The Janus syndrome: A perspective on a new era of computer-enhanced robotic cardiac surgery

W. Douglas Boyd
Kenneth D. Stahl

See related editorial on page 623.

It is what we know that makes what we don't know so much harder to learn.

—Dr. Christopher Kraft, Mission Control Director,
NASA Manned Flight Program

Since the time of Joseph Lister, more than 150 years ago, the core task of “surgery” (that is, “cutting and sewing”) with hand instruments and direct visualization of and contact with the organ or tissue has remained the same. During the last quarter of the 20th century, however, and especially during the last decade, there has been a paradigm shift in the methods by which surgery is performed. The “invasiveness” of many procedures has been dramatically reduced and the outcomes significantly improved, as evidenced by improved survival, fewer complications, and quicker return to functional health and productive life. This focus on less or “minimal” invasiveness has gained momentum and has been the subject of intense investigation in the past few years. It is an established fact that catheter-based intervention has long surpassed coronary artery bypass grafting (CABG) as the cornerstone of treatment of coronary artery disease, and although surgical interventions continue to decline, there has been no apparent reversal of this trend. Despite the fact that rates of angina recurrence and need for reintervention is significantly higher after catheter-based interventions as compared with surgery,¹ patients continue to vote with their feet: They consistently choose and will continue to choose the least invasive option. We are presently at a strategic inflection point in the treatment of coronary artery disease. As described by the founder of Intel Corporation (Santa Clara, Calif), Andy Grove, this is a time in the life of a business or specialty when its fundamentals are about to change.² Our response and adaptability when we hit these points dictate our future; we either rise up and transgress the shackles of established paradigms or fade away into obscurity. These ongoing changes in our clinical practice must be viewed as opportunity. To that end it is necessary for all in our profession to heed the advice of our Association's past presidents and embrace innovation, change, and progress^{3,4} and seek out better surgical treatment options. Such procedures will improve our patients' outcomes by offering the irrefutable benefits of arterial bypass grafting while avoiding the physical and physiologic trauma associated with traditional approaches to CABG. Regarding coronary artery disease, this inevitably means the ability to routinely and consistently perform totally endoscopic surgery with arterial conduits on the beating heart in a cost-effective manner. In the words of Colonel Richard Satava, one of the pioneers of robotic telesurgery, “Our future in surgery lies not in blood and guts, but in bits and bytes!”

At the present time, most surgeons likely consider robotic cardiac surgery to be a flashy, futuristic marketing tool, too expensive and difficult to use and not a technology that truly facilitates surgeon accuracy, patient comfort, and faster recovery by port-access procedures. Do these expensive, high-technology devices really facilitate minimally invasive cardiac surgery? It is now almost 4 years since members of our professional society and the general public met the earliest reports of telerobotic coronary bypass out of Europe with enthusiasm and excitement. The

From the Department of Cardiothoracic Surgery, Cleveland Clinic Florida, Weston, Fla.

Received for publication Oct 9, 2002; accepted for publication Oct 22, 2002.

Address for reprints: W. Douglas Boyd, MD, FRCS(C), Director, Minimally Invasive and Robotic Surgery, Section of Cardiothoracic Surgery, 2950 Cleveland Clinic Blvd, Weston, FL 33331 (E-mail: boydd1@ccf.org).

J Thorac Cardiovasc Surg 2003;126:625-30

Copyright © 2003 by The American Association for Thoracic Surgery

0022-5223/2003 \$30.00 + 0

doi:10.1016/S0022-5223(02)73573-3

media would have us believe that routine port-access coronary bypass was here. Clearly it was not. The reality is that the introduction of any completely new technology into any specialty is always dogged by questions regarding suboptimal early clinical results, inadequate patient safety, and increased procedure costs and efficacy. Robotic heart surgery has not been immune to these circumspect criticisms. Should these concerns halt the progress toward what may be a rebirth for cardiac surgery? Has robotic technology failed to live up to expectation, or is this an expected natural progression to a new future for cardiac surgery? To have proper perspective on this question I will adopt the role of Janus. Janus was the Roman god of beginnings and doorways; he was considered so important to the Romans that his name was assigned to the first month of the Roman calendar. He presided over the so-called solstitial gates, the "gate of men" and the "gate of gods." He is always depicted with two faces gazing in opposite directions, one forward with anticipation toward the future yet at the same time looking backward to the past from the place that brought him to the new beginning. Like Janus, to see more clearly where we are going with robotic technology, we must examine from where we have come, always mindful that our ultimate goal is improved outcomes for our patients.

In the late 1980s, great enthusiasm and momentum was initiated by laparoscopic cholecystectomy. For the first time, it was possible for surgeons neither to look directly at nor touch the tissues or organs that they operated on. Unfortunately, the resounding success of this excisional procedure led to unrealistic expectations of the early conversion of other surgical procedures, including microvascular reconstructive cardiac surgery, to less invasive approaches as well. The adoption of robotics to cardiac surgery was a result of the significant difficulties and obstacles encountered when applying endoscopic techniques to reconstructive microsurgery as is required in CABG.

Endoscopic surgery is technically more difficult in the vast majority of procedures and has ergonomic disadvantages for the surgeon. It is a fact that excisional or ablative procedures are easier to perform than reconstructive microvascular procedures and are more easily adaptable to endoscopic techniques. There are a number of reasons why this is so. When operating endoscopically, lateral movement of the instrument shaft is not possible at the incision, which thus acts as a fulcrum, reversing the directions of the surgeon's hand motions at the instrument tip and varying the mechanical advantage as the instruments move in and out. The video monitor is also most often located on the far side of the patient, and the difference in orientation between the endoscope and the monitor requires the surgeon to perform a difficult mental transformation between visual and motor coordinate frames.⁵ In addition to this, the difficulties of working from a 2-dimensional video image and lack of

direct control of the camera necessary to view the surgical field further contributes to the difficulties in performing microsurgical reconstructive procedures. With traditional endoscopic instruments, motion transmission is dependent on the ratio of internal and external instrument shaft length. This has the effect of exaggerating hand tremor, which may be inconsequential for excisional procedures but is prohibitive when trying to reconstruct a 2-mm coronary artery. At the same time, shear forces on the shaft of the instrument result in higher handle forces, leading to imprecision and muscle fatigue.⁶ Contact force perception is also impaired by friction and varying mechanical advantage at the incision during laparoscopic procedures and distributed tactile information is absent.⁷ When the relative lack of dexterity of conventional endoscopic surgical instruments with only 4° of freedom and cardiac motion is added to these other factors, the performance of a precise endoscopic microvascular anastomosis is virtually beyond the realm of human manual dexterity.⁸ To overcome these limitations, investigators turned to robotics and computer assistance. Robot-assisted coronary surgery is systematically evolving toward a totally endoscopic approach, and new facilitating technologies are continually being refined and adopted.

There are presently four levels of robotic coronary surgery currently being practiced:

1. Robotic camera control and video assistance with manual conduit harvesting: The surgeon harvests the arterial conduit with robotic camera control and performs the anastomosis through a mini-thoracotomy.⁹
2. Telerobotic conduit harvesting and manual anastomosis: The surgeon harvests the internal thoracic artery (ITA) from the master console and performs a manual anastomosis through a mini-thoracotomy.¹⁰
3. Computer-assisted endoscopic coronary anastomosis: The surgeon harvests the ITA manually through a conventional sternotomy and performs the coronary anastomosis on the arrested or the beating heart through a sternotomy or mini-thoracotomy.^{11,12}
4. Totally endoscopic coronary artery bypass (TECAB): Conduit harvesting, preparation, target vessel preparation, control, and anastomosis are all performed by the surgeon remotely from the master console via port-access.¹³⁻¹⁵

Initially approved by the US Food and Drug Administration in 1994, first-generation surgical robots approximate the form and function of a human arm to essentially provide the surgeon with a third arm for increased control and precision during minimally invasive procedures. This first surgical robot approved for clinical use in cardiac surgery in the United States is called AESOP, an acronym for Automated Endoscopic System for Optimal Positioning (Computer Motion, Inc, Goleta, Calif). With AESOP, the thoracoscope can be held in a more stable manner than by any

human and the surgeon is afforded direct “surgeon-brain-camera” positioning control while operating with two hands. The robot is controlled with simple voice commands. By optimizing visualization, decreasing surgeon distraction, and improving surgeon ergonomics during video-assisted cardiac procedures, robotic assistants can decrease surgical error.¹⁵ The use of robots in this manner has facilitated the introduction of video assistance to cardiac surgery. This is a critical and mandatory step in our progression from conventional cardiac surgery toward our ultimate goal of a totally endoscopic procedure.

The major obstacle to the successful completion of a totally endoscopic coronary bypass procedure has traditionally been the performance of the anastomosis. The futility of attempting to perform precise microvascular surgical tasks with traditional endoscopic instruments is equivalent to trying to accurately sign one’s name with an 18-inch pencil while holding it by the eraser! A powerful incentive for the clinical application of telerobotic systems came when laboratory studies unequivocally demonstrated that robotic telemanipulation systems could significantly increase the precision of an endoscopic coronary anastomosis.^{8,16}

With the introduction of computer-enhanced manipulation systems into clinical practice, endoscopic CABG became possible.^{13,14,17,18} The performance of conduit harvesting and/or robotic coronary anastomosis represents a rational and stepwise integration of new robotic and other associated technology into a well-established procedure in a manner that will allow us to formally evaluate and demonstrate clinical efficacy. These approaches will also serve as a skill platform from which surgeons can evolve to a totally closed-chest approach. At present, a totally endoscopic approach to CABG is performed at a limited number of centers in a highly selected subset of patients. Detractors of robotics suggest that robotics add nothing to the endoscopic cardiac procedures and that we would be better off using more conventional and cheaper manual endoscopic instruments. Is this technology really necessary for us to realize our goal of routine closed-chest cardiac procedures?

When compared with conventional nonrobotic stand-and-manipulate endoscopic procedures, the telerobotic surgeons console is an ergonomic control center that allows a more natural viewing angle of the surgical image. This modification restores “visual transparency” (which refers to a correct spatial mapping between what the surgeon sees and does), which results in a more natural correspondence in motions. The systems computer software also enhances the surgeon’s comfort and accuracy by pedal-actuated indexing of the end-effectors. Robotic indexing allows surgeons to maintain a comfortable and ergonomic arm position at the console while performing surgical tasks. While operating from the master console, the surgeon also experiences no discomfort or fatigue caused by instrument torque, a com-

mon occurrence with manual endoscopic procedures. Decreasing muscle fatigue and stress can reduce muscle fasciculations and tremor, increasing surgical accuracy. The computers low-frequency (4 to 6 Hz) motion filters also enhance surgical accuracy by eliminating natural human tremor. The controller software also digitally restores natural hand motions by eliminating the fulcrum effect of reversing instrument direction. Placing a microprocessor between the surgeon’s hand and the tip of the surgical instrument also enhances dexterity. “Motion scaling” in which gross hand movements can be reduced and in which precision and eventually force feedback can be enhanced to allow surgeons to perform tasks not possible without computer enhancement. One such example is retinal vein cannulation with a needle for administration of a local therapy for retinal vein thrombosis; this technique (involving cannulation of a 100- μ structure) would not be possible without the dexterity enhancement of robotic assistance.¹⁹

Dr Mohr’s group in Leipzig and Dr Wimmer-Greinecker’s group in Frankfurt have reported on 26 and 45 patients, respectively, who underwent TECAB.^{14,18} These results and our own experience with beating-heart TECAB²⁰ have demonstrated that a completely endoscopic approach to CABG is possible in carefully selected patients. The bigger question may be whether single-vessel TECAB on the beating or arrested heart has any significant advantage over endoscopic atraumatic coronary artery bypass (ENDO-ACAB).^{20,21} Our own experience suggests that TECAB is technically more difficult and fraught with more potential hazards than ENDO-ACAB. Because of the low cost and excellent outcomes associated with this beating-heart video-assisted procedure, the performance of single-vessel TECAB with robotically sutured anastomosis on the arrested heart may soon be justifiable only as a developmental procedure on the learning curve toward multivessel TECAB. It is also likely that any potential advantages of TECAB may only be realized when concurrent new technologies involving facilitated anastomotic devices, integrated real-time imaging, and guidance control systems are integrated into the procedure.

At the present time there are many limitations to the routine application of robotics to cardiac surgery. The mechanical design of the robotic manipulators must be modified to allow increased dexterity within the constrained working space frequently encountered in closed-chest intrathoracic cardiac procedures. End-effector singularity (or loss of 1° of freedom because of extreme working angles) may also occur with suboptimal port placement that is still very reliant on user experience. In beating-heart TECAB cases where additional technology such as myocardial stabilizers, sternal lifters, transthoracic bulldogs to control the ITA, and assistant tools are needed, extra thoracic working space is limited and manipulator-instrument collisions are difficult to avoid. Intrathoracic working space is a dynamic

parameter that varies with insufflation, ventilation, and myocardial compression with stabilization. Significant potential changes in working space during critical times in closed-chest procedures have also presented serious challenges to patient safety.

Although telerobotic systems have been shown to be enabling in the performance of microsurgical tasks on the still heart,²² their ability to enhance performance in beating heart cases is less clear. The significance of robotic system inertia and hysteresis as a potential source of performance limitation in manual control and tracking during beating-heart surgery has not been well defined. There can be no doubt that even slight increases in refractory times associated with this human-machine interface technology affects prehension and target vessel tracking strategies adopted by experienced beating-heart surgeons, and almost certainly new internal cognitive tracking models have to be developed by telerobotic surgeons.²³

Adequate visualization is another challenge faced by surgeons performing TECAB. Usually because of working space constraints the endoscope is too close to the working field and the resulting field of view is so narrow that the working instruments frequently leave the operating field of view. Bringing the instruments safely back into the working field presently requires reorientation of the scope so that the "lost" instrument may be brought back into the working field under direct vision. When working distance between the endoscope and anastomotic site becomes close, visualization may frequently be impaired by blood spatter from the working site caused by the blower/mister.

The challenges of 3-dimensional heart motion and the necessary design and development of endoscopic stabilizers has been another hurdle faced by TECAB surgeons. Although the current state-of-the-art designs have significantly reduced the complexity, amount, and velocity of target vessel movement and allowed off-pump TECAB to be successfully completed, residual motion is still present. The amplitude of target motion can still exceed 1 mm, especially when mediastinal motion augmented by the effect of single-lung ventilation is considered. Other ongoing challenges with TECAB include effective assistance and finding and preparing the target vessel for anastomosis.

Regarding the design of computer-enhanced robotic systems, there is still considerable room for improvement of kinematic configurations, as well as more compact and efficient actuator and transmission technologies. In terms of sensing and control, robots are controlled by computers and thus share many of their all-too-familiar shortcomings, especially for autonomous operation. Robots follow instructions literally, are unable to integrate diverse sources of information, and cannot use qualitative reasoning or exercise meaningful judgment. Although complex 3-dimensional imaging information can be preprocessed to allow

execution of very precise tasks, robots still have a limited ability to use information from disparate sensors to control behavior during the course of a procedure. Increasing computational power in accordance with Moore's law will certainly improve robot control capabilities, but the resulting complexity will make it increasingly difficult to program and debug these systems.

Much effort is being expended to improve endoscopic coronary bypass surgery. We have learned from our clinical experience to date that to overcome the challenges of closed-chest bypass, an integration of new technologies and procedures with robotics will be necessary. To facilitate a totally endoscopic robotic approach on a beating heart, there is an intense interest in the use of facilitated vascular anastomosis with connectors, coupling devices, glues, and sealants to perform a task now possible only with suturing. At least two of these devices have already successfully been adapted to robotic end-effectors and endoscopically actuated on a beating heart in animal models. New-generation endoscopic cardiac positioning devices and stabilizers have also already been designed and are presently undergoing laboratory testing. Virtual immobilization or motion stillness should eventually allow beating heart surgery under the illusion of stillness by "gating" or timing the instrumentation and scope with the heartbeat. New robotic systems will rely heavily on digital integration and image-guided control algorithms. New-generation robots will be revolutionary devices that use micro-electro-mechanical systems (MEMS) technology. MEMS is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the use of micro-fabrication technology. MEMS is truly an enabling technology allowing the development of smart products by augmenting the computational ability of microelectronics with the perception and control capabilities of micro-sensors and micro-actuators. If there is any doubt about the potential impact of this new technology, a review of its pedigree reveals that its origin was the Defense Advanced Research Projects Agency (the same organization that brought us the Internet). Microelectronic integrated circuits can be thought of as the "brains" of systems, and MEMS augments this decision-making capability with "eyes" and "arms" to allow microsystems to sense and control the environment.

The past 4 years of robotic application to cardiac surgery has taught us at least one thing for certain: Robots are not optimally used as high-technology sewing machines. This is a simplistic and inappropriate use of this technology. It seems more likely that robots will serve more effectively to efficiently and precisely manipulate and deliver task-specific technologies, such as Harmonic Scalpels (Ethicon Endo-Surgery, Inc, Cincinnati, Ohio) to harvest internal thoracic arteries, specialized arteriotomy tools, and anastomotic devices.

Our group has already been investigating the use of intelligent robotic systems that allow remote operation with supervised autonomy. Future refinements in robotic control algorithms and kinematics in combination with the integration of new effector and sensor technology will certainly have a revolutionary impact on our specialty, resulting in significant augmentation of our surgical capabilities while markedly reducing the morbidity of coronary bypass procedures.

In the future, we must also be ready to adapt what is best from other fields. The introduction of drug-eluting stents will surely have a significant impact on “best revascularization” strategies. In the future it is likely that optimal revascularization strategies for patients will involve a combination of facilitated endoscopic robot-assisted arterial grafting and catheter-based interventions²⁴ in addition to the real-time, image-guided application of transmyocardial laser therapy, angiogenic factors, or stem cells to nonrevascularizable areas of the myocardium. To efficiently accommodate this approach, new operating rooms have to be designed to allow the integration of space-consuming robotic systems and imaging and guidance systems as part of a complete hybrid operating room.

Training and Simulation

Robots are also finding applications in surgical training and simulation, where they provide force feedback from computer models of instrument–tissue interaction. In these systems, users manipulate surgical instrument handles that are attached to specialized robot manipulators. A computer senses the user-generated motions and commands the robot to apply the forces that would have resulted from the instrument’s interaction with real tissue. The computer also generates images of the simulated surgical site. These systems are similar to telesurgical systems where the user interacts with the master manipulator, but here a computer model replaces the actual surgical robot and patient. Systems have been developed for many procedures, including arthroscopic knee surgery,²⁵ tubal anastomosis, and laparoscopic surgery.²⁶ These virtual environment systems offer a number of potential advantages. Compared with cadaver and animal training, costs may be reduced, and compared with conventional patient-based surgical training, there are fewer time and performance constraints. Because these systems measure all of the actions during each procedure, trainees can review their data to analyze technique, and trainers can evaluate progress and skill level. Finally, surgeons can explore new and enhanced surgical techniques, and by incorporating preoperative image data, can rehearse patient-specific procedures.

Telecommunication technologies applied to robotics in cardiac surgery will also help transfer surgical expertise among surgeons and centers and will facilitate information

transfer and accelerate the diffusion of new surgical techniques among leading centers. The addition of telecommunication technology assistance will permit both consulting and manipulation from a remote distance. Recently, Marescaux and associates²⁷ reported the world’s first transatlantic remote telesurgery when surgeons in New York successfully removed the gallbladder of a woman in Paris using a prototype tele-ZEUS System (Computer Motion, Inc). New-generation robots with telecollaboration capability are emerging and remote endosurgical telementoring is emerging as a new link between institutions worldwide.

Future refinements in these technologies will certainly have a revolutionary impact on our specialty, resulting in significant augmentation of our surgical capabilities while markedly reducing the morbidity of coronary revascularization procedures. Further refinement of robotic systems is essential before they can routinely be applied to the treatment of multivessel coronary disease.

A Practical Interim Robotic Approach: ENDO-ACAB

Although robot-assisted totally endoscopic coronary artery bypass using facilitated anastomotic devices is still in development, a practical, less invasive surgical strategy that can start surgeons on a trek to totally endoscopic surgery is already being applied.²⁰ The procedure addresses the technical educational needs of cardiac surgeons and provides a logical stepping-stone to newer, more complex revascularization methods. ENDO-ACAB involves the following steps:

1. Endoscopic ITA harvesting with robotic assistance
2. Endoscopic control of the ITA proximally with application of a transthoracic bulldog under direct vision, and distally with endoscopic skeletonization, clipping and division
3. Endoscopic removal of the pericardial fat pad, localization of the LAD, and determination of anatomic suitability for a minimal access, beating-heart surgical approach
4. Muscle-sparing incision of the pectoralis muscle (no cutting, splitting in direction of fibers)
5. Use of a Heartport (Heartport, Inc, Redwood City, Calif) soft-tissue retractor to prevent rib spreading and trauma
6. Use of the camera ports as access for endostabilizer and transthoracic bulldog
7. Manual, off-pump coronary anastomosis through the thoracic working port

Although it is evident that a new era in cardiac surgery is evolving, it is also apparent that a significant technology gap still exists before TECAB will become routine. The recent introduction of magnetic anastomotic coupling devices, new endostabilizers, and future integration of real-time intraoperative imaging systems will undoubtedly take us closer to

our goal. Although early results are encouraging¹⁷ and new technologies are evolving, understanding and learning how to use these technologies economically and responsibly will be one of our toughest challenges for the new millennium.

The field of telerobotic cardiac surgery is still only 4 years old and today's difficulties surely will give way to tomorrow's success. It was more than 50 years after Robert Goddard first launched a liquid fuel rocket in the fields of Massachusetts that man eventually landed successfully on the moon. We must heed the advice of our leaders^{3,4} and not shun innovative revascularization strategies, but rather embrace and pursue them. Let us not close our eyes and shut out these new technologies, but instead find out for ourselves how we can turn this new era into the opportunity with which Dr Cosgrove⁴ has challenged us. If we accept this opportunity, it can lead us to greater levels of surgical skills and knowledge and will offer our patients lifelong cures with minimal surgical trauma. Now that we have come to the "end of the beginning era of cardiac surgery,"²⁸ we must accept that the world in which we practice cardiothoracic surgery has changed and accept that our specialty will need to change to keep abreast. Dr Goddard himself said, "It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow." Janus would agree.

References

- Diegler A, Thiele H, Falk V, et al. Comparison of stenting with minimally invasive bypass surgery for stenosis of the left anterior descending coronary artery. *N Engl J Med*. 2002;347:561-6.
- Grove AS. Only the paranoid survive. New York: Doubleday; 1996. p. 210.
- Cohn LH. What the cardiothoracic surgeon of the twenty-first century ought to be. *J Thorac Cardiovasc Surg*. 1999;118:581-7.
- Cosgrove DM. The innovation imperative. *J Thorac Cardiovasc Surg*. 2000;120:839-42.
- Tendick F, Jennings RW, Tharp G, Stark L. Sensing and manipulation problems in endoscopic surgery: experiment, analysis, and observation. *Presence*. 1993;2:66-81.
- Macedo JA, Kaber DB, Endsley MR, et al. The effect of automated compensation for incongruent axes on teleoperator performance. *Hum Factors*. 1998;40:541-53.
- Hutchinson S, Hager GD, Corke PI. A tutorial on visual servo control. *IEEE Trans Robotics Automation*. 1996;12:651-70.
- Boyd WD, Desai ND, Kiaii B, et al. A comparison of robot-assisted versus manually constructed endoscopic coronary anastomosis. *Ann Thorac Surg*. 2000;70:839-43.
- Boyd WD, Kiaii B, Novick RJ, et al. RAVECAB: improving outcome in off-pump/minimal access surgery with robotic assistance and video enhancement. *Can J Surg*. 2001;44:45-50.
- Kiaii B, Boyd WD, Rayman R, et al. Robot-assisted computer enhanced closed-chest coronary surgery: preliminary experience using a Harmonic Scalpel and ZEUS. *Heart Surg Forum*. 2000;3:194-7.
- Reichenspurner H, Damiano RJ, Mack M, et al. Experimental and first clinical use of the voice-controlled and computer-assisted surgical system ZEUS for endoscopic coronary artery bypass grafting. *J Thorac Cardiovasc Surg*. 1999;118:1-16.
- Damiano RJ, Tabai HA, Mack MJ, et al. Initial prospective multicenter clinical trial of robotically-assisted coronary artery bypass grafting. *Ann Thorac Surg*. 2001;72:1263-9.
- Loulmet D, Carpentier A, d'Attellis N, et al. Endoscopic coronary artery bypass grafting with the aid of robotic assisted instruments. *J Thorac Cardiovasc Surg*. 1999;118:4-10.
- Mohr FW, Falk V, Diegeler A, et al. Computer-enhanced robotic cardiac surgery: experience in 148 patients. *J Thorac Cardiovasc Surg*. 2001;121:842-53.
- Carthey J, de Leval MR, Reason JT. The human factor in cardiac surgery: errors and misses in a high technology domain. *Ann Thorac Surg*. 2001;72:300-5.
- Stephenson ER, Ducko CT, Sankholkar S, et al. Computer-assisted endoscopic coronary artery bypass anastomosis: a chronic animal study. *Ann Thorac Surg*. 1999;68:838-43.
- Boyd WD, Rayman R, Desai ND, et al. Closed-chest coronary artery bypass grafting on the beating heart using a computer-enhanced surgical robotic system. *J Thorac Cardiovasc Surg*. 2000;120:807-9.
- Dogan S, Aybek T, Andreben E, et al. Totally endoscopic coronary artery bypass grafting on cardiopulmonary bypass with robotically enhanced telemanipulation: report of forty-five cases. *J Thorac Cardiovasc Surg*. 2002;123:1125-31.
- Riviere CN, Jensen PS. A study of instrument motion in retinal microsurgery. Abstract presented at 21st Annual Conference of IEEE Eng Med Biol Soc, June 26, 2000, Chicago Ill.
- Boyd WD, Kadera K, Stahl KD, et al. Current status and future directions in computer-assisted video-and robotic-assisted coronary bypass surgery. *Semin Thorac Cardiovasc Surg*. 2002;14:101-9.
- Vassiliades TA. Atraumatic coronary artery bypass (ACAB): techniques and outcome. *Heart Surg Forum*. 2001;4:331-4.
- Taylor RH, Jensen M, Whitcomb L, et al. A steady-hand robotic system for microsurgical augmentation. *Rob Res*. 1999;12:1201-10.
- Falk V. Manual control and tracking—a human factor analysis relevant for beating heart surgery. *Ann Thorac Surg*. 2002;74:624-8.
- Stahl KD, Boyd WD, Vassiliades TA, et al. Hybrid robotic coronary artery surgery and angioplasty in multivessel coronary artery disease. *Ann Thorac Surg*. 2002;74:1358-62.
- Gibson S, Samosky J, Mor A, et al. Simulating arthroscopic knee surgery using volumetric object representations, real-time volume rendering and haptic feedback. In: Troccaz J, Grimson E, Mosges R, editors. CVR Med-Mrcas 1997: First Joint Conference on Computer Vision, Virtual Reality and Robotics in Medicine, Medical Robotics and Computer-Assisted Surgery, Grenoble, France, Proceedings. 1977 March; New York: Springer Verlag; 1997. Vol 120, p. 369-78.
- Cotin S, Delingette H, Clement JM, et al. Volumetric deformable models for simulation of laparoscopic surgery. In: Lemke HU, Vannier MW, Inamura K, Farman AG, editors. Computer-assisted radiology. Proceedings of the International Symposium on Computer and Communications Systems for Image Guided Diagnosis and Therapy. International Congress Series. 1996 June; Amsterdam: Elsevier; 1996. Vol 1124, p. 793.
- Marescaux J, Leroy J, Gagner M, et al. Transatlantic robot-assisted telesurgery. *Nature*. 2001;27:379-80.
- Loop FD. The first living and the last dying. *J Thorac Cardiovasc Surg*. 1998;116:683-8.