INTRODUCTION

Robotic Surgery is a microsurgery in which the surgeon performs surgery by manipulating the hands of a robot. Robotic surgery is the use of robots in performing surgery. Three major advances aided by surgical robots have been remote surgery, minimally invasive surgery and unmanned surgery. Major advantages of robotic surgery are precision, miniaturization, smaller incisions, decreased blood loss, less pain, and quicker healing time. Further advantages are articulation beyond normal manipulation and three-dimensional magnification.

Robots are being used in increasingly complex surgical procedures. However these robots are not autonomous machines that carry out simple, pre-programmed instructions.

Operating theatre robots are designed to supplement a surgeon's abilities, translating human movements into incredibly steady and accurate robotic movements, which, in turn, manipulate instruments to aid delicate operations. But minimally invasive procedures, using instruments controlled by humans, have their limitations. For one, instruments are not in the surgeon's direct control, being manipulated by assistants. And the instrument's positioning within the body is subject to human tremors and fatigue, which makes working on minute structures difficult and dangerous.

By handing control of the surgical instruments over to a robot- and positioning the surgeon at a comfortable console with a 3D or and high-resolution display at 10 to 20 times magnification - surgery is easier and more accurate. Rather than stopping the heart and performing a sternotomy or a thoracotomy, just three 8 to 10 mm-long incisions are required for two robotic arms with tiny instruments and a third for a camera.

Patients of conventional open heart surgery need, on average, two weeks recovery in hospital, followed by two to three months rest before they can resume normal physical exercise- this is how long the sternum takes A robotic wrist provides articulated motions with a full 7 degrees of freedom inside the abdominal or thoracic cavities (EndoWrist™ technology)

Computer interfacing allows for remote control surgery.
(telesurgery), for more precise manipulations by downscaling the surgeon’s motions and by allowing surgeon’s good ergonomic position.

Human robotic surgery was introduced by Cadiere’s team (St. Pierre Hospital, Surgical robotics is a new technology that holds significant promise. Robotic surgery is often heralded as the new revolution, and it is one of the most talked about subjects in surgery today. Up to this point in time, however, the drive to develop and obtain robotic devices has been largely driven by the market. There is no doubt that they will become an important tool in the surgical armamentarium, but the extent of their use is still evolving.

Several centers are currently using surgical robots and publishing data. Most of these early studies report that robotic surgery is feasible. There is, however, a paucity of data regarding costs and benefits of robotics versus conventional techniques.
Background and History of Surgical Robots

Since 1921 when Czech playwright Karel Capek introduced the notion and coined the term robot in his play Rossom’s Universal Robots, robots have taken on increasingly more importance both in imagination and reality. Robot, taken from the Czech robota, meaning forced labor, has evolved in meaning from dumb machines that perform menial, repetitive tasks to the highly intelligent anthropomorphic robots of popular culture. Although today’s robots are still unintelligent machines, great strides have been made in expanding their utility. Today robots are used to perform highly specific, highly precise, and dangerous tasks in industry and research previously not possible with a human work force. Robots are routinely used to manufacture microprocessors used in computers, explore the deep sea, and work in hazardous environment to name a few. Robotics, however, has been slow to enter the field of medicine.

The lack of crossover between industrial robotics and medicine, particularly surgery, is at an end. Surgical robots have entered the field in force. Robotic telesurgical machines have already been used to perform transcontinental cholecystectomy. Voice-activated robotic arms routinely maneuver endoscopic cameras, and complex master slave robotic systems are currently FDA approved, marketed, and used for a variety of procedures. It remains to be seen, however, if history will look on the development of robotic surgery as a profound paradigm shift or as a bump in the road on the way to something even more important.

Paradigm shift or not, the origin of surgical robotics is rooted in the strengths and weaknesses of its predecessors. Minimally invasive surgery began in 1987 with the first laparoscopic cholecystectomy. Since then, the list of procedures performed laparoscopically has grown at a pace consistent with improvements in technology and the technical skill of surgeons. The advantages of minimally invasive surgery are very popular among surgeons, patients, and insurance companies. Incisions are smaller, the risk of infection is less, hospital stays are shorter, if necessary at all, and convalescence is significantly reduced. Many studies have shown
that laparoscopic procedures result in decreased hospital stays, a quicker return to the workforce, decreased pain, better cosmesis, and better postoperative immune function. As attractive as minimally invasive surgery is, there are several limitations. Some of the more prominent limitations involve the technical and mechanical nature of the equipment. Inherent in current laparoscopic equipment is a loss of haptic feedback (force and tactile), natural hand-eye coordination, and dexterity. Moving the laparoscopic instruments while watching a 2-dimensional video monitor is somewhat counterintuitive. One must move the instrument in the opposite direction from the desired target on the monitor to interact with the site of interest. Hand-eye coordination is therefore compromised. Some refer to this as the fulcrum effect. Current instruments have restricted degrees of motion; most have 4 degrees of motion, whereas the human wrist and hand have 7 degrees of motion. There is also a decreased sense of touch that makes tissue manipulation more heavily dependent on visualization. Finally, physiologic tremors in the surgeon are readily transmitted through the length of rigid instruments. These limitations make more delicate dissections and anastomoses difficult if not impossible. The motivation to develop surgical robots is rooted in the desire to overcome the limitations of current laparoscopic technologies and to expand the benefits of minimally invasive surgery.

From their inception, surgical robots have been envisioned to extend the capabilities of human surgeons beyond the limits of conventional laparoscopy. The history of robotics in surgery begins with the Puma 560, a robot used in 1985 by Kwoh et al to perform neurosurgical biopsies with greater precision. Three years later, Davies et al performed a transurethral resection of the prostate using the Puma 560. This system eventually led to the development of PROBOT, a robot designed specifically for transurethral resection of the prostate. While PROBOT was being developed, Integrated Surgical Supplies Ltd. of Sacramento, CA, was developing ROBODOC, a robotic system designed to machine the femur with greater precision in hip replacement surgeries. ROBODOC was the first surgical robot approved by the FDA.

Also in the mid-to-late 1980’s a group of researchers at the National Air and Space Administration (NASA) Ames Research Center working on virtual reality became interested in using this information to develop telepresence surgery. This concept of telesurgery became one of the main driving forces behind the development of surgical robots. In the early 1990s, several of the
scientists from the NASA-Ames team joined the Stanford Research Institute (SRI). Working with SRI’s other robotocists and virtual reality experts, these scientists developed a dexterous telemanipulator for hand surgery. One of their main design goals was to give the surgeon the sense of operating directly on the patient rather than from across the room. While these robots were being developed, general surgeons and endoscopists joined the development team and realized the potential these systems had in ameliorating the limitations of conventional laparoscopic surgery.

The US Army noticed the work of SRI, and it became interested in the possibility of decreasing wartime mortality by “bringing the surgeon to the wounded soldier—through telepresence.” With funding from the US Army, a system was devised whereby a wounded soldier could be loaded into a vehicle with robotic surgical equipment and be operated on remotely by a surgeon at a nearby Mobile Advanced Surgical Hospital (MASH). This system, it was hoped, would decrease wartime mortality by preventing wounded soldiers from exsanguinating before they reached the hospital. This system has been successfully demonstrated on animal models but has not yet been tested or implemented for actual battlefield casualty care.

Several of the surgeons and engineers working on surgical robotic systems for the Army eventually formed commercial ventures that lead to the introduction of robotics to the civilian surgical community. Notably, Computer Motion, Inc. of Santa Barbara, CA, used seed money provided by the Army to develop the Automated Endoscopic System for Optimal Positioning (AESOP), a robotic arm controlled by the surgeon voice commands to manipulate an endoscopic camera. Shortly after AESOP was marketed, Integrated Surgical Systems (now Intuitive Surgical) of Mountain View, CA, licensed the SRI Green Telepresence Surgery system. This system underwent extensive redesign and was reintroduced as the Da Vinci surgical system. Within a year, Computer Motion put the Zeus system into production.
Robotic Surgical Technology

Robotic Surgery is innovative and frightening to most people because it uses machines, or robots. These robots are complex and require a good deal of training. The main operating machines, the da Vinci System and the ZEUS Surgical System use three surgical arms. The ZEUS System has two main operating arms, which contain tools for incisions and for the surgery. For example, small cutters are used in Gallbladder surgery to cut the Gallbladder out. The other arm on the ZEUS is a digital high quality 3D camera. The camera and video system that the surgeon operates on have to be within .2 seconds of each other. If the video is not streamed in real time, then the error percentage increases dramatically.
Robotic surgical system

There are no more than five major robotic surgical systems:

- ZEUS
- AESOP
- da Vinci
- Hermes
- Socrates

Da Vinci Surgical System

The Da Vinci Surgical System was approved for use in operating rooms last July 11, 2000 by the US Food and Drug Administration. This surgical system was developed by Intuitive Surgical and
enables the surgeon to see the surgical site in clearer detail than the human eye allows. Surgeons can now work on a smaller than usual scale. The two main components of the Da Vinci Surgical System are the View/Control console and the surgical arm.

Used in a gallbladder surgery, a Da Vinci Surgical System uses 3 stainless steel rods (two rods for surgical instruments and one for the camera) held in place by robotic arms. These rods are then inserted into the patient via three small incisions in the abdomen. The images from the camera are then displayed on the console giving the surgeon a clear view of the surgical area. Using joystick-like controls to control the surgical instruments at the tips of the two rods, the surgeon can remotely operate on the patient.

**ZEUS System**

The ZEUS System by Computer Motion is another surgical robot in the process of being cleared by the FDA. The system is already being used in Europe and is showing promising results. In fact, the ZEUS system has already been used to perform coronary bypass surgery in Germany. The ZEUS System at $750,000 is less expensive than the Da Vinci Surgical System, which costs around $1 million.

**AESOP**

The AESOP or the Automated Endoscopic System for Optimal Positioning by Computer motion was the first surgical robot to be approved by the FDA. Its main feature is its Through the use of foot pedals and voice activated software, a surgeon can keep his hands free to perform surgery on the patient. mechanical arm that can be utilized by the surgeon to accurately position the endoscope.

**CURRENT ROBOTIC SURGICAL SYSTEMS**

Today, many robots and robot enhancements are being researched and developed. Schurr et al at Eberhard Karls University’s section for minimally invasive surgery have developed a master-slave manipulator system that they call ARTEMIS. This system consists of 2 robotic arms that are controlled by a surgeon at a control console. Dario et al at the MiTech laboratory of Scuola Superiore Sant’Anna in Italy have developed a prototype miniature robotic system for computer-enhanced colonoscopy. This system
provides the same functions as conventional colonoscopy systems but it does so with an inchworm-like locomotion using vacuum suction. By allowing the endoscopist to teleoperate or directly supervise this endoscope and with the functional integration of endoscopic tools, they believe this system is not only feasible but may expand the applications of endoluminal diagnosis and surgery. Several other laboratories, including the authors’, are designing and developing systems and models for reality-based haptic feedback in minimally invasive surgery and also combining visual servoing with haptic feedback for robot-assisted surgery.
and the systems mentioned above several other robotics systems have been commercially developed and approved by the FDA for general surgical use. These include the AESOP system (Computer Motion Inc., Santa Barbara, CA), a voice-activated robotic endoscope, and the comprehensive master-slave surgical robotic systems, Da Vinci (Intuitive Surgical Inc., Mountain View, CA) and Zeus (Computer Motion Inc., Santa Barbara, CA). Of being at the surgical site
Types of Robotic Surgeries

Minimally invasive surgery is particularly useful in certain situations or surgeries. For example, in laparoscopic surgeries, or surgeries in which a laparoscope is used, the arms of the robot are extremely helpful. The most common procedures are gastro-jejunostomy, pyloroplasty, RY gastric bypass for obesity, esophageal myotomy for achalasia, living-related nephrectomy for transplantation and bile duct surgery.

Other types of robotic surgeries are

General

- Adrenalectomy
- Cholecystectomy
- Esophagectomy
- Gastric Bypass

Thoracic

- Esophageal surgery
- Thymectomy
- Mediastinal Tumor Resection
- Lobectomy
- BiVentricular Resynchronization Epicardial leads

Cardiac

- Atrial
- Septal Defect Repair
- Mitral Valve Repair
WORKING

THE SURGEON’S CONSOLE

The da Vinci™ system consists of a master console that connects to a surgical “manipulator” with two instrument arms and a central arm to guide the endoscope. Two “master” handles at the surgeon’s console are manipulated by the user. The position and orientation of the hands on the handles trigger highly-sensitive motion sensors and translate to the end of the instrument at a remote location. The surgeon sits comfortably at a master console located at a distance from the patient with eyes focused down toward the operative site mirroring an open surgical technique and the slave unit provides “tele-presence” within the abdomen or chest for micro instruments manipulation.

Superior ergonomic design allows the surgeon to become immersed in the operative field. A 10 mm high-resolution 3D 0° or 30° endoscope (with two three-chip charge coupled device – CCD cameras) is used for better perception of depth and optical resolution. The endoscope is held by the central four DOF manipulator of a remote centre design, similar to the slave tool manipulator. The camera manipulator is capable of positioning the tip of the endoscope in 3D by working through the fulcrum made by the port incision at the body wall. This Navigator™ Camera Control system gives the surgeon a 3rd arm to hold and move the camera without the need for an assistant.

THE SURGICAL ARM CART

Handles motions are sensed by high-resolution motion sensors, processed and transferred to the two surgical manipulators. These slave manipulators (surgical arms) provide three degrees of freedom (pitch, yaw, insertion). The surgical instrument is attached to the surgical arm. The instrument tip is provided with a mechanical cable-driven wrist (Endo-wrist Technology), which will add four more degrees of freedom (internal pitch, internal yaw, rotation and grip).
The grip is programmed to 1.0 Newton. In order to enhance precision, the system allows for scaling of the handles-surgical arms motion relationship. A motion scale of 3:1 will move the instrument 1 mm inside the abdomen for every 3 mm motion at the master console. In addition, unintended movements caused by human tremor are filtered by a 6 Hz motion filter. The robotic arms together with robotic instruments attached on it can be disconnected from the master-handles by the clutch foot pedal, in order to obtain a more comfortable and ergonomic position of the surgeon hands at the console.

**THE 3D IMAGING SYSTEM**

The high resolution 3D endoscope consists of two three chip charge-coupled (CCD) device cameras (InSite) with two high-intensity light sources to ensure a bright image of the operative field. Lenses of 0° as well as 30° can be used. The 30° scope can be fixed either down or upside looking. The video image enables up to 10-15 fold magnification according to the working distance compared to the operative field. The endoscope is attached to the robotic camera arm and once inserted it can be moved from the console by the surgeon by pressing the camera food switch. This will lock the instrument arms and gives the operator control of the camera through the master manipulators.

**COMMUNICATION BETWEEN OPERATING AND ASSISTANT SURGEON**

Adequate coordination between the surgeon at the console and his assistant at the operating table is guaranteed by a permanent communication. In some operating rooms the surgeon’s console is installed in a separate room connected with a microphone to the operating room. In other hospitals the console may be in the same room.
SYSTEM ACCURACY

Because the da Vinci™ System naturally becomes a part of the surgeon’s eye-hand coordination loop, the most telling measure of the system’s accuracy is through touch tests where the surgeon is an active participant. At Intuitive Surgical, we have performed tests to measure the total performance of the man-machine system. The test was conducted as follows. Sonomicrometry measurements were obtained for a crystal sutured to a stabilized porcine LAD with respect to a fixed coordinate frame. The data were processed to produce a driving signal for a cardiac anastomosis trainer, which we modified to drive with a servo-controller. The sampling frequency exceeded 1 kHz. The data contained up to 14 beat cycles before repeating and included breathing modes, therefore closely replicating the quasiperiodic motion of the target vessel.

A target was mounted to the trainer, consisting of lined graph paper with a gel backing. Surgeons were tasked with touching the graph paper at prescribed locations as accurately as possible while the target beat. A 6-0 needle was used. Afterwards, the target was analyzed by standard inspection techniques to determine the accuracy of each touch. For this extremely demanding dynamic test the mean error for three subjects with eight touches each was 220 μm, and the standard deviation was 150 μm. The da Vinci™ Surgical System uses high-resolution optical encoders to measure the position of each powered joint. The system checks the position of these joints by reading the sensors over 1300 times each second. The sensors give extreme positional precision: more than 2000 sensing points per degree of arc for the major revolute axes and over 750 sensing points per millimeter for the prismatic axis. This corresponds to well over 500 sensing points per millimeter in any direction at the worst case working depth. With this resolution ability, the da Vinci™ System takes full advantage of fine surgical skills.

To periodically check that the accuracy of the system is maintained, it is a simple matter to recreate a static version of the above test. A baseline performance for the surgeon(s) should be established when the system is new, and repeated as often as desired. Commercial optical inspection machines are well suited to quick measurement of errors. Standard graph paper taped onto a
gel material works well as a target.

PLANNING AND SIMULATION OF ROBOTICALLY ASSISTED MINIMALLY INVASIVE SURGERY

A common telemedicine project research in robotics and medical images is currently carried out between INRIA (Sophia Antipolis, France) Georges Pompidou Hospital (Paris, France) and Intuitive Surgical Inc. Mountain View, CA. The project defines a framework for pre-operative planning and simulation of robotically assisted minimally invasive surgery (MIS). The approach consists of a planning, validation and simulation phase in order to propose optimal incisions sites for the robot, to validate the sites and to enable realistic simulation of the intervention. With the patient’s pre-operative data, we formulate the needs of the surgeon and the characteristics of the robot as mathematical criteria in order to optimize the settings of the operation. Then, we automatically reproduce expected surgeon’s movements and guaranty their feasibility. Finally we simulate the intervention in real-time, paying particular attention to potential collisions between the robotic arms.
Robotic Surgery

Robots in the field of surgery have dramatically changed the procedures for the better. The most significant advantage to Robotic Surgery to the patient is the decrease in pain and scaring. By using cameras and enhanced visual effects, doctors can make the tinniest of incisions. The da Vinci and Zeus system each use “arms” to operate. In order for these arms to get inside the body and operate, they only need a few centimeters for an incision. In fact, The San Matteo Hospital in Pavia, Italy performed a Cardiac Bypass surgery that included three incisions, each about one
centimeter in length. Typically in that type of surgery the incision is about 30 centimeters in length.

The smallness of the incisions also causes many other advantages that make Robotic Surgery worth the risk. Due to the small and precise cuttings, the patents hospital stay is greatly reduced. A person needs far less recovery time when they have 3-centimeter scars then when they have a scar almost 10 times as large. Also, the risk of infection or complications decreases as the incision size does. The patient mentioned earlier with the Closed Heart Bypass surgery is a terrific example. After his surgery, he was cleared by his surgeon Dr. Mauro Rinaldi and released from the hospital after only 12 hours of recovery. The next week he was actually able to join his family on a vacation.

**Less Personnel Required**

Because the surgical robots could take over the job of some of the people inside the operating room, future surgeries will require fewer personnel yet still be able to perform a more effective and safer surgery.
Surgery at a Distance

With improvements in telecommunications and speed of data transfer, robotic surgery can even be done from a distance. This means that the surgeon could perform the operation even though he is in another city or even another country far from the patient.

Reduced Trauma and Faster Patient Recovery

Because robotic surgery would allow for operations needing only small incisions on the patient's body, the rate of patient's recovery would be accelerated. This would translate to less pain during and after the operation as well as less risks and complications for the patient.

Besides the obvious rewards to the patient, Robotic Surgery is also very advantageous to the surgeon and hospital. In the ZEUS Surgical System, an “arm” on the machine is dedicated to the Automated Endoscopic System for Optimal Positioning (AESOP). AESOP is a 3D camera used in robotic surgery. It can be zoomed in by either voice activation or pedals located at the surgeon's foot. Doctors who have used this actually argue that AESOP gives a better image than in real life. This is particularly true with surgeons that have poor vision or in microscopic surgery’s that deal with nerves. Also, by using the hand controls the surgeons can reach places in the body that are normally unreachable by the human hand. Finally, the most clear advantage to using robots in surgery is in long operations, particularly ones that deal with nerve or tissue reconstruction. Surgeons often tire easily after performing microscopic surgery’s that last hours. However, by having the ability to be seated and have less strain on the eyes, doctors can control their natural flinching or nerves more efficiently.

ADVANTAGES OF ROBOT-ASSISTED SURGERY

The advantages of these systems are many because they overcome many of the obstacles of laparoscopic surgery (Table 1). They increase dexterity, restore proper hand-eye coordination and an ergonomic position, and improve visualization (Table 2). In
addition, these systems make surgeries that were technically difficult or unfeasible previously, now possible.

These robotic systems enhance dexterity in several ways. Instruments with increased degrees of freedom greatly enhance the surgeon’s ability to manipulate instruments and thus the tissues. These systems are designed so that the surgeons’ tremor can be compensated on the end-effector motion through appropriate hardware and software filters. In addition, these systems can scale movements so that large movements of the control grips can be transformed into micromotions inside the patient.

Another important advantage is the These robotic systems eliminate the fulcrum effect, making instrument manipulation more intuitive. With the surgeon sitting at a remote, ergonomically designed workstation, current systems also eliminate the need to twist and turn in awkward positions to move the instruments and visualize the monitor. By most accounts, the enhanced vision afforded by these systems is remarkable. The 3-dimensional view with depth perception is a marked improvement over the conventional laparoscopic camera views. Also to one’s advantage is the surgeon’s ability to directly control a stable visual field with increased magnification and maneuverability. All of this creates images with increased resolution that, combined with the increased degrees of freedom and enhanced dexterity, greatly enhances the surgeon’s ability to identify and dissect anatomic structure.
DISADVANTAGES OF ROBOT-ASSISTED SURGERY

There are several disadvantages to these systems. First of all, robotic surgery is a new technology and its uses and efficacy have not yet been well established. To date, mostly studies of feasibility have been conducted, and almost no long-term follow up studies have been performed. Many procedures will also have to be redesigned to optimize the use of robotic arms and increase efficiency. However, time will most likely remedy these disadvantages.

Another disadvantage of these systems is their cost. With a price tag of a million dollars, their cost is nearly prohibitive. Whether the price of these systems will fall or rise is a matter of conjecture. Some believe that with improvements in technology and as more experience is gained with robotic systems, the price will fall. Others believe that improvements in technology, such as haptics, increased processor speeds, and more complex and capable software will increase the cost of these systems. Also at issue is the problem of upgrading systems; how much will hospitals and healthcare organizations have to spend on upgrades and how often? In any case, many believe that to justify the purchase of these systems they must gain widespread multidisciplinary use.

Another disadvantage is the size of these systems. Both systems have relatively large footprints and relatively cumbersome robotic arms. This is an important disadvantage in today’s already crowded operating rooms. It may be difficult for both the surgical team and the robot to fit into the operating room. Some suggest that miniaturizing the robotic arms and instruments will address the problems associated with their current size. Others believe that larger operating suites with multiple booms and wall mountings will be needed to accommodate the extra space requirements of robotic surgical systems. The cost of making room for these robots and the cost of the robots themselves make them an especially expensive technology.

One of the potential disadvantages identified is a lack of compatible instruments and equipment. Lack of certain instruments increases reliance on tableside assistants to perform part of the surgery. This, however, is a transient disadvantage because new technologies have and will develop to address these shortcomings. Most of the disadvantages identified will be remedied with time and improvements in technology. Only time will tell if the use of these
systems justifies their cost. If the cost of these systems remains high and they do not reduce the cost of routine procedures, it is unlikely that there will be a robot in every operating room and thus unlikely that they will be used for routine surgeries.

CURRENT CLINICAL APPLICATIONS AND EARLY DATA

Several robotic systems are currently approved by the FDA for specific surgical procedures. As mentioned previously, ROBODOC is used to precisely core out the femur in hip replacement surgery. Computer Motion Inc. of Goleta, CA, has 2 systems on the market. One, called AESOP, is a voice-controlled endoscope with 7 degrees of freedom. This system can be used in any laparoscopic procedure to enhance the surgeon’s ability to control a stable image. The Zeus system and the Da Vinci system have been used by a variety of disciplines for laparoscopic surgeries, including cholecystectomies, mitral valve repairs, radical prostatectomies, reversal of tubal ligations, in addition to many gastrointestinal surgeries, nephrectomies, and kidney transplants.

The number and types of surgeries being performed with robots is increasing rapidly as more institutions acquire these systems. Perhaps the most notable use of these systems, however, is in totally endoscopic coronary artery grafting, a procedure formerly outside the limitations of laparoscopic technology.

The amount of data being generated on robotic surgery is growing rapidly, and the early data are promising. Many studies have evaluated the feasibility of robot-assisted surgery. One study by Cadiere et al evaluated the feasibility of robotic laparoscopic surgery on 146 patients. Procedures performed with a Da Vinci robot included 39 antireflux procedures, 48 cholecystectomies, 28 tubal reanastomoses, 10 gastroplasties for obesity, 3 inguinal hernia repairs, 3 intrarectal procedures, 2 hysterectomies, 2 cardiac procedures, 2 prostatectomies, 2 artiovenous fistulas, 1 lumbar sympathectomy, 1 appendectomy, 1 laryngeal exploration, 1 varicocele ligation, 1 endometriosis cure, and 1 neosalpingostomy.

This study found robotic laparoscopic surgery to be feasible. They also found the robot to be most useful in intra-abdominal microsurgery or for manipulations in very small spaces. They
reported no robot related morbidity. Another study by Falcone et al tested the feasibility of robot-assisted laparoscopic microsurgical tubal anastomosis. In this study, 10 patients who had previously undergone tubal sterilization underwent tubal reanastomosis. They found that the 19 tubes were reanastomosed successfully and 17 of the 19 were still patent 6 weeks postoperatively. There have been 5 pregnancies in this group so far. Margossian and Falcone also studied the feasibility of robotic surgery in complex gynecologic surgeries in pigs. In this study, 10 pigs underwent adnexal surgery or hysterectomy using the Zeus robotic system. They found that robotic surgery is safe and feasible for complex gynecologic surgeries. In yet another study by Marescaux et al, the safety and feasibility of telerobotic laparoscopic cholecystectomy was tested in a prospective study of 25 patients undergoing the procedure. Twenty-four of the 25 laparoscopic cholecystectomies were performed successfully, and one was converted to a traditional laparoscopic procedure. This study concluded that robotic laparoscopic cholecystectomy is safe and feasible. Another study by Abbou et al found telerobotic laparoscopic radical prostatectomy to be feasible and safe with dramatically enhanced dexterity.

One of the areas where robotic surgery is transforming medicine the most and one of the areas generating the most excitement is minimally invasive cardiac surgery. Several groups have been developing robotic procedures that expand laparoscopic techniques into this previously unexplored territory with encouraging results. Prasad et al successfully constructed left internal thoracic artery (LITA) to left anterior descending (LAD) artery anastomoses on 17 of 19 patients with the use of a robotic system. They conclude that robotically assisted endoscopic coronary bypass surgery showed favorable short-term outcomes with no adverse events and found robotic assistance is an enabling technology that allows surgeons to perform endoscopic coronary anastomoses. Damiano et al conducted a multicenter clinical trial of robotically assisted coronary artery bypass grafting. In this study 32 patients scheduled for primary coronary surgery underwent endoscopic anastomosis of the LITA to LAD. Two-month follow-up revealed a graft patency of 93%. This study concluded that robotic assisted coronary bypass grafting is feasible. In another study, Mohr
et al used the Da Vinci system to perform coronary artery bypass grafting on 131 patients and mitral valve repair on 17 patients. They used the robot to perform left internal thoracic artery takedown, LITA-LAD anastomosis in standard sternotomy bypass, and total endoscopic coronary artery bypass grafting LITA-LAD anastomosis on the arrested heart and the beating heart. They found that robotic systems could be used safely in selected patients to perform endoscopic cardiac surgery.

Internal thoracic artery takedown is an effective modality, and total endoscopic bypass on an arrested heart is feasible but does not offer a major benefit to the minimally invasive direct approach because cardiopulmonary bypass is still required. Their study suggests that robotic systems have not yet advanced far enough to perform endoscopic closed chest beating heart bypass grafting despite some technical success in 2 of 8 patients. In addition, robotic endoscopic mitral valve repair was successful in 14 of 17 patients. In contrast, several groups in Europe have successfully performed closed-chest, off-pump coronary artery bypass grafting using an endoscopic stabilizer. Kappert and Cichon et al performed 37 off-pump totally endoscopic coronary artery bypass (TECAB) on a beating heart with the Da Vinci system and an endoscopic stabilizer. In this series, they reported a 3.4% rate of conversion to median sternotomy. They concluded that their results promote optimism about further development of TECAB. Another study by Boehm and Reichenspurner et al using a similar stabilizer with the Zeus system had similar results and conclusions about TECAB. Interestingly, a study by Cisowski and Drzewiecki in Poland compared percutaneous stenting with endoscopic coronary artery bypass grafting in patients with single-vessel disease. In this series of 100 patients percutaneous stenting resulted in restenosis in 6% and 12% at 1 and 6 months, respectively, compared with 2% at 6 months in the endoscopic bypass group.

Another use for robotic systems being investigated is pediatric laparoscopic surgery. Currently, laparoscopic pediatric surgery is limited by an inability to perform precise anastomoses of 2 to 15 millimeters. Although laparoscopic techniques may be used to treat infants with intestinal atresia, choledochal cysts, biliary atresia, and esophageal atresia, it is not the standard approach because of the technical difficulties. To evaluate the feasibility of robotic systems in pediatric minimally invasive surgery, Hollands and Dixey developed a study where enteroenterostomy, hepaticojejunostomy, and portoenterorostomy were performed on piglets. They found all the
procedure to be technically feasible with the Zeus robotic system. The study concludes that robotic-assisted laparoscopic techniques are technically feasible in pediatric surgery and may be of benefit in treating various disorders in term and preterm infants. More recently, Hollands and Dixey devised a study using 10 piglets to develop the procedure and evaluate the feasibility of performing a robot-assisted esophagoesophagostomy. In this study, robot-assisted and thoracoscopic approaches were evaluated and compared for leak, narrowing, caliber, mucosal approximation, as well as anesthesia, operative, anastomotic, and robotic set-up times. They found that the robot-assisted approach is feasible. They also discerned no statistically significant difference between the 2 approaches based on the above variables.

Despite many studies showing the feasibility of robotic surgery, there is still much to be desired. More high-quality clinical trials need to be performed and much more experience needs to be obtained before the full potential of these systems can be realized.

**PRACTICAL USES OF SURGICAL ROBOTS TODAY**

In today’s competitive healthcare market, many organizations are interested in making themselves “cutting-edge” institutions with the most advanced technological equipment and the very newest treatment and testing modalities. Doing so allows them to capture more of the healthcare market. Acquiring a surgical robot is in essence the entry fee into marketing an institution’s surgical specialties as “the most advanced.” It is not uncommon, for example, to see a photo of a surgical robot the cover on of a hospital’s marketing brochure and yet see no word mentioning robotic surgery inside.

As far as ideas and science, surgical robotics is a deep, fertile soil. It may come to pass that robotic systems are used very little but the technology they are generating and the advances in
ancillary products will continue. Already, the development of robotics is spurring interest in new tissue anastomosis techniques, improving laparoscopic instruments, and digital integration of already existing technologies.

As mentioned previously, applications of robotic surgery are expanding rapidly into many different surgical disciplines. The cost of procuring one of these systems remains high, however, making it unlikely that an institution will acquire more than one or two. This low number of machines and the low number of surgeons trained to use them makes incorporation of robotics in routine surgeries rare. Whether this changes with the passing of time remains to be seen.

**Robotic Surgery: The Future**

The future of robotic surgery is hard to believe but ....it is now. If you haven't noticed, robotic surgery has come long ways and it was only a dream for doctors and engineers to have something that you no longer had to make big, hideous scars that would mess up somebody's body for the rest of their lives. Doctors, before robotic surgery, worked on making minimally invasive surgery that would take hours of surgery time. Now, surgery is still made in hours, but shorter hours are now in check with the robotic surgery. So you can't really say there is a future of robotic surgery, but you can say that this has been the future for doctors long ago so all you can say is...the future is now!!
The field of surgery is entering a time of great change, spurred on by remarkable recent advances in surgical and computer technology. Computer-controlled diagnostic instruments have been used in the operating room for years to help provide vital information through ultrasound, computer-aided tomography (CAT), and other imaging technologies. Only recently have robotic systems made their way into the operating room as dexterity-enhancing surgical assistants and surgical planners, in answer to surgeons' demands for ways to overcome the surgical limitations of minimally invasive laparoscopic surgery, a technique developed in the 1980s.

On July 11, 2000, FDA approved the first completely robotic surgery device, the daVinci surgical system from Intuitive Surgical (Mountain View, CA). The system enables surgeons to remove gallbladders and perform other general surgical procedures while seated at a computer console and 3-D video imaging system across the room from the patient. The surgeons operate controls with their hands and fingers to direct a robotically controlled laparoscope. At the end of the laparoscope are advanced, articulating surgical instruments and miniature cameras that allow surgeons to peer into the body and perform the procedures.

This system and other robotic devices developed or under development by companies such as Computer Motion (Santa Barbara, CA) and Integrated Surgical Systems (Davis, CA) have the potential to revolutionize surgery and the operating room. They provide surgeons with the precision and dexterity necessary to perform complex, minimally invasive surgical (MIS) procedures, such as beating-heart single- or double-vessel bypass and neurological, orthopedic, and plastic surgery, among many other future applications.

Manufacturers believe that their products will broaden the scope and increase the effectiveness of MIS; improve patient outcomes; and create a safer, more efficient, and more cost-effective operating room. It is the vision of these companies that robotic systems will one day be applicable to all surgical specialties, although it is too early to tell the full extent to which they'll be used.

Surgical robotics manufacturers working toward FDA approval of their devices are encouraged by Intuitive Surgical's recent FDA approval. "The future looks bright," says Yulun Wang, MD, founder and chief technical officer of Computer Motion. "This approval sends a positive signal to industry, and there are
tremendous opportunities." According to Wang, "The goal of robotic surgery is to offer superior quality and reduced trauma to the patient. Today, the skeptical surgeon would say that's not proven yet, but the progressive surgeon would say that these goals are achievable. Thus far, the results have been phenomenal."

And many researchers and industry participants in the field say that the capabilities of first-generation systems are just the beginning. According to Richard E. Wood, MD, chief of cardiothoracic surgery at Baylor University Medical Center (Dallas), robotic surgery systems "will certainly make it easier to perform major surgeries, but these systems still need to evolve. They're not for every patient, but with time we will gain more experience and do more procedures, and the instruments will evolve from this first generation." Currently, the three principal device manufacturers in this area are Intuitive Surgical, Computer Motion, and Integrated Surgical Systems. Their systems are described below.

**Future Outlook**

Surgeons and device executives agree that first-generation robotics systems have already displayed many advantages over traditional laparoscopic surgery and open surgery, especially in terms of speedier patient recovery and reduced pain. But they also insist that the technology is still evolving and will become more capable with time. "We're on the cusp of redirecting and improving surgical capability, but we are in the first generation of this process," says San Ramon's Gardiner. "The technology will be applied selectively early on, but as patients begin to insist on the new technology, it will become state-of-the-art and the standard of care for selected procedures." In Gardiner's opinion, as a general surgeon, "basically, the most promising applications for these systems will be in any surgery in which suturing is an important feature."

Continued evolution of robotic surgical systems is inevitable, says Gardiner. "Down the road, as with PCs, the systems will become smaller, lighter, faster, and easier to set up, and this will increase their applications. As with CT scans, you will find uses and needs for the technology in excess of what the projections were, and surgeons will want and need these devices. The surgeon actually does a better, more precise, elegant, dexterous, controlled procedure with robotics, with less tissue damage, which leads to a better outcome."
In the next five to seven years, almost all ORs worldwide will have robotic assistance of some kind for major surgeries,” says ISS’s Trivedi. “We will never, ever, replace the surgeon, but robotics will take over a lot of the things they do by hand, with more precision and accuracy." UCLA’s Schulam, who has been using robotic surgical systems since 1995, when the first products were being developed, says that the elaboration of such systems may change the relationships between surgeons and industry. "Robotics are here to stay. However, it will take time for these devices to revolutionize the way surgery is done, and educational programs are the key to their success. We need to change how industry and surgeons interact," he continues. "In the past, surgeons have had a consumerlike relationship with the device industry, where the consumer buys the product and is off. But now, what will be required is a much more collaborative relationship, in order to get surgeons to change the way they're used to doing things." Baylor's Wood is even interested in forming a robotic surgery institute, perhaps within the next year, where surgeons from many specialties can meet and discuss how to bring robotics technology to the next level.

According to surgeons, patients have been asking about robotic surgery, and their feedback has been very positive. This demand is another key to the success of the robotics industry. "People are very informed today, because of the Internet," says Wood. "About 8% of my patients have asked about robotic surgery." "Frankly, I was very surprised," says Gardiner. "I thought patients would feel robotics is too impersonal, but I have found that not one patient has not wanted it." Robotic surgery is in its infancy. Many obstacles and disadvantages will be resolved in time and no doubt many other questions will arise. Many question have yet to be asked; questions such as malpractice liability, credentialing, training requirements, and interstate licensing for tele-surgeons, to name just a few.

Many of current advantages in robotic assisted surgery ensure its continued development and expansion. For example, the sophistication of the controls and the multiple degrees of freedom afforded by the Zeus and da Vinci systems allow increased mobility and no tremor without comprising the visual field to make micro anastomosis possible. Many have made the observation that robotic systems are information systems and as such they have the ability to interface and integrate many of the technologies being developed for and currently used in the operating room. One exciting possibility is expanding the use of preoperative (computed tomography or magnetic resonance) and intraoperative video image fusion to
better guide the surgeon in dissection and identifying pathology. These data may also be used to rehearse complex procedures before they are undertaken.

The nature of robotic systems also makes the possibility of long-distance intraoperative consultation or guidance possible and it may provide new opportunities for teaching and assessment of new surgeons through mentoring and simulation. Computer Motion, the makers of the Zeus robotic surgical system, is already marketing a device called SOCRATES that allows surgeons at remote sites to connect to an operating room and share video and audio, to use a “telestrator” to highlight anatomy, and to control the AESOP endoscopic camera. Technically, much remains to be done before robotic surgery’s full potential can be realized. Although these systems have greatly improved dexterity, they have yet to develop the full potential in instrumentation or to incorporate the full range of sensory input.

More standard mechanical tools and more energy directed tools need to be developed. Some authors also believe that robotic surgery can be extended into the realm of advanced diagnostic testing with the development and use of ultrasonography, near infrared, and confocal microscopy equipment. Much like the robots in popular culture, the future of robotics in surgery is limited only by imagination. Many future “advancements” are already being researched. Some laboratories, including the authors’ laboratory, are currently working on systems to relay touch sensation from robotic instruments back to the surgeon.

Other laboratories are working on improving current methods and developing new devices for suture-less anastomoses. When most people think about robotics, they think about automation. The possibility of automating some tasks is both exciting and controversial. Future systems might include the ability for a surgeon to program the surgery and merely supervise as the robot performs most of the tasks. The possibilities for improvement and advancement are only limited by imagination and cost.
Robotic Telesurgery

Long Distance Robotic Surgery

During the recent 86th Annual Clinical Congress of the American College of Surgeons, a live robotic Telesurgery session was organized between the convention hall at McCormick Place in Chicago, Illinois, and the Johns Hopkins Bayview Medical Center in Baltimore, Maryland. The male patient underwent a successful remote-controlled and computer-assisted minimally invasive operation to treat chronic groin pain. The telerobotic system which was utilized, has been developed by the Johns Hopkins School of Medicine, Applied Physics Laboratory, and ICE Communications Inc. in 1993 to serve initially as a remote surgical training system for laparoscopic procedures.

Telecollaborative Surgery

SANTA BARBARA, Calif. -- Computer Motion Inc. (NASDAQ: RBOT), the leader and pioneer in medical robotics, announced that a London Health Sciences Center (LHSC) team of surgeons in London, Ontario, Canada performed the world's first series of Telecollaborative surgeries using Computer Motion's SOCRATES™ Telecollaborative System. To date a total of six robotically assisted procedures have been completed with the surgical mentor telecollaborating from the University Campus and the operative surgeon performing the procedure at the Westminster Campus, some 15 miles away:

- Drs. Douglas Boyd, Alan Menkis and Reiza Rayman completed a mitral valve repair and two heart bypass surgeries;
- Drs. Brian Taylor and Winston Hewitt performed an appendectomy procedure; and
- Drs. Richard Inculet and Richard Malthaner completed a lung biopsy and a lung resection procedure.
The medical community agrees that one of the most effective ways for surgeons to learn new procedures is directly from another surgeon. As a result, surgeon champions are routinely called upon to lend their clinical expertise and direction to surgeons who are still gaining expertise in advanced or complex procedures. Often, there are travel costs and scheduling challenges associated with this method.

There has been a growing interest in finding a better way to economically and effectively augment minimally invasive and conventional "open" surgical training. Standard teleconferencing systems are proving to be inadequate to the task of transmitting a clear, steady, non-pixilated operative image for the remote surgeon. The Computer Motion SOCRATES system eliminates these and other problems. SOCRATES provides the remote surgeon access to a precise and stable image via Computer Motion's AESOP(R) Endoscope Positioned plus much more.

Yulun Wang, Ph.D., founder and chief technical officer of Computer Motion, commented, "Computer Motion has taken telecommunications one important step further by developing the SOCRATES system to eliminate the distance barrier for physical interaction, enabling a new class of training and education required for the advancement of open and endoscopic surgical techniques. In the late 1980s and early 1990s when the medical community realized the full significance of laparoscopy for patients, thousands of surgeons had to learn new surgical techniques. This situation is repeating itself as emerging technology is enabling new advanced surgical procedures that yield improved patient outcomes across a broad range of surgical disciplines. We now sit on the threshold of another training and education opportunity, and Computer Motion is uniquely positioned to facilitate the necessary transfer of knowledge with our SOCRATES, AESOP and HERMES technologies." "SOCRATES is a huge step beyond just sharing audio and video feedback via teleconference," said Dr. Ken Harris, chief of surgery at LHSC. "For the first time, the mentoring surgeon is able to actively participate in a `hands-on' manner from a remote location. This translates to a very economical and effective method to shorten the learning curve for surgeons applying new surgical techniques to their practice. SOCRATES also facilitates the expansion of minimally invasive surgery into areas that may not currently have access to or the budget for surgical experts. This is something that patients around the world will benefit from." LHSC is comprised of three separate sites across the city of London, Ontario. "This is a splendid example of the innovative spirit at this hospital," said Tony Dagnone,
president and CEO of LHSC. "The positive impacts to patient care delivery as a result of the telementoring approach are astounding. We believe the SOCRATES technology will someday mean patients will be able to access the care they need closer to home in their community hospitals. Beyond our region, this technology will also allow us to share with and learn from other world-class healthcare providers. LHSC is committed to pursuing robotically assisted surgeries because we believe it is in the best interest of patients for improved outcomes and quality of life," Dagnone added.

Early development work on Computer Motion's telerobotic systems began in 1996 when Johns Hopkins University, under the direction of Dr. Louis Kavoussi, pioneered the development of telerobotics with Computer Motion's first telerobotic system, the AESOP(R) 1000 TS. Johns Hopkins was the first institution to use Computer Motion's telerobotic system in multi-center U.S. and transcontinental clinical trials. Dr. Kavoussi and a number of notable surgeons, including Dr. Peter Schulam of University of California, Los Angeles Medical Center, published their initial telerobotic experience and continue to work with the technology today. Several other world-class institutes, including the Medical College of Virginia and the Medical University of South Carolina, have partnered with Computer Motion in the development and testing of SOCRATES. The new system is currently under FDA regulatory review.
CONCLUSION

Although still in its infancy, robotic surgery has already proven itself to be of great value, particularly in areas inaccessible to conventional laparoscopic procedures. It remains to be seen, however, if robotic systems will replace conventional laparoscopic instruments in less technically demanding procedures. In any case, robotic technology is set to revolutionize surgery by improving and expanding laparoscopic procedures, advancing surgical technology, and bringing surgery into the digital age. Furthermore, it has the potential to expand surgical treatment modalities beyond the limits of human ability. Whether or not the benefit of its usage overcomes the cost to implement it remains to be seen and much remains to be worked out. Although feasibility has largely been shown, more prospective randomized trials evaluating efficacy and safety must be undertaken. Further research must evaluate cost effectiveness or a true benefit over conventional therapy for robotic surgery to take full root.

Robotic surgery is still in its infancy and its niche has not yet been well defined. Its current practical uses are mostly confined to smaller surgical procedures. Robotic surgery is a new and exciting emerging technology that is taking the surgical profession by storm.
Up to this point, however, the race to acquire and incorporate this emerging technology has primarily been driven by the market. In addition, surgical robots have become the entry fee for centers wanting to be known for excellence in minimally invasive surgery despite the current lack of practical applications. Therefore, robotic devices seem to have more of a marketing role than a practical role. Whether or not robotic devices will grow into a more practical role remains to be seen.

Robotic surgery is now routinely performed in specialized centers throughout the world. Da Vinci™ surgery offers a number of advantages over standard laparoscopy: 3D magnified imaging, tremor filtering, motion scaling and restoration of all degrees of freedom which should allow surgeons to surpass the current limitations of human performance. In the future the development of new instruments, reduction in the size of the system and improvements in ergonomics will likely result in wide spread dissemination of this technology.

REFERENCES


