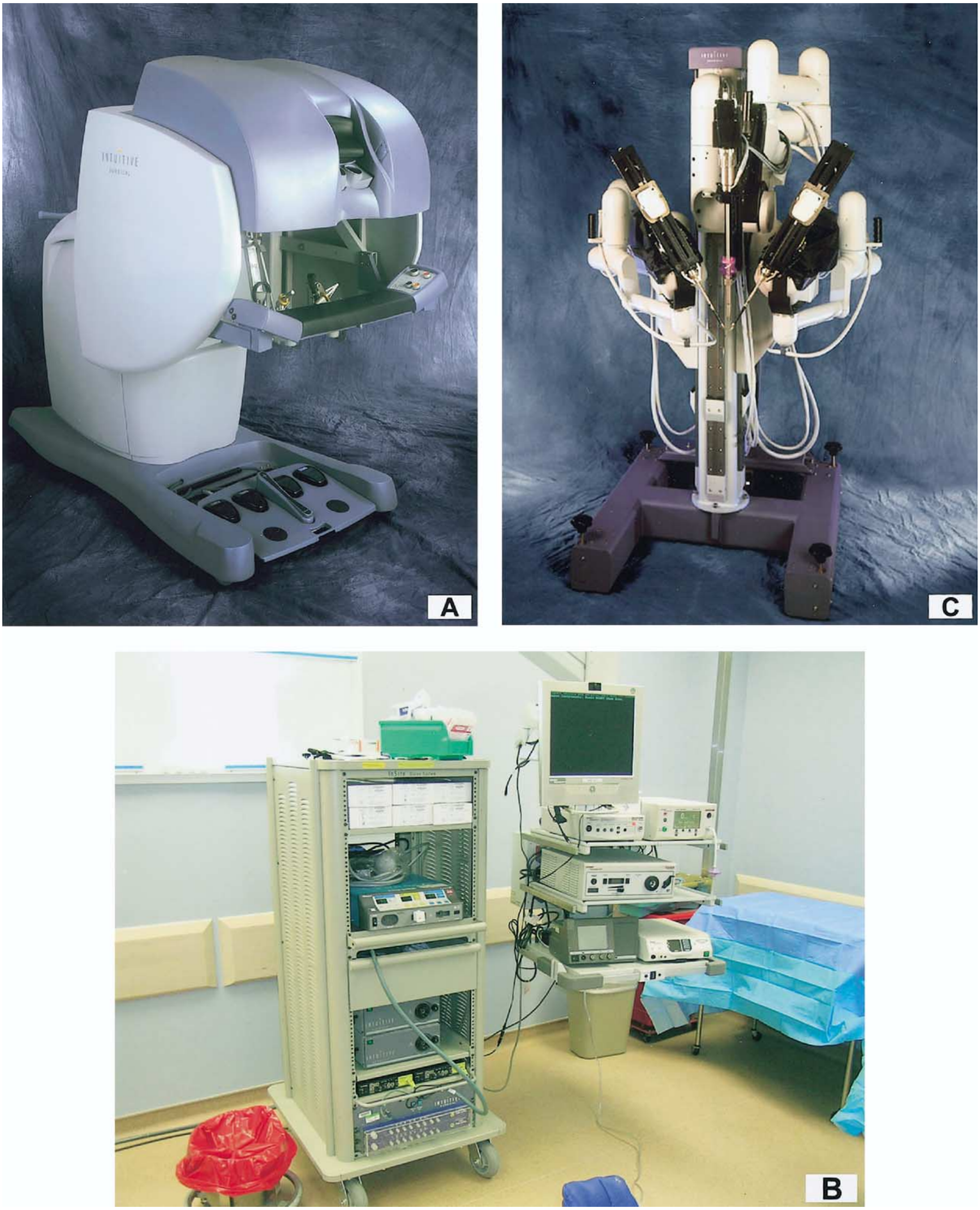

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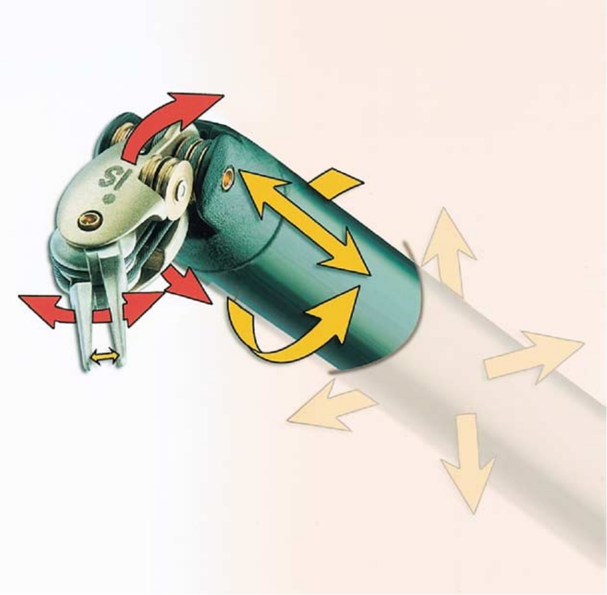
FIGURE 2

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*). Permission from Intuitive Inc.



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filtration, and motion scaling, which makes it ideal for complex laparoscopic movements such as intracorporeal suturing and microsurgical movements in an anatomically confined space. In addition, the da Vinci affords intra-abdominal articulation with most instruments, which allows for microsurgical or complex laparoscopic movements in seven different planes (Fig. 2). Disadvantages include the lack of tactile feedback, bulky robotic arms with large excursion arcs that can lead to frequent collisions, limited instrumentation, and the inability to move the surgical table once the robot arms are attached to the ports. Furthermore, the large size of the robot limits the ability of surgical assistants to maneuver around the patient. One potential disadvantage is the economics of the da Vinci. The current cost for the da Vinci surgical system is approximately 1 million dollars. Each instrument costs $2,000 for ten uses.

CURRENT APPLICATIONS OF ROBOTIC SURGERY IN GYNECOLOGY

Although gynecologists were among the first to use laparoscopic surgical techniques, the role of robotic surgery in gynecology has developed after other surgical specialties. The first use of robotics in the gynecologic literature was by Mettler et al. (46), who used AESOP in 50 gynecologic procedures.

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

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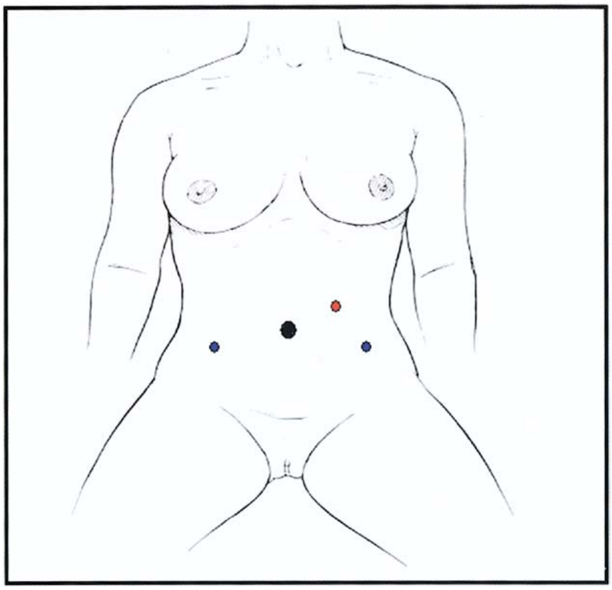
In the subspecialty of reproductive endocrinology, the predominant procedure using robotic technology is microsurgical tubal reversals (Table 1). Using the Zeus surgical system, the first procedure performed was microsurgical uterine horn anastomoses in six female pigs in 1998 (49). This procedure capitalizes on the advantages of the robotic system by providing the fine motor movements required for intracorporeal suturing, three-dimensional vision, and motion scaling to assist in microsurgery. Falcone et al. (50) performed the first human clinical trial using the Zeus robotic system in 1998 on 10 patients with previous tubal ligations who underwent a robotically assisted laparoscopic tubal reanastomosis. The set-up included placement of the ports in the lower quadrants bilaterally for the robotic arms and one port was placed suprapubically for introduction of suture. To perform the reanastomosis, 6-0 polygalactin (Polyglactin 910; Ethicon, Inc., Piscataway, NJ) was used on the mesosalpinx and 8-0 used on the fallopian tube. The mean operative time to perform the anastomosis was 159 ± 33.8 minutes. Chromopertubation established patency in 17 of 19 tubes reanastomosed with a pregnancy rate of 50%. They then compared their robotic reanastomoses to traditional laparoscopic reanastomosis and found that operative times were significantly longer (2 hours) with use of the Zeus robotic system, but all other outcomes were comparable (51). Degueldre et al. (52) then performed a feasibility study with the Da Vinci surgical system on 8 patients. The mean operating time was 181.5 minutes and although follow-up was limited to 4 months, 2 of the 8 patients achieved a pregnancy and 5/8 patients demonstrated at least unilateral patency. Subsequently, Dharia et al. (53) performed a feasibility study in a fellow-

FIGURE 3

Once peritoneal access is obtained, a 12-mm camera port (*black*) is placed at the umbilicus. Subsequently, two da Vinci ports (*blue*) are placed in the midclavicular line, 1–2 cm below the level of umbilicus, lateral to the rectus muscle. An additional accessory port (*red*) on the left side of patient is used for irrigation, placement, and removal of sutures.



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ship training program using the da Vinci surgical system on 18 patients who desired reversal of tubal sterilization and compared these to 10 patients who underwent a traditional open microsurgical reanastomosis. For the preoperative set-up, the da Vinci surgical tower was positioned between the patient's lower extremities and port placement as described in Figure 3. Operative times were significantly greater in the patients who underwent robotic-assisted surgery, however, hospitalization time, time to recovery, and time to return of independent activities of daily living were significantly shorter in the robotic group. Patency rates were 100% and pregnancy rates were 50%, comparable in both groups (53). Although limited, a preliminary cost-effective analysis demonstrates comparable cost per delivery in patients who underwent a robotic tubal reanastomosis ($92,488.00) as compared to those underwent a traditional open reanastomosis ($92,205.90) (54).

In the subspecialty of urogynecology, the role of robotics has been focused on abdominal sacrocolpopexy (55). DiMarco et al. (55) published a feasibility study on five women who underwent this procedure without complication with a mean follow-up of 4 months. In this procedure, they used conventional laparoscopy (nonrobotic) to prepare the anatomic sites, vagina, and presacral space, and used the robot to suture the mesh in place. The mean operative time was 3 hours and 42 minutes.

In gynecologic oncology and benign gynecology, a pilot study on 10 female pigs who underwent hysterectomy and bilateral salpingoopherectomy using the Zeus robotic system was completed within 370 minutes with no complications and no intraoperative conversions (56). Subsequently, a preliminary report on 11 human patients who underwent a robotically assisted laparoscopic hysterectomy was published in 2002. Ten women underwent a hysterectomy with salpingo-oopherectomy. Most patients required a vaginal component. One patient underwent a hysterectomy, pelvic/para-aortic lymph node biopsies, and infracolic omentectomy. Operative times ranged from 4.5 to 10 hours (mean of 253 minutes) and estimated blood loss was 50–1,500 mL. One patient required reoperation for bleeding with subsequent transfusion (57).

Advincula et al. (58) reported their preliminary experience with the use of the robot for laparoscopic myomectomies. In this report of 35 patients, the mean weight of the leiomyoma was 223 ± 244 g (95% confidence interval [CI] 135–310), the mean number of leiomyomas was 1.6 (range 1–5), and the mean diameter was 7.9 ± 3.5 cm (95% CI 6.6–9.1). The mean blood loss was 169 ± 198 mL. The mean operative time was 230 ± 83 minutes (95% CI 201–260). Five cases required between 350 and 400 minutes to complete the procedure. There was a trend toward decreased operative times with experience. There were three conversions to laparotomy.

There are no published comparative clinical trials of robotic surgery with laparoscopic myomectomy or hysterectomy. However, when we compare these robotic results to published trials (59) without the robot there does not appear to be any advantage with these prototypes. It is possible that these robots may be more useful to the surgeon who is presently performing these procedures by laparotomy to perform them by laparoscopy rather than in the hands of the expert laparoscopic surgeon.

There are case reports of the use of the robot with other less common procedures. In a case report, the da Vinci surgical system was used without complication to perform an ovarian transposition in a patient before she received radiotherapy for a stage 1B-1 cervical cancer (60). Three interrupted 3-0 silk sutures were used to suture the transected utero-ovarian ligament to the psoas muscle.

The role of robotic surgery has also been investigated in the pediatric and fetal population. Gutt et al. (61) performed a bilateral gonadectomy in a 16-year-old pediatric patient with a gonadoblastoma. Using the da Vinci surgical system, the operative time was 95 minutes and no complications were reported.

An in utero sheep model demonstrated the feasibility of creation and repair of a full-thickness skin lesion (for repair of myelomeningocele) using the da Vinci surgical system. Four of the six fetal lambs survived until sacrifice. This study entertains the role of intrauterine endoscopic surgery to reduce the risks associated with fetal surgery (62).

THE ROLE OF ROBOTICS IN TEACHING/TRAINING/SIMULATION

The concept of the first structured surgical training program in the United States was created by Dr. William Halsted (1). This concept was based on clinical service with subjective feedback from mentors (apprenticeship), and prevailed for most of the 20th century (63).

Recently, economic constraints have focused more attention on the efficacy of surgical education. Bridges and Diamond (64) found that education in the operating room accounted for more than 2,050 hours, which translates to $47,970 per graduating resident or $53 million per year for the surgical specialty. Other factors that affect the cost of surgical training include an increase of the per capita workload for faculty to bring in clinical dollars, decreasing time dedicated to education (65), decreases in Medicare graduate medical education funding, and a requirement by insurance companies for intense supervision by faculty, allowing less autonomy of housestaff (66). From the viewpoint of the residents, their experience is limited by fewer working hours (80 hours/wk) and the operating room may not be a conducive environment for optimal learning (67, 68).

To maximize surgical training, one must identify the different components that contribute to the overall experience. Using Rasmussen's model of human behavior, surgical education can be broken down into three tiers: [1] skill-based behavior (e.g., instrument handling/dissection); [2] rule-based behavior (e.g., surgical anatomy); and [3] knowledge-based behavior (e.g., how to handle hemorrhage or unexpected situations) (69). Currently, training models available for surgical education include animate models, cadaveric models, inanimate models (simulators and virtual reality), robotics, and the operating room.

Animate models provide a realistic environment (haptic feedback, hemorrhage) that approaches the traditional operating room experience. However, disadvantages include the cost of the animal, anatomical differences, and the ethical use of animals for training (70). Although cadaveric models share the same anatomy, they do not respond similarly in terms of bleeding/ haptic feedback, are costly, and require adequate facilities for maintenance (71, 72). This has turned attention to inanimate models as a training tool in surgery. Inanimate models can include both simulation and virtual reality. Although not currently realistic, inanimate models can provide reinforcement or emphasis on the different levels of surgical training with immediate formative and summative assessment. Other advantages include the ability to be used multiple times, flexibility for usage according to the provider's schedule along with good measures of reliability, feasibility, and validity (67, 73). This has made surgical simulators popular in the rapidly developing area of surgical education.

Another teaching tool that is emerging onto the education forefront is the use of robotics with inanimate models, animate models, cadaveric models, or patients. Robotics with intra-abdominal articulation, three-dimensional vision, and motion scaling allow for an increase in precision, which may attenuate the learning curve in minimally invasive surgical training. A survey of general surgery program directors around the country revealed that 11% of programs used robotics in their surgical practice, 14% provided resident exposure in robotic training, and just under 25% were planning to incorporate robotics in their training programs (74). To evaluate whether basic laparoscopic skills could be improved with robotic technology in attending physicians, Chang et al. (75) compared times and composite scores (involving precision, time, reliability, etc.) of traditional laparoscopic tasks, tasks using the robotic surgical system without training on the robot, and tasks after various levels of robotic training. They found that those with laparoscopic experience had equal measures of time-to-completion, but the amount of error decreased with robotic training. In surgically naïve subjects, Nio et al. (76) found that 20 medical students, when asked to performed both basic tasks (dropping beads in receptacles or capping a hypodermic needle) and complex tasks (suturing and performing a laparoscopic cholecystectomy), demonstrated smoother and straighter movements with less grasping actions using robotics than conventional laparoscopy. The increase in precision and accuracy was identified as an advantage by other investigators (77, 78) and suggests that robotic training may allow for acquisition and refinement of skill for those in training. Yohannes et al. (79) evaluated a small group of surgeons in training and compared skills using manual laparoscopy and robot-assisted surgery. They found that beginners start off with a slower performance time, but experience a greater degree of improvement than those who have laparoscopic experience. Although both groups improve, beginners appear to learn difficult tasks easier with robotic-assisted surgery, which might make it an ideal training tool. One question that remains to be answered is whether the improvement in precision and accuracy improves performance in the operating room.

Improvement in efficiency has not been identified in all studies. However, a small study in six medical students, who used traditional laparoscopy or the da Vinci surgical system to complete basic tasks, found that the da Vinci surgical system allows laparoscopic procedures to be performed quicker and more efficiently than traditional laparoscopy (80). In addition, Sarle et al. (81), when comparing 21 surgeons on eight timed drills, found that the mean time to completion of a task was faster using the da Vinci surgical system. Dakin and Gagner (82) addressed skill outcomes of all three methods studied: traditional laparoscopy, the Zeus surgical system, or the da Vinci surgical system. Eighteen surgeons were compared based on the performance of basic tasks and fine motor tasks (intracorporeal suturing). There was no difference in basic tasks, but there was an increased precision in fine motor tasks in the robotic groups, although time-to-task completion remained the same. Again the principal advantage was in precision.

The assimilation of new technology for training can be limited by the learning curve for that instrument (83). The learning curve for robotics has been addressed using the da Vinci surgical system in 23 experienced laparoscopic surgeons in seven different subspecialties. Hanly et al. (83) found that mean operative times began to decrease after the third case regardless of the procedure.

Small number of subjects studied and the lack of validation demonstrating improvement of skill in the operating room limit these preliminary studies. As the field of robotics continues to evolve, its translation to the operating room may provide a new method of training in surgical education.

Currently for clinical use of the da Vinci surgical system, the FDA requires a 2-day training course to understand the set-up, maintenance, and applications of the surgical system, in addition to animate laboratory training. Further training recommendations by the company include case observations and mentored cases.

TELEMENTORING

The introduction of teleconferencing stimulated interest in telementoring. This would allow an experienced surgeon in one location to both teach and mentor those in training at a different location using either audiovisual equipment, robotics such as AESOP or the da Vinci. It would limit the travel and the time lost from work to teach or learn. One of the first telementors was Rosser in 1997 who telementored laparoscopic colectomies across campus (84). He then telementored laparoscopic Nissen fundoplications from a remote hospital 5 miles away (43). Surgeons at Johns Hopkins Hospital also developed a telementoring program and taught a laparoscopic adrenalectomy in Innsbruck, Austria (85); a laparoscopic varicocelectomy in Bangkok, Thailand (86); among others. The first military experience with telementoring occurred in 1999, where land-based surgeons telementored the performance of five inguinal herniorrhaphies on the USS *Abraham Lincoln* (87). These telementors used audiovisual technology as their medium for teaching. There may be a role for robotics in telementoring. Using AESOP may allow the mentor to visually guide the procedure step by step. The robotic surgical system may allow demonstration of a new procedure to surgeons from a remote location. The role of telementoring may allow training surgeons to learn procedures, techniques, or skills from leaders around the world, improving the quality of training, and allowing global dissemination of new techniques and procedures.

TELEPRESENCE SURGERY

Telepresence surgery essentially would allow a surgeon at one location to operate on a patient at a different location through the use of a integrated robotic surgical system. One of the first telepresence procedures performed was in 1998. Bauer et al. (88) reported on a percutaneous renal access performed on a patient in Rome that was controlled from Maryland. Subsequently, in 2001 Marescaux et al. (89), while in New York, performed a robotically assisted laparoscopic cholecystectomy on a patient in Strasbourg. French Telecom provided the connection and the procedure lasted 45 minutes. To operate over long distances, the current system uses ISDN and Internet methods, which brings up issues of consistency and reliability. In addition, another consideration is the speed of transfer of information from operator to robot. The lag time from operator to execution should be less than 300 milliseconds for the surgeon to compensate, although ideally the delay should be less than 200 milliseconds (90).

Telepresence surgery brings up a host of ethical dilemmas. Patient privacy and responsibility for the care of the patient are critical issues when dealing with a surgeon at the bedside and a surgeon operating from a remote location and will need to be addressed before incorporation of this technology. .

THE FUTURE

The future of robotic surgery has significant potential. Currently for robotic surgical systems, areas of research include using miniaturized motors to decrease the size of the robotic tower, evaluating the potential for mounting the robotic tower to the ceiling or wall to increase access points to the patient, and real-time or non-real-time image integration into the endoscopic view on the console. Image integration would allow the surgeon to operate on the target organ and evaluate blood supply by real-time ultrasound, or identify a lesion by integrating magnetic resonance imaging (MRI)/CT images into the operative image. (Miguel Canales, Intuitive Surgical, Inc., personal communication, December, 2004)

From an educational standpoint, areas of active research involve adding a mentoring console to the system. This could be used for training, whereby a resident/fellow would sit at one console, the mentor at another and control over the “masters” could be toggled from mentor to student. In addition, there is research on robotic simulators, which with summative and formative assessment would have tactile feedback. (Miguel Canales, Intuitive Surgical, Inc., personal communication, December, 2004)

Robotics in telementoring would allow for international exchange of health care ideas and new surgical techniques and provide the ability to standardize surgical training. This may also have a role in credentialing or certifying new and renewing surgeons. (Miguel Canales, Intuitive Surgical, Inc., personal communication, December, 2004)

The potential for telepresence surgery points toward global health care. A patient with a rare disease process could be surgically treated by a world expert without travel or other barriers that may prevent health care access.

CONCLUSION

Robotics began as a form of entertainment and has evolved into a technology used in the fields of computers, automotives, entertainment, ocean/space exploration, and health care. In medicine and more specifically surgery, robotic technology has become a viable surgical alternative to provide minimally invasive surgery with the advantages of traditional open surgical techniques. In addition, robotics has a role in the surgical training of residents by increasing the precision and accuracy of the learning process, although this has yet to be translated to the operating room. Robotics may also allow for telementoring and telepresence surgery facilitating global access health care.

However, economic and ethical issues will have to be evaluated and further data collected on the cost-effectiveness of robotics. Larger trials comparing the efficacy of robotics compared to traditional laparoscopic or laparotomy approaches are needed to definitively determine the future role of robotics.

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