Chapter 11

Robotics in Cardiac Surgery

Michael D. Diodato Jr, MD, Hersh S. Maniar, MD,
Sunil M. Prasad, MD, Ralph J. Damiano Jr, MD

Many surgical disciplines have been quick to adopt endoscopic technology because of the decreased morbidity and shorter recovery times.[1–3] These procedures are performed through small 5 to 10 mm ports with visualization using an endoscopic camera. Traditionally, most of these procedures have been excisional in nature rather than reconstructive and microsurgical. This is primarily a result of the limitations of conventional endoscopic instrumentation. For this reason, until recently, endoscopic approaches to cardiac surgery have not met with any success.

With the development of robotic surgical systems, or computer-assisted surgery, many of the limitations of conventional endoscopy have been overcome. While computers have long since transformed our office and hospital practice, they have had little direct impact upon the operating room. However, the introduction of computer-assisted surgery over the last several years has for the first time brought together the information technology revolution and the technical performance of surgery. In robotic surgery, there is a digital interface between the surgeon's hands and the instruments. This interface can be used to enhance surgical technical ability, thus enabling endoscopic microsurgery. Over the last few years, the use of robotic systems has allowed cardiac surgeons to perform minimally invasive endoscopic coronary artery bypass grafting (CABG) and valve procedures. This chapter summarizes the use of robotics in cardiac surgery and discusses their potential to transform our specialty.

History of Robotics

Aristotle is credited with the original concept of automation. In the fourth century B.C., he wrote, "If every instrument could accomplish its own work, obeying or anticipating the will of others . . . if the shuttle could weave, and the pick touch the lyre, without a hand to guide them, chief workmen would not need servants, . . ."[4] The first generation of robots consisted of automatons. An automaton is a self-moving machine, constructed for the purpose of imitating animate motions.[5] Most of the earliest automatons were clock-controlled ornamentations. In the year 1350, an automated rooster was erected on top of the cathedral in Strasbourg, France. Within the same time period, an Arab named al-Jazari wrote a book on automatons. The book included an illustration of an automated Arab lady that filled and emptied a washbasin.[6] In 1774, Droz invented one of the most complicated automatons in history. The "automatic scribe" could write any message up to 40 characters long.[7] In 1801, Joseph Jacquard invented a textile machine operated by punch cards, which went into mass production as a programmable loom.[8] In 1805, Maillardet constructed a spring-activated automaton that could draw pictures and write in both French and English.[5] At the 1876 World's Fair, life-sized automatons, including brass instrument players, artists, and card magicians, entertained large audiences. A few years later, Thomas Edison used a condensed version of his phonograph invention in the design of the famous talking doll.[9]

Although this concept is centuries old, the term *robot* was first coined in 1920. It is a derivative of the Czech word for serf, "robota," and is attributed to the playwright Karel Capek and his play, *Rossum's Universal Robots* (Figure 11-1). The play was a parody on a utopian society where all menial labor was performed by machines thereby freeing man to enjoy a life of leisure. In 1940, Westinghouse created two of the first robots that used an electric motor for entire body motion in the rectangular coordinate plane.[9] Interestingly, the term *robotics* did not come into use until 1942, when Isaac Asimov published the story "Runaround" in the magazine *Astounding*. It was in this manuscript that Asimov's "Three Laws of Robotics" were expounded. These laws, which still hold validity for modern robotics, state that (1) robots may not injure a human being or, through inaction, allow a human to

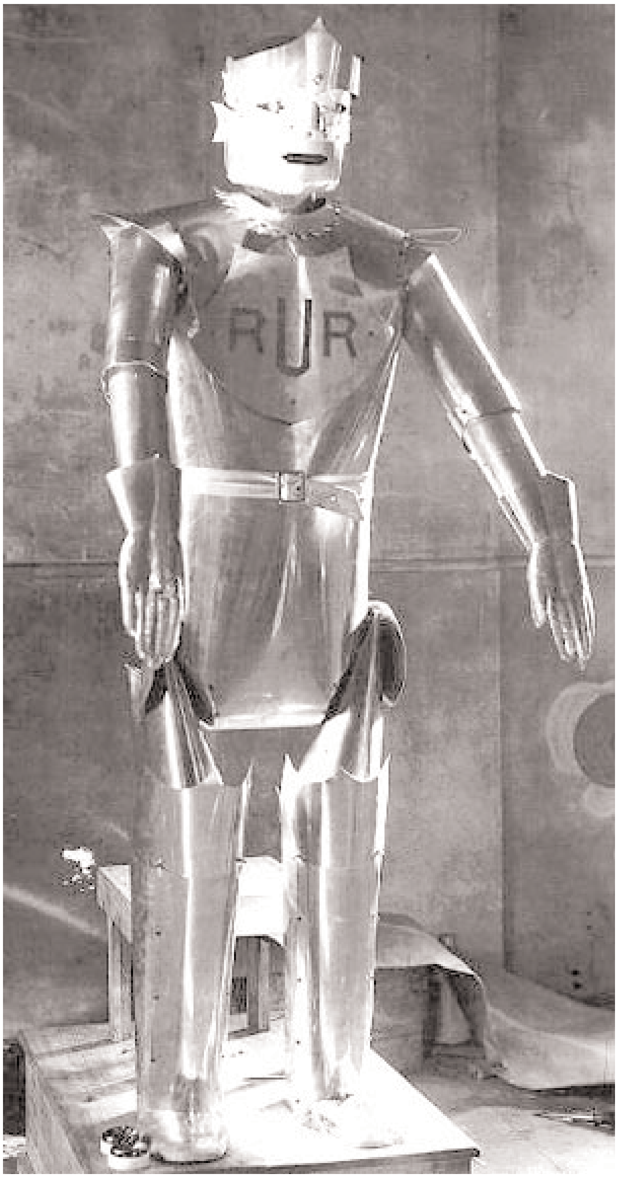

FIGURE 11-1. A representation of Rossum's Universal Robot from Karel Capek's play.

come to harm; (2) a robot must obey the orders given to it by human beings except such orders that would conflict with the first law; and (3) a robot must protect its own existence as long as such protection does not conflict with the first or second laws.[10]

While there was progress in both computer development and robotics in the early twentieth century, it was the invention of the transistor in 1948 that accelerated the development of robots and computers. In 1951, Raymond Goetz developed a teleoperated articulated arm for the Atomic Energy Commission. George Devol designed the first programmable robot and coined the term *universal automaton* in 1954. He was the founder of the first robot company.

General Motors installed robots onto production lines in Trenton, NJ, in 1962. By 1964, artificial intelligence laboratories were opened at Massachusetts Institute of Technology, Stanford University, and the University of Edinburgh. In 1968, Shakey, a robot with visual capabilities, was developed at the Stanford Research Institute and was soon followed by a robotic arm that was electrically powered. Richard Hohn at Cincinnati Milacron Corporation developed the first commercially available minicomputer-controlled robot, T3 (the Tomorrow Tool) in 1973. Professor Scheinman, the developer of the Stanford arm, formed Vicarm Incorporated in 1974 to market an industrial-strength version of the arm, which was computer controlled. The National Aeronautics and Space Administration (NASA) used these arms on the Viking space probes.

By the beginning of the 1980s, with the computer industry just beginning to blossom, the robot industry experienced a time of rapid growth. Fujitsu Fanuc Company of Japan developed the first totally automated factory in 1980. New robotics companies were appearing nearly every month. However, by 1990, most of the small companies had been purchased by large conglomerates that now control what has become a $170 billion industry.[11] Throughout the 1990s, these robotics companies tried to deal with problems in the human-robot interface, and the first visual servo-controlled systems were developed. As computer technology evolved, effective feedback systems were developed, which spurred a second wave of start-up companies and research. Over the last decade, the field of robotics expanded from its early industrial origins and began to focus on new markets, including medicine.

Two main companies have produced surgical robotic systems for cardiac surgery: Computer Motion and Intuitive Surgical. Computer Motion, Inc. (Goleta, CA), was founded in 1989 by Yulun Wang, PhD, and introduced a voice-controlled arm, AESOP, to position and hold an endoscopic camera in 1993. In October 1994, AESOP became the first Food and Drug Administration (FDA)–cleared surgical robot. In November 1996, AESOP 2000 became the first voice-controlled robot cleared by the FDA. The ZEUS Robotic Microsurgical System was introduced into clinical use in September 1998.

Frederic Moll, MD, Robert Younge, and John Freund, MD, formed Intuitive Surgical in 1995 based on technology developed by Stanford Research Institute, now SRI International. The da Vinci Surgical System (Intuitive Surgical, Inc., Mountain View, CA) consisted of a surgeon console, a computer controller, and endoscopic instruments with articulated "endowrists" at the end of two surgical arms. The first robotically assisted cardiac surgeries in the world were performed using the da Vinci system. Dr. Carpentier, in Paris, performed a mitral valve procedure in April 1998. In the same month, Dr. Friedrich Mohr, in Leipzig, performed the first robotically assisted CABG.

Overview and Advantages of Robotic Surgical Systems

Robotic systems have been developed to assist in endoscopic procedures. These systems consist of three main components: a surgeon interface device, a computer controller, and specially designed instrument tips attached to robotic arms. The surgeon controls the instrument handles from an interface device. His movements are subsequently relayed to and digitized by a computer controller. The information is then passed along to robotic arms, which are positioned on or near the operating table. Current surgical robotic arm systems are able to move with multiple degrees of freedom, simulating the movement of the human arm, elbow, and wrist.

A third robotic arm is capable of manipulating the endoscope and is controlled by the surgeon. The direct control of the robotic arm has eliminated the need for a human assistant. The robotic camera arm is more precise than a human assistant, and the number of times the camera needs cleaning has been reduced three- to fivefold.[12] With the AESOP arm, movements can be stored in the computer's memory and be returned to with a simple voice command. The endoscope allows for much greater magnification than traditional surgical loupes, enhancing the surgeon's visualization of the anatomic detail of small structures. Although the loss of depth perception because of two-dimensional video monitors has been a traditional drawback to endoscopic visualization,[13,14] both companies offer high-resolution three-dimensional monitors.[15]

The computer interface is the major difference between robotic and traditional surgery. It allows for digitization of the surgeon's movements. This "digital" information can then be manipulated by the computer to enhance surgical movement. The two principal manipulations include filtering and motion scaling. The filtration of high-frequency oscillating motion effectively eliminates the surgeon's natural tremor. This helps to overcome the disadvantages of traditional endoscopy, in which the long instruments significantly magnify even the smallest tremor. This elimination of tremor enhances precision and may even facilitate ambidexterity. The computer controller also permits a variable degree of motion scaling, anywhere from 1- to 10-fold, changing gross hand movements at the console to fine movements in the operative field. This phenomenon has been termed *scaled telepresence*[16] and aids the surgeon in operating on extremely small structures. Recent work in our laboratory shows that motion scaling is most responsible for the enhanced precision seen with robotic systems.

The instrumentation available with computer-assisted endoscopic surgery offers significant advantages over those instruments used for conventional handheld instruments. Conventional nonrobotic laparoscopic equipment is limited to four degrees of freedom (a degree of freedom is a direction in which an instrument can move). Furthermore, the operator's motions are reversed (ie, the tip and handle move in opposite directions), and shear forces on the laparoscopic instruments are high, leading to increased operator fatigue. These pitfalls are both caused by the phenomenon known as the "fulcrum effect."[17] Separating the instrument tip from the handle eliminates this problem. With the help of the computer controller, intuitive motion is restored such that when the surgeon moves the instrument handle one way, the instrument tip moves in the same direction. Robotic systems allow for more intuitive hand movements by maintaining both the natural eye–hand axis as well as the oculovestibular orientation. This is in sharp contrast to the mirror image movements required in conventional endoscopic surgery. Robotic systems also allow for more degrees of freedom in movement by including a "wrist" joint on the instrument, creating a more natural handlike articulation.

However, a drawback of these systems is the loss of direct human contact with the tissue. As a result of the design of the robotic system, there can be no true haptic or force feedback given to the surgeon. While computer software and laparoscopic surgical models are being developed to create accurate haptic sensation, these are not currently clinically available.

A final advantage of the robotic systems is improved ergonomics. Operator fatigue results from many factors during conventional laparoscopic procedures. The surgeon is required to stand at the operating table, in often awkward positions, depending on trocar placement. Furthermore, the video monitor may be situated in a way that does not allow for convenient unobstructed viewing. The resulting common complaints of neck and back stiffness may lead to less-than-optimal surgical performance. In robotically assisted surgery, the surgeon is seated at the console, positioned directly in front of the monitor. This interface style immerses the surgeon in the operating field, minimizes distractions, and increases operator comfort. This serves to increase the surgeon's concentration and focus on the task at hand. It has been hypothesized that these improved ergonomics should help the surgeon's performance remain optimal for longer periods of time.

In summary, with better visualization, improved dexterity, and reduced fatigue, robotically assisted cardiac surgery allows for a level of precision superior to that obtainable with conventional endoscopic and open surgical techniques. This has expanded the use of endoscopy into the clinical microsurgical and reconstructive specialties.

Current Robotic Systems

Computer Motion

The current version of AESOP was introduced in January 1998. This robotic arm controls the endoscope and is mounted on the operating table. AESOP responds to more than 20 simple voice commands (Figure 11-2).

FIGURE 11-2. The AESOP robotic arm. It can be mounted to the operating table and accommodates most conventional endoscopes.

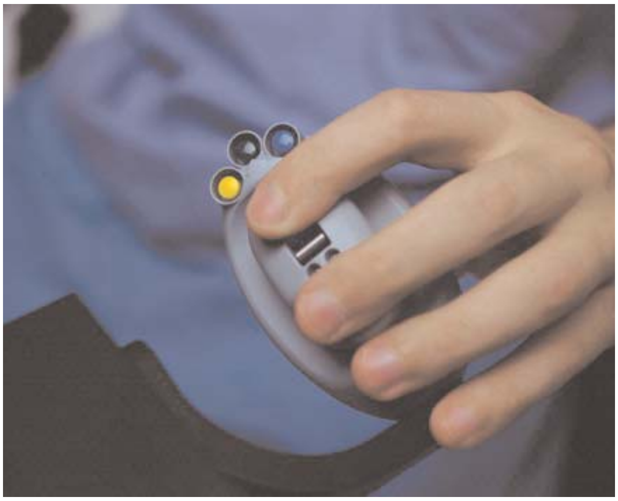

FIGURE 11-3. The Microwrist handle by Computer Motion.

FIGURE 11-4. The ZEUS Robotic Microsurgical System. The three robotic arms are shown in the background, attached to the operating room table.

AESOP has eliminated the need for a dedicated camera holder and has an established track record of performance in more than 125,000 clinical procedures.[18]

The ZEUS Robotic Microsurgical System was introduced into clinical use in September 1998. Designed as a telemanipulator, the surgeon's movements are digitized and filtered by a signal processor, before being relayed to the robotic arms for the completion of a given movement. The surgeon is seated at an interface device or console. The surgeon holds form-fitted handles that provide an extremely sensitive natural robotic interface (Figure 11-3). The system mechanically relays the surgeon's hand movements to a computer controller.

Housed within the console is a 16-inch video monitor that displays the operative field (Figure 11-4). A three-dimensional flat-screen display is also available. The surgeon remains seated, with the endoscopic image displayed perfectly centered at eye level and close to the hands. Overall surgical performance has been shown to be improved by this surgeon-instrument orientation.[19] A second display located immediately beneath the video monitor functions as a touch screen to provide control of instrument type, motion scaling, and performance characteristics of the instrument end-effectors.

The final components of the ZEUS system are the robotic arms, which are mounted on the operating table. These three arms are all lightweight (20 kilograms total) and independent, allowing for maximum flexibility in port placement. The surgical assistant and the remainder of the surgical team are positioned in close proximity to the robotic arms while the surgeon is seated away from the table at the ZEUS console. If necessary, the arms can be repositioned to accommodate the workspace requirements of the operative team.

The robotic arms hold the endoscopic instruments. Several of them have a designed "microwrist" near the instrument tip that provides for five degrees of freedom (Figure 11-5). The endoscopic instruments used in the ZEUS system are custom designed by Scanlan International (St. Paul, MN). More than 20 different end-effectors are offered, including needle drivers, ring forceps, tissue graspers, and microscissors. The instruments are between 3 and 5 mm in diameter and are easily inserted through 5 mm ports. These instruments are smaller than conventional endoscopic instruments, are reusable, and may be sterilized in the conventional manner. They are easily interchangeable during the operation, and the time to set up the ZEUS system has routinely been less than 20 min.[20]

Intuitive Surgical

The da Vinci Surgical System by Intuitive Surgical permits the intracavitary manipulation of various 2 to 4 mm instrument tips through six degrees of excursion, emulating the human wrist (Figure 11-6). The surgeon operates from a master console and controls the camera, which has a wide-angle lens with a 10-fold magnification (Figure 11-7). The image of the surgical site is transmitted to the surgeon through a high-resolution stereo display (two separate channels), which helps to restore hand–eye coordination. The Insite High-Resolution 3-D Endoscope and imaging processing equipment provide true-to-life three-dimensional images of the operative field. Operating images are enhanced, refined, and optimized by using image synchronizers, high-intensity illuminators, and camera control units. A robotic cart located at the patient's side positions and drives the wristlike devices, while an assistant adjusts and performs instrument changes (Figure 11-8). The operator at the console becomes immersed 1n the surgical landscape creating a "telepresence" with optimal access and dexterity. Robotic arms and "wrist" instruments are placed through 10 mm

FIGURE 11-5. The ZEUS microsurgical instruments with jointed tips.

FIGURE 11-6. The da Vinci surgical EndoWrist provides articulation for surgical instruments.

FIGURE 11-7. The da Vinci surgical console.

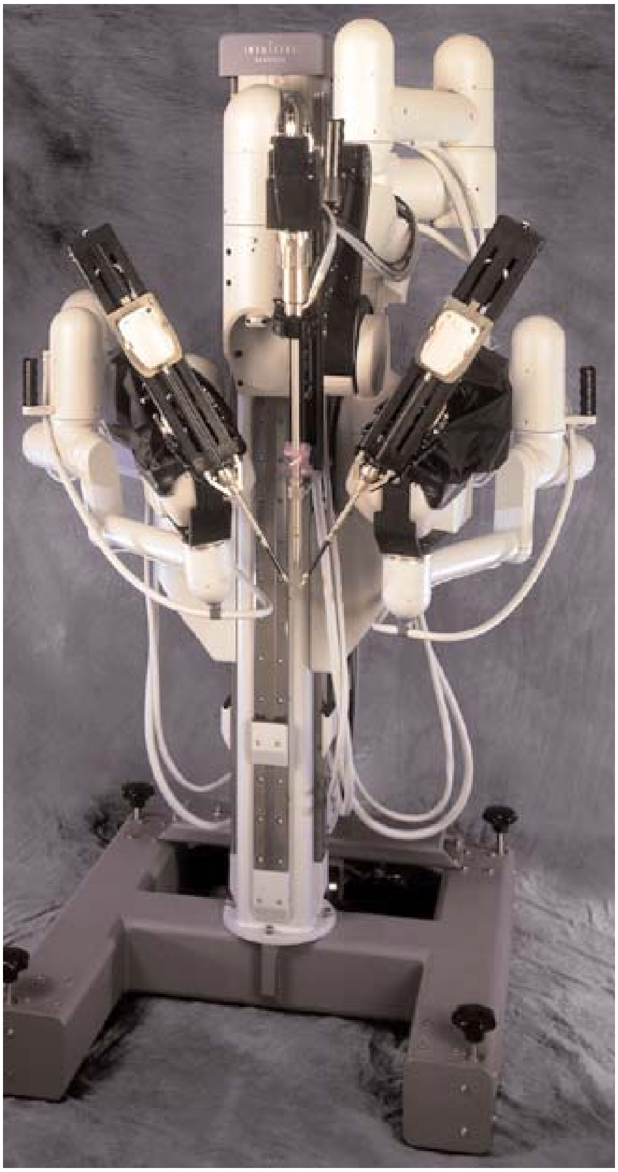

FIGURE 11-8. The da Vinci surgical robotic cart.

ports and converge in the surgical field. Six degrees of motion freedom are offered by this combination of trocar-positioned arms (insertion, pitch, and yaw) and articulated instrument wrists (roll, grip, pitch, and yaw). From the operating console, full *x*, *y*, and *z*-axis agility is effected by coordinating foot-pedal clutching and hand-motion sensors. Console surgeon hand activity is emulated precisely at the surgical field. Console foot pedals control the camera, its spatial orientation, and its focus. Moreover, if the surgeon's hands engage in a clumsy position, a foot-pedal clutching mechanism allows for easy and immediate repositioning. These eye–hand–foot interactions allow the surgeon to ratchet articulated wrists smoothly through every coordinate, configuring a myriad of complex instrument positions while providing maximum ergonomic comfort.

Robotics in Cardiac Surgery

Coronary Artery Bypass Grafting

There is extensive experience worldwide with robotically assisted CABG. While these operations are still performed on highly selected patients, spectacular progress has been made over the last several years. The worldwide experience for the ZEUS and the da Vinci systems is summarized below.

THE ZEUS EXPERIENCE

The European experience with the ZEUS system has principally been reported by Dr. Reichenspurner and his group in Munich.[21] They were the first in the world to use the ZEUS system, in September 1998. In August 2002, Dr. Reichenspurner reported that 41 patients had been operated upon using the ZEUS system between 1998 and 2001. These patients had single- or multivessel disease. The use of ZEUS occurred in a stepwise progression. In the initial 12 patients, the system was used for endoscopic internal thoracic artery (ITA) harvest. This was done to familiarize the surgeon with the device and the environment. The system was then used to perform 17 coronary anastomoses on arrested hearts in the next 13 patients. The anastomoses were performed endoscopically using robotic assistance and included left internal thoracic artery (LITA) to left anterior descending (LAD) (n = 13), right internal thoracic artery (RITA) to obtuse marginal (OM) (n = 2), and saphenous vein graft to diagonal targets (n = 2). The next 6 patients had the anastomoses (LITA to LAD) performed on a beating heart through a median sternotomy. Only one patient had to be converted to a manually performed anastomosis. The robotically assisted anastomoses took a median time of 21 min (range, 14 to 32 min) on the arrested and 25 min (range, 19 to 42 min) on the beating heart (p = not significant). There was no significant difference in operating room (OR) time or date of discharge between these first two groups.

Two patients underwent endoscopic CABG with port-access cardiopulmonary bypass. LITA harvest took 83 and 110 min, and bleeding occurred in the first case, which required minithoracotomy to control. The anastomoses took 42 and 40 min to complete, and the surgeries took 4.5 and 5.3 h, respectively.

The last eight patients of this series underwent endoscopic CABG without cardiopulmonary bypass (CPB) on a beating heart. Median time for LITA harvest was 55 min (range, 43 to 74 min), and the median time for anastomotic completion was 32 min (range: 22 to 50 min). OR time was 5.5 h (range, 4.6 to 8.0 h), and median discharge day was 5.0 (range, 4 to 11 days). One patient was converted to an open procedure. The median times to perform the anastomoses were significantly longer in the endoscopic groups, but the median length of hospitalization was 5 days in the endoscopic groups and 8 days in the sternotomy groups. Postoperative angiography showed a

97% patency of all grafts, with only two anastomoses showing mild narrowing of less than 50%.

In the United States, Dr. Damiano and his group at Pennsylvania State University performed the first robotically assisted cardiac surgical procedure in North America, in December 1998.[22] The Food and Drug Administration approved a single-center clinical trial to evaluate the efficacy and safety of robotically assisted endoscopic CABG. Nineteen patients underwent a robotically assisted anastomosis of the LITA to the LAD. Primary outcome measurements were device-related complications and graft patency 6 to 8 weeks postoperatively.

All anastomoses were performed endoscopically through three-instrument ports (Figure 11-9). A modified subxiphoid approach was used for port placement. A zero-degree endoscope was attached to the AESOP voice-controlled robotic arm. A continuous end-to-side anastomosis was performed with a specially designed 7 cm double-armed 7–0 suture. Because this study was only approved for single-vessel bypass, all other grafts were completed manually prior to the robotic anastomosis.[23]

The system required an average set-up time of 16 ± 1 min. There were no intraoperative complications related to port placement or mechanical failures of the system. The time required to perform the LITA-to-LAD anastomosis was 22.5 ± 1.2 min, and the last five anastomoses were each performed in less than 20 min. Eighty-nine percent (17 of 19) of the grafts measured were patent and had excellent diastolic flow by ultrasound. Average graft flow was 38 ± 5 mL/min. Two of the grafts had inadequate flow and were manually reconstructed. The average intensive care unit (ICU) stay was 1.1 ± 1 days, and the average hospital stay was 4 ± 0.4 days. There was 100% late follow-up of these patients at 17 ± 4 months. At that time, there were no late complications and all patients were New York Heart Association (NYHA) class I. Eight weeks after surgery, graft patency was assessed by coronary angiography. This revealed all grafts to be patent and no graft stenosis of greater than 50%.[24]

In Canada, Dr. Boyd accumulated a significant experience with endoscopic ITA harvesting using the ZEUS system and has the largest series of totally closed endoscopic CABG. Initially, his group investigated the use of the AESOP robotic arm during ITA harvest.[25] In 55 consecutive patients, the ITA was harvested endoscopically using a 30° endoscope. Anastomoses were initially completed

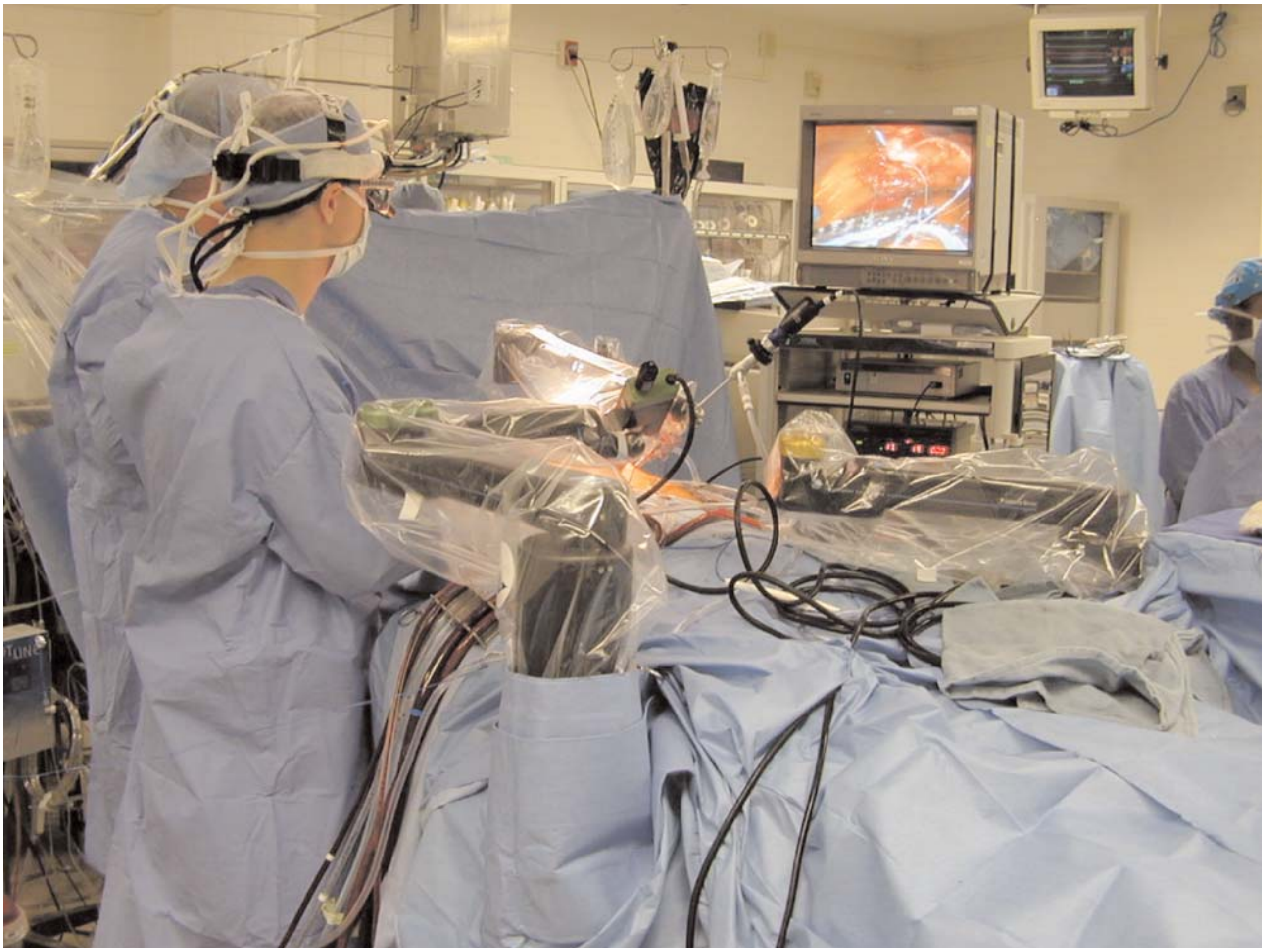

FIGURE 11-9. Intraoperative photograph of the ZEUS Robotic Microsurgical System in use for CABG.

manually through a limited thoracotomy. The average harvest time was 57 ± 23 min. Robotic camera assistance significantly reduced the number of endoscopic cleanings and was felt to facilitate the more difficult dissections. The AESOP arm reliably responded to more than 95% of verbal commands, and there was 100% patency in the 14 patients who underwent postoperative angiography.

Subsequently, the Harmonic Scalpel (Ethicon Endo-Surgery, Cincinnati, OH) was adapted to a ZEUS robotic arm, and 19 patients underwent LITA harvest using a robotically controlled Harmonic Scalpel with computer-assisted video control.[26] The investigators concluded that the ZEUS system could be used safely for ITA harvesting even when the anterior–posterior working space was limited. The advantages of the robotically controlled endoscope included greater exposure, superior image quality, and a consistent quality of assistance, which improved video dexterity and lessened surgeon fatigue.

Dr. Boyd's group has used the ZEUS system for beating-heart coronary anastomoses in 12 patients undergoing single-vessel CABG through a limited thoracotomy. The anastomotic times from ITA to LAD were 80 ± 27 min. No repair sutures were required, and average graft flows were 38 ± 24 mL/min. Postoperative angiography was performed on all patients, all anastomoses were patent, and 10 of 12 were Fitzgibbon's grade A.

Dr. Boyd has since performed a closed-chest totally endoscopic beating-heart CABG on six patients, using the ZEUS robotic system.[27] The first case was performed on September 24, 1999. Using a zero-degree endoscope, the AESOP, and warm carbon dioxide gas insufflation, sufficient working space and visibility were established in the mediastinum. A specially designed sternal elevator also was employed to increase the anterior–posterior intrathoracic space. With the patients in a right lateral decubitus position, trocars were inserted in the third, fifth, and seventh interspaces along the mid to anterior axillary lines (Figure 11-10). In preparation for the beating-heart anastomosis, an articulating end stabilizer (Computer Motion, Goleta, CA) was inserted through a port in the second interspace at the axillary line for LAD stabilization.

In this clinical series, anastomotic times varied between 40 and 74 min (mean, 55.8 min). All anastomoses had acceptable flows with a mean of 28 mL/min (range, 12 to 46 mL/min), and no patient required conversion from the robotic technique. Median operative time was 6 h (range, 4.5 to 7.5 h). All patients underwent coronary angiography prior to discharge, and five of six grafts were found to be patent. One had a 50% stenosis in the region of the distal snare site. The average length of hospital stay was 4.0 ± 0.9 days. All patients were free from angina, had returned to work, and had normal exercise capacity at a mean follow up of 145.3 ± 29.6 days.[27]

THE DA VINCI EXPERIENCE

As of May 2001, the da Vinci telemanipulation system (Intuitive Surgical, Mountain View, CA) had been used in 1,250 endoscopic cardiac procedures ranging from the harvesting of arteries (1,137) to endoscopic CABG and

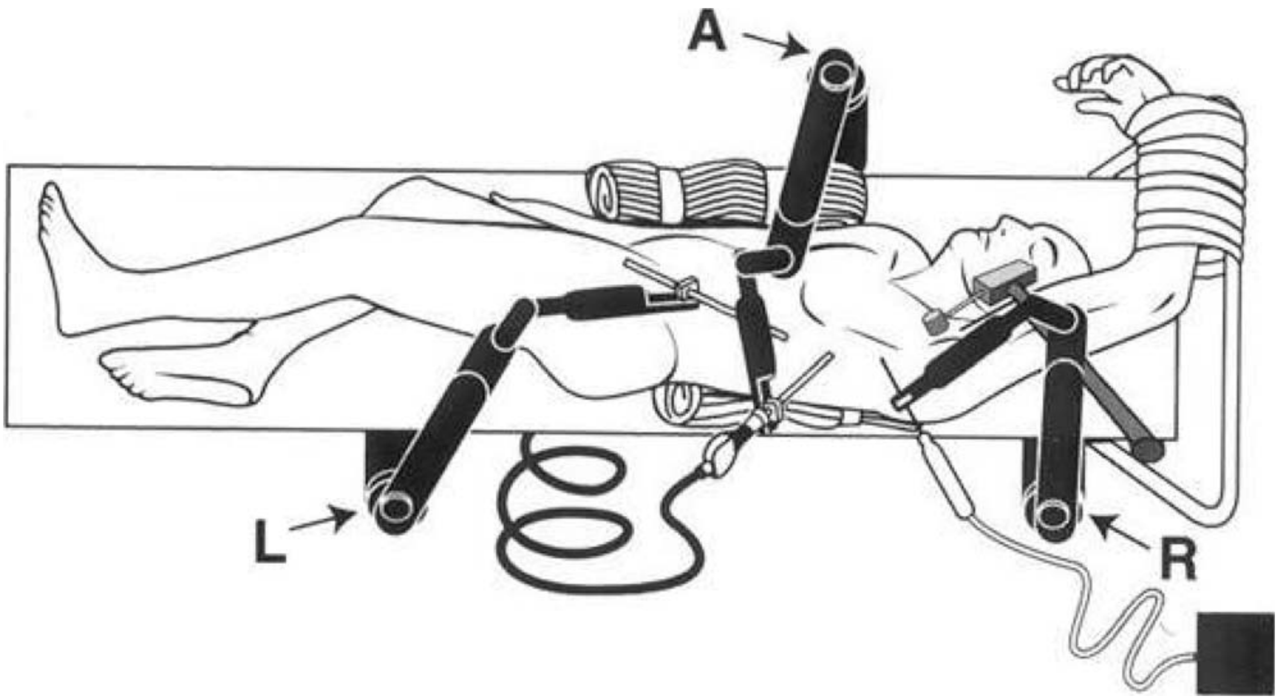

FIGURE 11-10. Port placement used by Dr. Boyd in London, Ontario, Canada, for endoscopic beating-heart CABG. *A* is the AESOP robotic arm. *R* is the right instrument arm. *L* is the left instrument arm. Note the left subclavicular placement of the endoscopic stabilizer.

mitral valve repair. This system was clinically introduced in 1998. Dr. Loulmet performed the first total endoscopic CABG using da Vinci in June 1998.[28]

Dr. Mohr and his group reported their experience in 131 patients undergoing coronary artery bypass grafting from December 1998 to April 2000.[29] This group also proceeded in a stepwise fashion, using the system initially to take down the ITA (n = 81), and then expanded its use to perform the ITA-to-LAD graft in a standard sternotomy (n = 15). The operation was then changed to a total endoscopic CABG on an arrested heart (n = 27) and then on a beating heart (n = 8). There were no technical problems reported, and 79 of 81 ITA takedowns were performed successfully. The average time for the ITA takedown was 48.3 ± 26.3 min, but in the last 20 patients, this improved to 35.4 ± 7.7 min. The anastomosis was performed manually in the initial ITA harvests, and there was a 96.3% patency on postoperative angiographic follow-up at 3 to 6 days. At 6 months' follow-up, all patients were free from angina. Through a sternotomy, the mean time to perform the anastomosis using the robotic system was 16 ± 11 min, and all anastomoses were patent postoperatively.

The group then progressed to the third stage of the trial, a total endoscopic CABG on an arrested heart. Twenty-two of 27 patients underwent the operation successfully. Four patients were converted to an open procedure during the operation, and one was converted postoperatively. There was no mortality, and at 3 months' follow-up, 95.4% of grafts were patent by angiography. The operation took 3.5 to 8 h to complete.

The final stage of this study had the surgeon performing a total endoscopic CABG on a beating heart. Eight patients were initially selected to undergo this procedure. Four patients achieved sufficient stabilization to undergo the procedure. Two patients completed the operation uneventfully; two needed revision of the anastomosis, one for occlusion of the graft and one for a low flow on angiography. In these four patients, the anastomosis was performed in 24 to 49 min. The other four patients were not able to undergo the procedure for several reasons, including small intracavitary space, calcification of the LAD, septal branch bleeding, and cardiac arrhythmia prior to LAD occlusion. This last patient had an anterior wall myocardial infarction and succumbed on the sixth postoperative day. All other patients had uneventful postoperative courses and were discharged between days 6 and 8.

Between May 1999 and January 2001, Dr. Stephan Schueler's group in Dresden used the da Vinci on 201 patients.[30] Group A consisted of 156 patients placed into either minimally invasive direct coronary bypass surgery (MIDCAB) (n = 106) without cardiopulmonary bypass or a robotically enhanced Dresden technique coronary artery bypass (REDT-CAB) with cardiopulmonary bypass (n = 50). All anastomoses were performed manually under direct visualization. The ITA was harvested endoscopically in these groups. In group B, eight patients had endoscopic LITA takedown with robotically enhanced CABG via median sternotomy. In group C, 37 patients underwent totally endoscopic CABG, 8 on pump and 29 off pump.

The mortality rate was 0.6% (1 of 201) for all groups. Ten patients (4.9%) were converted intraoperatively to a conventional median sternotomy. Stress ECG was performed 4 weeks postoperatively in 97.5% of patients. Seven patients from group A (4.5%) had angina. Four of these patients had anastomotic stenosis. One patient in group B was found to have a previously undiagnosed lesion of the circumflex coronary artery by angiography and was treated with angioplasty. Of the 56 patients scheduled for total endoscopic CABG, 19 (33.9%) were converted to a MIDCAB procedure because of several factors, including calcification of the LAD, intramural LAD course, pleural adhesions, and difficulty with stabilization. There was no difference in the length of ICU stay, ventilation time, or hospital stay between any of the groups.

A third German group in Frankfurt, headed by Dr. Wimmer-Greinecker, has also been active using the da Vinci system for totally endoscopic CABG.[31] From June 1999 to February 2001, 45 patients had the procedure performed on an arrested heart. Thirty-seven patients had a single-vessel ITA-to-coronary artery bypass, and eight patients had double-vessel bypass. Initially, there was a 22% conversion rate, but this fell to 5% in the last 20 patients. All patients with angiographic follow-up had patent grafts. There was no mortality reported in this series. The anastomoses took an average of 18.4 ± 3.8 and 21.1 ± 6.3 min to complete in the single- and double-vessel groups, respectively. The cross-clamp time in these groups was 61 ± 16 min for single-vessel bypass and 99 ± 55 min for double-vessel bypass. The bypass time was 136 ± 32 min when only one bypass was performed and 197 ± 63 min when two bypasses were performed. When compared with a patient cohort receiving conventional CABG, there was no difference in ICU length of stay, ventilation requirement, or duration of hospital stay.

In summary, the experiences at centers around the world demonstrate the capabilities of robotic assistance for enabling endoscopic CABG. As surgeons become more experienced and computer components continue to develop, the safety and efficacy of these procedures will continue to improve. At present, totally endoscopic CABG is reserved for highly selected patients with limited disease. Widespread application awaits the development of more sophisticated robotic systems and the introduction of parallel technologies to aid in target site stabilization, to increase the amount of intrathoracic space, and to facilitate the anastomosis.

Mitral Valve Surgery

The first steps in minimally invasive valve surgery involved the use of smaller incisions than the traditional median sternotomy but were performed under direct vision.

Surgeons found that these incisions provided adequate exposure, and they reported encouraging results with low morbidity and mortality.[32,33] These initial experiences were often performed with HeartPort (Redwood City, CA) technology. This endovascular cardiopulmonary bypass system was usually inserted via the femoral vessels and, as a result, removed the perfusion tubing from the thoracic incision.[34] This made the operative field less cluttered and more accessible. Recently, several groups reported their experience with robotically assisted mitral valve surgeries through small thoracotomies.

In Europe, Dr. Mohr in Leipzig has one of the world's largest experiences with robotically assisted mitral valve surgery. A recent report included 449 patients over a 5-year period, June 1996 to July 2001.[35] Of these patients, 327 had a mitral valve repair and 122 had replacement. The procedure was changed during the middle of this study secondary to a high rate of complications, and the group adopted the procedure developed by Dr. Chitwood in 226 cases.[35] In 366 cases, the voice-controlled robotic-arm AESOP 3000 was used for videoscopic guidance. In only 23 cases was the procedure completely performed using the da Vinci telemanipulation system. The mean length of the surgical incision was 4.3 ± 0.5 cm, and the surgery was completed in 176 ± 56 min. These authors found a significant learning curve as the surgeons gained experience in the minimally invasive procedures. Only 9 patients had failed repairs, all in the first 80 patients. The addition of the da Vinci system "allows a precise controlled mitral valve repair, with the technical potential for a completely endoscopic procedure."[36] The authors concluded that patients were more satisfied with the minimally invasive procedure, had less pain, and were able to return to previous activities more quickly.

Working at the same time in Munich, Dr. Reichenspurner and his group reported similar results in 50 patients undergoing minimally invasive mitral valve procedures using HeartPort port-access technology and three-dimensional video assistance.[38] Twenty-four patients had replacements, and 20 patients had repairs, and there were multiple etiologies. The last 20 patients utilized the AESOP-controlled endoscope. These patients were compared to 49 patients undergoing the traditional procedure during the same time period. Using a right submammary incision, 4 to 7 cm in length, and a three-dimensional endoscopic camera (Vista Cardiothoracic Systems Inc., Westborough, MA), the surgeon was able to simultaneously see the operative site by looking into the incision and at the endoscopic picture inside of his helmet. The endoscopic picture was most useful in viewing the subvalvular apparatus and checking the position of sutures and knots. There was a trend toward longer duration of cardiopulmonary bypass and aortic cross-clamp time in the minimally invasive group. However, the length of stay in the ICU and hospital was less in the minimally invasive patients. In this series, there was no mortality and 85% of patients were in NYHA class I at 3 months' follow-up. These authors stressed the need for careful preoperative selection of patients for the minimally invasive repair.

In the United States, Dr. W. Randolph Chitwood and his team have progressively increased the role for computer assistance for both mitral valve repair and replacement.[38,39] In June 1998, this group performed the first video-directed mitral operation in the United States using an AESOP 3000–controlled endoscope. This initial series used a 5 to 6 cm submammary minithoracotomy for exposure. Dr. Chitwood compared 127 patients that underwent minimally invasive video-assisted mitral valve surgery with 100 sternotomy-based mitral valve procedures.[40] Of the 127 minimally invasive patients, 55 had a manually directed endoscope whereas 72 had a computer-directed endoscope (AESOP). The average cross-clamp times in the computer-directed minimally invasive and conventional groups were identical, but both were significantly lower than the manually directed minimally invasive group. Seven patients in the conventional group required reexploration for bleeding whereas none of the manually directed and only three of the robotically directed patients required reoperation. Moreover, 13% of the conventional sternotomy group had prolonged ventilatory requirements as compared to 0% and 1% in the manually and robotically directed groups, respectively. The 30-day operative mortality for the minimally invasive group was 2.3%, which was identical to their previously reported mortality rate for the conventional procedure. The length of hospital stay was significantly lower in the minimally invasive groups. The authors concluded that the minimally invasive approach was a safe and feasible approach to mitral valve surgery in the hands of an experienced surgeon. The surgeon-controlled camera tracking was more intuitive. Technically, the video assistance was particularly advantageous for providing stable lighting and vibration-free viewing of the subvalvular apparatus. These benefits have quickly helped transition this team and others from video-assisted surgery toward video-directed mitral procedures, where almost all of the procedure is performed under endoscopic vision.

Dr. Chitwood performed the first complete computer-enhanced robotic mitral valve repair in North America in May 2000.[41] The da Vinci system was used to perform this operation and seven subsequent operations. The procedure is still performed through a 5 to 6 cm incision, but all leaflet resections, chordal procedures, and defect closures are done with the da Vinci system. These procedures were undertaken in a highly select group.[42] His early results are promising and confirm the feasibility of robotically assisted valve surgery.

Investigators have now begun to use the ZEUS robotic system in mitral valve procedures. Using a "service entrance" incision and a right anterior 6 cm thoracotomy, Dr. Grossi was able to repair the mitral valve in a 50-year-old patient with posterior leaflet prolapse.[43] The valve repair required 3 h and 2 min of cardiopulmonary bypass, and the ZEUS robotic instrumentation was used for 69 min. Dr. Grossi has performed six minimally invasive mitral valve replacements in the laboratory, taking an average 69.3 ± 5.4 min to complete.[44]

In summary, the initial clinical trials of the robotic and telemanipulation systems show that they can be used to assist mitral valve surgery. There has been a significant learning curve with this technology, and its role and precise value in the surgical treatment of valvular heart disease remain to be determined.

Atrial Septal Surgery

Dr. Alfieri's group from Milan, Italy, has employed the da Vinci surgical system in the repair of atrial septal defects (ASDs) in seven patients.[45] Five patients had ASDs, while the other two had a patent foramen ovale with atrial septal aneurysms. All procedures were performed on an arrested heart. Four ports were placed into the right chest. An endoaortic balloon occluded the ascending aorta, and cardioplegia was delivered. Bypass was established using the HeartPort system. A right atriotomy was performed, and the defect was closed with interrupted (one patient) or continuous suture (six patients). All procedures were completed endoscopically, and there were no complications reported. At 1-month follow-up, all of the repairs were intact.

Dr. Michael Argenziano recently reported the use of the da Vinci robotic surgical system to close an ASD in a 33-year-old woman.[46] This procedure was performed on cardiopulmonary bypass using four thoracic ports. Cross-clamp time was 43 min. The patient was ambulatory within 15 h and was discharged on day 3. At 30-day follow-up, the patient was doing well.

Future Directions

Although there has been tremendous progress in the development of robotically assisted cardiac surgery over the last several years, there are still many challenges that must be overcome in order to widen the applicability of these techniques in the clinical arena. At present, these operations are often lengthy, technically difficult, and applicable to only carefully selected patients. However, as was seen after the introduction of laparoscopy in general surgery, the accumulation of surgical experience with this sophisticated instrumentation will, over time, improve operative choreography and shorten operative times. The development of parallel technologies to facilitate these procedures also will likely result in significant advances in the field.

One of the most significant challenges that face surgeons embarking on endoscopic procedures is the determination of optimal port placement. Both surgical experience and the use of computer guidance should facilitate this in the future. By using computerized tomography and magnetic resonance imaging, preliminary efforts toward the development of a three-dimensional virtual cardiac surgical planning platform have been initiated for use with totally endoscopic cardiac surgery.[47] Improved instrumentation will also aid the development of this field. Smaller and more precise instruments, perhaps with more flexibility in the shaft, may also simplify port placement in the future.

The real significance of robotically assisted cardiac surgery lies in the resultant integration of computers into the operating theater. Primarily, three areas will be impacted: surgeon control, intraoperative imaging, and information access. Future improvements in the digital–manual interface will continue to enhance a surgeon's technical ability with these systems. Endoscopic procedures will become more feasible as computers become more powerful, smaller, and less expensive. Continued technologic advancements in robotic systems should bring us closer to a more ideal surgical system over the next several years. This ideal system would include fully replicated master kinematics, a full range of end effectors, effective and simple site delivery, tactile feedback, superb three-dimensional optics, and data fusion capability to allow for computer- and image-guided surgery.

With further enhancements, simple surgical maneuvers may be able to be programmed in order to assist in suturing and in the performance of an anastomosis. Systems may eventually "learn" surgical techniques through the use of neural networks. This will allow present procedures to be performed less invasively, as well as enable surgeons to perform an ever-expanding repertoire of procedures previously thought impossible because of the inherent physical shortcomings of human beings.

Computer technology will also revolutionize intraoperative imaging. Undoubtedly, the future will see the introduction of image-guided cardiac surgery. Surgeons will be able to manipulate images intraoperatively and view digital echocardiograms, angiograms, and computed tomography and magnetic resonance imaging scans directly on the video monitor. Furthermore, these images could be superimposed on the operative field. Fusion of these images with endoscopic pictures will allow surgeons to precisely define the cardiac anatomy without direct visualization. Further manipulation of the digital visual interface may also make it possible to work on the beating heart in "virtual stillness." The movement of the robotic camera and instruments could be synchronized with each heartbeat, effectively canceling cardiac motion and increasing surgical precision.

Finally, there will be continued advances in information access. In the operating room, networked video monitors will provide access to the hospital information system and ancillary services. In addition, this system could be linked to local area networks, the global Internet, and the hospital library. This technology will allow surgeons to share their acumen with their colleagues around the globe via high-speed video links.

As cardiac surgeons, our challenge will be to not let ourselves be defined by the size of our incisions. We must become cardiac interventionists, performing percutaneous interventions on various intrathoracic structures. Our understanding of the anatomy of the chest and our training make us ideally suited to perform these procedures and handle the potential complications. The dawn of the era of computer-assisted surgery has commenced and promises to bring dramatic advances in our capabilities as cardiac surgeons in the treatment of all forms of cardiac pathology. The continued advance of robotic and computer technology has the potential to transform both the operating rooms and our specialty as we enter the new millennium. Computers and robots have allowed human beings to explore the reaches of the universe and the depths of the oceans. They have allowed us to delve into our past and see our future. Hopefully, with continued clinical research and developing technology, they will aid cardiac surgeons in performing our complex procedures with progressively less invasiveness and morbidity, adding yet another facet to their improvement of the human condition.

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