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Robotically-Assisted Coronary Artery Bypass Surgery: Moving Toward a Completely Endoscopic Procedure

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ABSTRACT

Background : Endoscopic coronary artery bypass grafting (ECABG) has not been possible with traditional techniques. This report details our animal experience determining the feasibility of using a robotically-assisted microsurgical system to perform ECABG.

Methods: Following preliminary work using a cadaveric pig heart model, acute and chronic animal studies were performed. Calves were placed on cardiopulmonary bypass after the left internal mammary artery (LIMA) was harvested. Subxiphoid endoscopic ports (2 instrument, 1 camera) were placed and a robotic system was used to perform ECABG between the LIMA and left anterior descending coronary artery. LIMA graft flow ($LIMA_Q$) was measured, and excised hearts underwent angiographic and histologic analyses.

Results: All anastomoses were successfully completed in both the acute and chronic studies (mean time of 33.9 ± 1.9 and 33.2 ± 3.4 minutes, respectively). Angiographic patency was 100% in both the acute (8/8) and chronic (6/6) studies, which was confirmed by histology. In the chronic study, there was no difference in $LIMA_Q$ between intraoperative and autopsy measurements.

Conclusions: This study shows that ECABG is feasible in an animal model with excellent results. The FDA has recently given approval for clinical trials of this new technology.

INTRODUCTION

The introduction and widespread acceptance of minimally invasive techniques have revolutionized surgical practice in many disciplines over the last two decades. Endoscopic operations have been shown to reduce patient morbidity and provide a more rapid return to work. Until recently, these new endoscopic approaches have had little impact on the field of cardiac surgery. However, over the past few years, minimally invasive direct coronary artery bypass (MID-CAB) procedures have been introduced and are rapidly gaining acceptance [Shennib 1997]. The MID-CAB procedure typically is done on the beating heart through a small incision (left thoracotomy or partial sternotomy) without cardiopulmonary bypass. With improved techniques and instrumentation, results have been favorable [Benetti 1991, Buffolo 1996, Calafiore 1996, Izzat 1997, Jansen 1997]. However, several shortcomings have become apparent. Access to target vessels is limited and performance of the anastomosis is somewhat more technically challenging. Despite respectable patency rates, it has been suggested that the anastomoses may be less precise as a result of cardiac motion and limited visualization [Pagni 1997]. This has led many surgeons to return to the median sternotomy incision for beating heart surgery.

Port-access cardiac surgery was introduced to overcome some of these shortcomings [Stevens 1996a, Stevens 1996b, Fann 1997a]. Using specialized instruments and percutaneous cardiopulmonary bypass, port-access surgery provides improved exposure of target vessels in a quiescent operative field and thereby allows for multiple vessel bypass grafting [Fann 1997b, Schwartz 1997]. However, this approach still requires an incision. At the present time, endoscopically-sutured anastomoses have not been possible with either approach. The length and imprecision of standard endoscopic instruments have contributed to this failure [Mack 1997].

Recently, surgical robotic systems have been developed to assist in endoscopic suturing [Garcia-Ruiz 1997, Shennib 1998]. These systems consist of three main components: a surgeon interface device, a computer controller, and specially-designed instruments attached to robotic arms. The surgeon manipulates traditional surgical instrument handles

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at the interface device. His movements are relayed in real-time by a computer to robotic arms which are attached to the operating room table. These robotic arms hold specially designed endoscopic instruments which are placed through small ports. By the use of computer elimination of tremor and motion-scaling, robotics provide the precision necessary to perform endoscopic coronary anastomoses. These robotic devices have been demonstrated to enhance surgical dexterity during a microvascular anastomosis in *in vitro* models [Garcia-Ruiz 1997, Stephenson 1998a]. Our laboratory recently completed a series of investigations designed to test the feasibility and efficacy of using a robotically-assisted microsurgical system to perform completely endoscopic coronary anastomoses. Preliminary work was done using a cadaveric model, and then acute and chronic *in vivo* studies were undertaken. This manuscript serves as a review of the Penn State experience.

MATERIALS AND METHODS

Yorkshire/Landrace crossbred swine of either sex, weighing 40–50 kg, were used for the initial cadaveric study. In the acute and chronic *in vivo* studies, male Holstein calves weighing 70–100 kg were used. All animals received humane care in AAALAC, USDA registered (#23-R-02) facilities in compliance with the "Principles of Laboratory Animal Care" formulated by the National Society for Medical Research and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources and published by the National Institutes of Health (NIH Publication No. 85-23, revised 1985).

Experimental Preparation for the Cadaveric Study

Preparation of the animal: Swine were anesthetized with an intramuscular injection of tiletamine and zolazepam (2.5 mg/kg), followed by an intravenous injection of sodium pentobarbital (15 mg/kg). A tracheostomy was performed and the animals were placed on mechanical ventilation. Hearts were then rapidly excised through a right thoracotomy, as the animals were euthanized with a 20-cc intravenous injection of concentrated pentobarbital. The intact hearts and great vessels were placed in normal saline solution and transported to the laboratory.

Conduit har vesting: The right coronary artery was chosen as the conduit. Extraneous tissue surrounding the great vessels was excised and an appropriate place for the anastomosis on the left anterior descending coronary artery (LAD) was located. The right coronary artery was identified at its origin and completely dissected free from surrounding tissue for a length of 6–7 cm.

Preparation of the thoracic simulator: Hearts were placed in a custom-made holder, which reproduced the anatomic orientation of the *in vivo* human heart (see Figure 1 ◎). The thoracic trainer consisted of a reproduction of the human rib cage surrounded by a layer of 2-cm thick neoprene. This was used to simulate the musculature and soft tissues of the human thorax. The thoracic

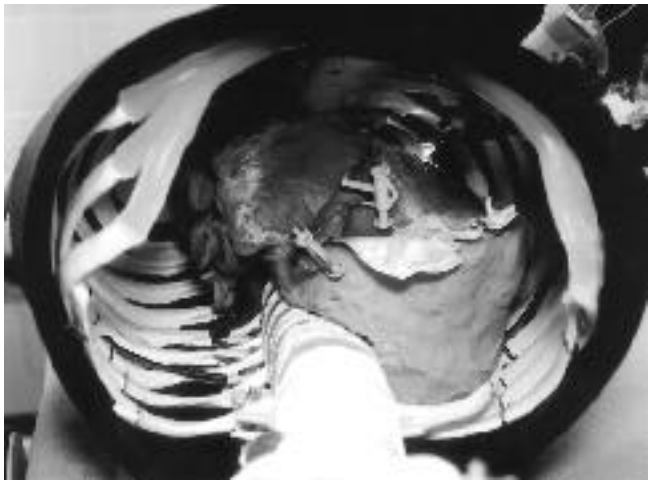

Figure 1.Cadaveric heart placed on holder inside the thoracic trainer. Modified endoscopic instruments and an endoscope have been placed through the thoracic ports.

trainer was secured on a standard operating table. A 10-mm endoscopic port (Endopath, Ethicon, Somerville, NJ) was placed in the fifth intercostal space along the anterior axillary line. Two 5-mm endoscopic ports (Endopath, Ethicon) were then placed in the fourth and sixth intercostal spaces in the mid-axillary line. A 0° endoscope (Karl Storz, Culver City, CA) was placed through the 10-mm port and attached to a video camera (Tricam SL, Karl Storz) and light source (Zenon 300, Karl Storz).The video image was displayed on a 21-inch color monitor (Trinitron, Sony Corp., Tokyo, Japan). After image adjustment, the endoscope was connected to a voice-controlled robotic camera arm (AESOP 2000, Computer Motion, Inc., Goleta, CA), which had been attached to the operating table. The robotic camera provided a steady video image and allowed for smooth, precise camera movements.

The Zeus Robotic Microsurgical System (Computer Motion, Inc.) was then attached to the operating table. This system consists of two robotic arms that are used to manipulate modified endoscopic instruments (Deknatel/Snowden Pencer, Genzyme Corp., Tucker, GA and Karl Storz). The surgeon controlled the instruments by manipulating specially designed handles at the surgeon console. These surgical controls allowed for four full ranges of motion (pan, roll, tilt, and in/out) as well as grasping (with various jaw opening widths). The surgeon's motions were directly and precisely translated from the console to the robotic arms by a computer interface. Critical to this interface was the instrument positioner controllers, which form the link between the surgeon at the console and the instruments at the table. These controllers analyzed the input data measured at the surgeon console as the surgeon moved the handles, and then directed the robotic arm instrument positioners to move appropriately, so that the movement of the instrument tips corresponded to the surgeon's directions given at the console.Custom-

designed software allowed for tremor elimination as well as motion scaling on a range from 2:1 to 10:1.

Endoscopic anastomosis: With adequate visualization, the appropriate anastomotic site on the LAD was identified and a small arteriotomy was made using modified endoscopic scissors. Each arteriotomy was extended to a length of approximately 2.5 mm. A fine hemostat was then passed into the chest through a separate stab incision, and used to gently grasp the adventitia of the arterial conduit (dissected right coronary artery). The conduit was positioned accordingly for the anastomosis. A 7-0 Prolene (Ethicon) suture 7 cm in length was used to make the anastomosis, which was performed in a continuous fashion.

The anastomosis was begun at the 12 o'clock position on the LAD and continued counter-clockwise, with the conduit suspended slightly above the anastomotic site. After completion of the back row of sutures, the conduit was gently pulled down to the LAD and the sutures tightened. The remaining front row of sutures was then placed. An intracorporeal instrument tie was completed and the anastomosis was visually inspected. Time to completion of the anastomosis (including knot tying) was recorded.

Data Acquisition for the Cadaveric Study

Following completion of the anastomoses, hearts were removed from the thoracic trainer and the anastomoses checked for patency. This was done by passing a 1 or 2 mm probe through the arterial conduit and into the LAD. The anastomoses were then transected and visually inspected.

Experimental Preparation for the In Vivo Studies

Preparation of the animal: Calves were weighed and taken to the preoperative preparation room. Anesthesia was induced with 8 mg/kg of intravenous methahexital. The calves were intubated and begun on mechanical ventilation. Isoflurane anesthesia was initiated at a rate of 2.5% and adjusted as needed. Two 14-gauge catheters (Angiocath, Becton Dickson Infusion Therapy Systems, Inc., Sandy UT) were placed in the external jugular vein for administration of intravenous fluid. The calves were then placed on the operating table in a supine position. For the chronic studies, all animals and instrumentation were handled using routine sterile technique.

An esophageal temperature monitor was inserted (Model BAT 8, Bailey Instruments, Saddle Brook, NJ) and a superficial branch of the right femoral artery was cannulated with a 20-gauge catheter connected to a pressure transducer (Model 041-500-503A, Maxxim Medical, Athens, TX). The blood pressure and the electrocardiogram (recorded from limb leads) were continuously displayed (Sirecust 404, Siemens Medical Systems, Inc., Danvers, MA). Following an intravenous bolus (80 mg), a continuous infusion (80 mg/hr) of lidocaine was started for dysrhythmia prophylaxis. The animals in the chronic study were given an intravenous injection of methylprednisolone (1 g). A longitudinal incision was made in the right neck (left neck for the acute study) and the carotid artery isolated in preparation for arterial cannulation for cardiopulmonary bypass.

Internal mammary artery harvesting in the acute study: A 4-cm left subcostal incision was made, and the subcutaneous tissue and abdominal musculature divided. The animal was systemically heparinized (5000–7500 U) to maintain an activated clotting time of 250–300 seconds (Hemochron 801, Technidyne International Corp., Edison NJ). The distal portion of the left internal mammary artery (LIMA) and vein were identified and ligated. The internal mammary vessels were then dissected free from the surrounding tissue using electrocautery and surgical clips (Ligaclip 20/20, Ethicon) for control of the branch vessels.

Using electrocautery, a small window was created in the diaphragm inferior to the mammary vessels. The distal, transected ends of the vessels were passed into the chest. A 10-mm endoscopic port (Endopath, Ethicon) was placed into the chest through a small incision just to the right of the xiphoid process. A 30° endoscope (Karl Storz) was placed through the 10-mm port and attached to a video camera (Tricam SL, Karl Storz) and light source (Zenon 300, Karl Storz, Culver City CA). The video image was displayed on a 21-inch color monitor (Trinitron, Sony Corp.). A 5-mm grasper (United States Surgical Corp., Norwalk, CT) and endoscopic electrocautery instrument (Surgiwand, United States Surgical Corp.) were placed directly through the subcostal incision for endoscopic dissection of the internal mammary vessels. The musculature overlying the internal mammary vessel was transected using electrocautery and its side branches were controlled with 5-mm endoscopic vascular clips (Endoclip, United States Surgical Corp.). The internal mammary artery was dissected free endoscopically to the level of the first rib.

A right thoracotomy was then performed to facilitate the initiation of cardiopulmonary bypass. During this time, a second dose of heparin was administered to achieve an activated clotting time of greater than 500 seconds prior to cannulation. The right internal mammary artery (RIMA) was exposed at the anterior limit of the thoracotomy for subsequent flow measurements. The distal end of the internal mammary artery was then prepared for anastomosis through the thoracotomy using standard instruments. Free flow in the LIMA was measured and the vessel was occluded with an atraumatic vascular clamp.

Internal mammary artery harvesting in the chronic study: A right fourth intercostal space thoracotomy was performed. The RIMA was exposed. The pericardium was dissected free from the sternum and the mediastinal pleurae opened to expose the LIMA. The left internal mammary vessels were dissected from the first intercostal space to the level of the diaphragm using standard instruments, electrocautery and ligature clips (Ligaclip 20/20, Ethicon). The animal was systemically heparinized (300 U/kg) and additional boluses were given as needed to maintain an activated clotting time of greater than 500 seconds. The distal internal mammary vessels were then ligated and divided. Free flow in the LIMA was measured and the vessel was occluded with an atraumatic vascular clamp. The

distal end of the artery was prepared for anastomosis using standard coronary instruments.

Cardiopulmonar y bypass: A conventional perfusion circuit was assembled (Pump Model 5000, Sarns3M, Ann Arbor, MI) and flushed with carbon dioxide. The bypass circuit was primed with 2 liters of Plasma-Lyte (Baxter Healthcare Corp., Deerfield, IL), 50 mEq sodium bicarbonate, 25 mg mannitol and 10,000 U of heparin. Arterial blood gases, electrolytes and serum hematocrits were measured prior to initiating cardiopulmonary bypass and at regular intervals thereafter. These values were maintained within the physiological range throughout the study.

The right carotid artery (left carotid for the acute study) was cannulated with a metal tip cannula (6.4 mm I.D.) for arterial inflow. A pericardiotomy was performed endoscopically (acute series) or in conventional fashion (chronic series), and a two-stage (34/48 Fr) venous cannula (Medtronic DLP, Grand Rapids, MI) was inserted into the right atrium. Cardiopulmonary bypass was instituted at a perfusion flow rate of 2.0–2.4 L/min/m^2. Mean arterial blood pressure was maintained between 60 and 80 mmHg with the administration of phenylephrine and fluids as needed.

After the initiation of bypass, the hemiazygos vein was ligated within the pericardium. A 16 Fr vent (Medtronic DLP) was placed into the apex of the left ventricle. The ascending aorta was encircled with an umbilical tape. A cannula (Model 24009, Medtronic DLP) was inserted into the proximal ascending aorta for cardioplegia delivery.

Preparation of the robotic system: A 10-mm endoscopic port (Endopath, Ethicon) was placed just to the right of the xiphoid process and passed into the chest. A 0° endoscope (Karl Storz) was placed through this port and attached to a video camera (Tricam SL, Karl Storz) and light source (Zenon 300, Karl Storz). The video image was displayed on a 21-inch color monitor (Trinitron, Sony Corp.). The endoscope was connected to a voice-controlled robotic camera holder (AESOP 3000, Computer Motion, Inc.). Two 5-mm endoscopic ports (Endopath, Ethicon) were then placed subcostally, 7 cm on either side of the endoscope port (see Figure 2). A schematic of the operating room setup is shown in Figure 3 ().

Cardioplegic arr est: The calves were systemically cooled to 30–32°C. Myocardial temperature was monitored in the ventricular septum with a needle probe (Model TM147T, Electromedics, Inc., Parker, CO). The aorta was cross-clamped and cold crystalloid cardioplegia was delivered in antegrade fashion at a pressure of 60–90 mmHg. The composition of the cardioplegia used for induction was (in mEq/L): Na^+, 130; K^+, 40; Cl^-, 109; Ca^{++}, 2.7; lac-

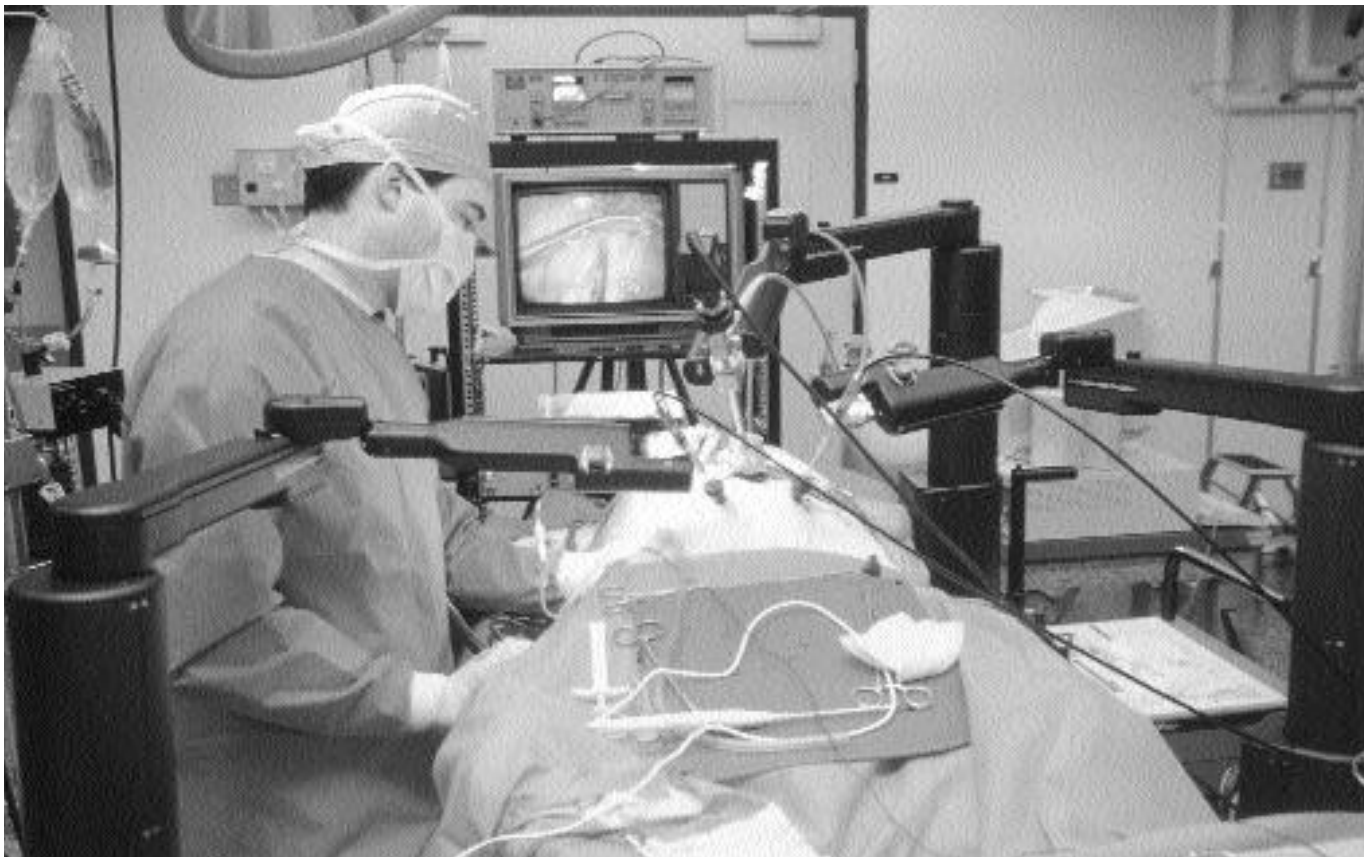

Figure 2. Intraoperative photograph demonstrating the positions for subxiphoid port placement.

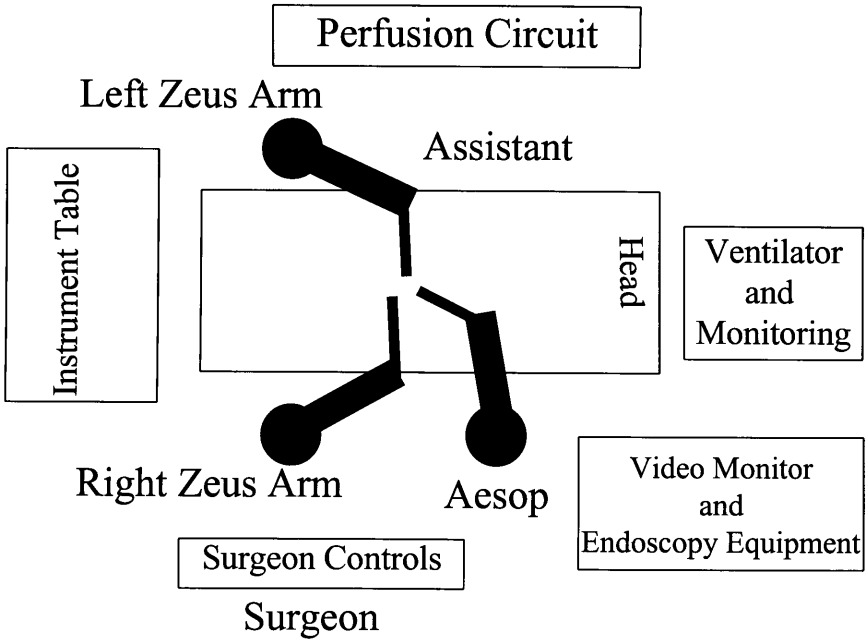

Figure 3. Schematic of the operating room setup, including the position of the robotic arms and surgeon console.

tate, 28; and $NaHCO_3$, 10. Maintenance cardioplegia was similar in composition with the exception of a lower K^+ concentration, 20 mEq/L. Cardioplegia (10 ml/kg) was administered every 20 to 30 minutes during the cross-clamp period. Systemic rewarming was initiated at the completion of the anastomosis.

Endoscopic anastomosis: Following cardioplegic arrest, an arteriotomy was made in the distal LAD. The proximal LAD was occluded with a MyOcclude clamp (United States Surgical Corp.). A continuous, end-to-side anastomosis was performed endoscopically using the robotic instruments and camera (see Movie). Exposure of the anastomotic site was enhanced with the use of a blower (Visuflo SSVW-002, Research Medical, Inc., Midvale, UT). The anastomosis was performed with a specially-designed 7-cm, double-armed 7-0 Gore-tex suture (W.L. Gore & Associates, Flagstaff, AZ). After completion of the anastomosis, the suture was tied endoscopically.

Reperfusion: Once the anastomosis was complete, the clamps on the proximal LIMA and the aorta were removed. Defibrillation was performed as needed (Model 78627A, Hewlett-Packard Co., Waltham, MA) and the animals were weaned from cardiopulmonary bypass. Following data acquisition, animals in the acute study were euthanized with a 50-cc intravenous injection of concentrated pentobarbital. The heart and a suitable length of the LIMA graft were rapidly excised for pathological fixation.

In the chronic study, animals were decannulated and protamine was administered for heparin reversal. The right chest and neck were closed in anatomic layers with stainless steel wires and sutures. A thoracostomy tube was placed in the dependent portion of the right chest prior to closure.

Postoperative care and termination of animals in the chronic study: The animals spent the first several postoperative days under monitored care. A nitroprusside infusion was used as needed to maintain a mean arterial blood pressure of 80–90 mmHg during the first 24 hours. When appropriate, the arterial catheter, chest tube and intravenous catheters were removed. Following clearance from a veterinarian, the animals were then taken to a barn facility.

At four to six weeks postoperatively, the animals were taken back to the operating room and anesthetized. Arterial blood pressure and the electrocardiogram were monitored and a right thoracotomy was performed. After chronic data acquisition, the animals were euthanized with a 50-cc intravenous injection of concentrated pentobarbital. The heart and the LIMA graft were rapidly excised for pathological fixation.

Data Acquisition for the In Vivo Studies

Graft-flow measurements: Following vessel harvest, free LIMA flow was measured using a timed collection. After the anastomosis was performed, LIMA and RIMA flow rates were assessed acutely, both on cardiopulmonary bypass and 30 minutes after being weaned. Flow measurements were made using a 3- or 4-mm probe (HT311, Transonic Systems, Inc., Ithaca, NY) placed on the proximal LIMA graft and recorded using FlowTrace 32 software (Transonic Systems, Inc.). In the chronic study, prior to termination of the animals, chronic LIMA graft flow was assessed in a similar fashion.

Transesophageal echocardiography in the chr onic study: A single plane, 2-D probe (Model I5100, Acuson

Computed Sonography, Mountain View, CA) was used to obtain transesophageal echocardiography (TEE) images with a 2-chamber view in the long axis (Model 128XP/10, Acuson Computed Sonography). Anterior wall motion and left ventricular ejection fraction were assessed as a measure of ventricular function. Studies were obtained prior to and following cardiopulmonary bypass, and chronically at autopsy.

Angiography: Excised hearts were fixed via the ascending aorta with 10% buffered formalin perfused at 100 mmHg for one hour. The hearts were then studied angiographically before being submitted for histologic analysis. Contrast (MD-76R, Mallinckrodt Medical, Inc., St. Louis, MO) was injected via the LIMA graft as radiographic images were obtained.

Histology: Gross descriptions of the fixed specimens were obtained following dissection and sectioning of the LIMA and LAD anastomosis. Microscopic slides were then made of the LIMA, LAD, anastomosis, left ventricular septum and left ventricular free wall using hematoxylin and eosin staining. Additional slides were obtained using Trichrome, Verhoff's Elastica and Von Kossa stains.

RESULTS

Cadaver Study

Twenty-five anastosmoses were completed using the robotic microsurgical system in the isolated porcine model. The time (mean ± SEM) to anastomosis completion was 31.7 ± 2.0 minutes. Following transection of each anastomosis, visual inspection under laparoscopic magnification (16X) was done to assess suture placement, evidence of trauma and patency. Inspection of the graft and LAD at the anastomotic site revealed good technical accuracy in all cases. Suture placement was precise and there was minimal evidence of trauma to the anastomotic site. Anastomotic probe patency was 100%.

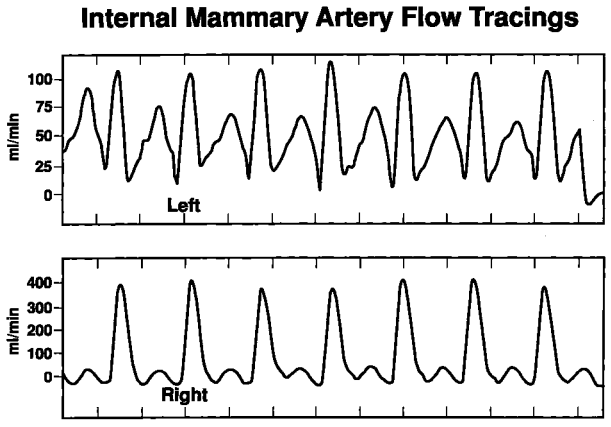

Figure 4. Typical blood flow tracings in the grafted left and *in situ* right internal mammary arteries off cardiopulmonary bypass.

In Vivo Studies

Intraoperative: The eight animals in the acute study group all had coronary grafts completed endoscopically using the robotic microsurgical system. Each animal was weaned from cardiopulmonary bypass without difficulty, with only one animal requiring inotropic support. The total bypass time (mean ± SEM) was 157.6 ± 5.1 minutes, with a cross-clamp time of 52.8 ± 4.1 minutes. The time for completion of the anastomosis (including knot tying) was 33.9 ± 1.9 minutes.

In the chronic study, all nine animals underwent successful coronary grafting and were weaned from bypass without difficulty. The total bypass time was 135.0 ± 7.3 minutes, with a cross-clamp time of 42.1 ± 2.6 minutes. The time for completion of the anastomosis was 33.2 ± 3.4 minutes. Eight animals received temporary support in the form of a low dose dopamine infusion (3–5 mcg/kg/min) during the immediate postoperative period (<2 hours). The graft patency rate, as measured by flow meter, following completion of the anastomosis was 89% (8 of 9). The one animal with poor graft flow was found to have a patent anastomosis, but with inadequate inflow via the LIMA. This was likely a result of vessel injury sustained during mammary harvesting, and this animal was removed from the study.

Postoperative: Two of the 8 animals in the chronic study died suddenly within the first two postoperative days (at 2 hours, and at 2 days). Neither animal had any sign of hemorrhage or graft occlusion at autopsy. In both animals, grafts were found to be patent by angiography. The cause of death remains speculative, but may have been an arrhythmia. The rest of the animals (n=6) recovered without complication and underwent autopsy at 31 ± 2 days postoperatively.

Coronary bypass graft flow: In the acute study, blood flow (mean ± SEM) in the *in situ* RIMA was 50.6 ± 8.7 ml/min while on bypass and 70.8 ± 10.7 ml/min off bypass. Graft flow (measured in the proximal LIMA) was 32.9 + 7.0 ml/min on bypass and 74.8 ± 10.2 ml/min off bypass.

For the chronic study, blood flow in the *in situ* RIMA was 47.0 ± 6.7 ml/min while on bypass and 82.5 ± 15.6 ml/min off bypass. Graft flow was 21.1 ± 5.9 ml/min on bypass and 40.9 ± 4.7 ml/min off bypass. Chronic graft patency as measured by flow meter was 100% (6 of 6), with a graft flow at autopsy of 38.5 ± 5.0 ml/min. Flow tracings from all grafts showed good diastolic augmentation (see Figure 4).

Angiography: The specimens were fixed and studied with contrast injected via the proximal LIMA graft. All specimens (n=7) studied from the acute group showed patent anastomoses, without stenosis or leakage. In the chronic group, patency rate was also 100% (6 of 6). A representative radiograph is shown in Figure 5 ().

Histology: Gross pathology revealed routine post-surgical changes without evidence of significant abnormality. Dissection of the LAD and LIMA grafts indicated patent grafts with no thrombus formation. This was confirmed by microscopic analysis, where all grafts were patent and free of thrombi.

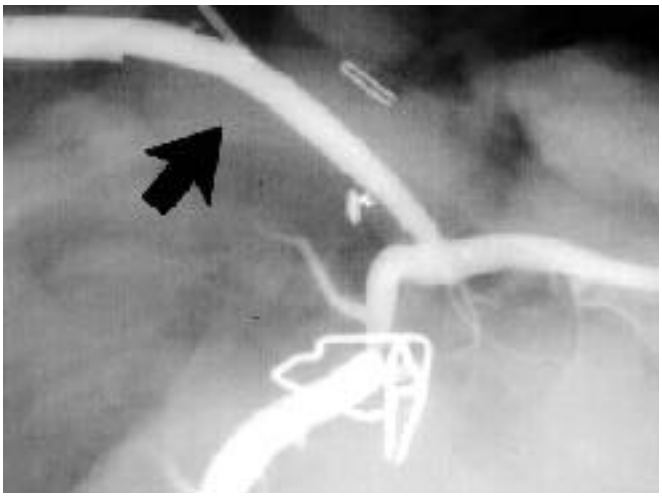

Figure 5. Postmortem angiogram demonstrating the anastomosis between the left internal mammary artery (arrow) grafted to the left anterior descending coronary artery. Contrast was injected through the proximal left internal mammary artery. A MyOcclude clamp is on the proximal left anterior descending coronary artery.

Echocar diography in the chronic study: The only postoperative regional wall motion abnormality evident in any animal was graded as slight anterior hypokinesia in one calf in the immediate postoperative period. This had resolved at chronic follow-up. Ejection fraction was preserved intraoperatively and chronically in all animals studied.

DISCUSSION

In the past several years, minimally invasive techniques have had a significant impact on the field of cardiac surgery. The potential benefits of these approaches include reduced costs, less blood loss, lower complication rates and shorter hospital stay [Magovern 1996, Doty 1997]. The initial results of both beating heart and port-access procedures have been encouraging, with acceptable graft patency and minimal morbidity in large series of patients [Benetti 1991, Buffolo 1996, Reichenspurner 1998]. Recent reports with more intermediate follow-up also have shown satisfactory outcomes [Gundry 1998]. However, with the present techniques it has not been possible to achieve the ultimate goal of minimal invasiveness, completely endoscopic coronary artery bypass grafting (ECABG).

Recently, robotically-assisted microsurgical systems have been introduced to increase the precision of endoscopic surgery. These computer-guided systems can control both surgical instruments [Garcia-Ruiz 1997] and endoscopic cameras [Kavoussi 1995]. The advantages afforded by robotic instrumentation may help overcome some of the obstacles to CABG. Specifically, robotic instrumentation may provide access to multiple target vessels and offer the surgeon the ability to precisely operate in very confined spaces. In the current series, the robotic microsurgical system was able to eliminate tremor by filtering high frequency motions, and smooth the surgeon's movements through computer motion scaling. Thus, computer assistance overcame perhaps the most significant limitation of standard endoscopic instruments; i.e., lack of precision due to instrument length and operator tremor. Endoscopic magnification of the operative site also enhanced the accuracy of suture placement by providing the surgeon with excellent visualization.

Our initial study using the cadaveric porcine heart model demonstrated that it was possible to perform a technically-sound coronary anastomosis using the robotic microsurgical system [Stephenson 1998a]. In the acute animal model, the performance of ECABG was technically feasible with excellent acute graft patency [Stephenson 1998b]. This endeavor was encouraging, in that the computer-assisted robotic technology performed well in the operating room under acute conditions. The experience gained from this work then set the stage for the performance of the chronic study, which analyzed the outcomes of robotically-assisted ECABG in a more clinically relevant model. Although time for completion of the anastomosis remained about the same, total bypass time and cross-clamp time were reduced in the chronic study. Furthermore, graft patency in the survival study was excellent, acutely in the operating room (89%, 8/9), and remained so chronically (100%, 6/6) as demonstrated both angiographically and histologically.

Limitations and Clinical Implications

The *in vivo* studies were performed using a bovine model, which had inherent anatomic limitations due to the configuration of the animal's chest. The percutaneous methods of cardiopulmonary bypass and cardioplegic arrest currently available were incompatible with the short ascending aorta of the calf, which necessitated a right thoracotomy. Additionally, the mammary artery was not harvested or prepared in endoscopic fashion in every case. Therefore, this was not a completely endoscopic approach. However, endoscopic mammary artery harvesting is already well described [Nataf 1997], and in this study all robotic anastomoses were performed endoscopically. The different chest wall anatomy of the human may require an alteration in the approach for clinical cases. Nonetheless, these studies confirm that robotically-assisted ECABG is feasible and efficacious with excellent anastomotic outcomes. Clinical trials are presently underway, and we soon hope to perform completely endoscopic procedures.

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REVIEW AND COMMENTARY

Invited Commentary from Volkmar Falk, MD, Department of Cardiac Surgery, Heart Center, University of Leipzig, Germany:

This manuscript by Ducko et al. demonstrates the feasibility of computer-enhanced endoscopic bypass grafting in an acute and chronic animal study. The authors have to be congratulated for their pioneering work in the field of robot-assisted coronary artery bypass surgery. In this well-designed trial, a telemanipulation system consisting of a master console and three manipulator arms was used in a live animal model. The authors were able to perform coronary artery bypass anastomoses endoscopically with a high angiographic patency rate and no evidence of graft injury or visible abnormalities at the anastomotic site. The use of the telemanipulation system allowed for precise suturing with anastomotic times averaging some 33 minutes. The authors mention tremor filtration and motion scaling as major advantages over conventional endoscopic instruments. Despite the fact that the internal thoracic artery (ITA) was not harvested using the telemanipulation system, this is a major step towards closed chest coronary artery bypass grafting (CABG), a procedure that will ultimately change the practice of cardiac surgery.

The biggest limitation of conventional endoscopic instruments that has to be stressed besides operator tremor and instrument length, as mentioned by the authors, is the limited number of degrees of freedom (DOF) at the tip of the instrument. Endoscopic instruments usually provide only 4 DOF resulting in a decrease of possible motions. Suturing, especially in a perpendicular axis to the shaft of the instrument, is almost impossible and knot tying requires a lot of training. The system used in this study enables temporary detachment of the instrument tips independent from the handles and thus allows for reorientation of the master handles within their workspace (a concept known as indexing) thereby providing favorable ergonomics. However, the surgical

instruments (also called end-effectors) still provide only 4 DOF. It is known that if a manipulator has less than 6 DOF, it cannot attain general goal positions and orientations in space. This has been recently demonstrated in a study where a 6 DOF telemanipulation system (Intuitive Surgical, Mountain View, CA) was used to perform a standard set of endoscopic tasks with either 4 (locked wrist) or 6 DOF. Both time and error rates were significantly less with 6 DOF [Falk 1999a]. Using this system, the quality of endoscopic coronary artery anastomosis was tested and compared to manually performed coronary anastomoses of a donor artery (the native circumflex) to the LAD in a randomized double blind study using isolated pig hearts. Mean time to perform a computer-enhanced anastomosis was 12 minutes with 100% patency and no vessel damage [Falk 1999b].

Our previous work does confirm the basic findings of the present study. Although the anastomosis is in general considered the most critical part of a bypass operation, our recent experience with 22 clinical CABG cases using the Intuitive Surgical telemanipulation system revealed more obstacles that need to be overcome. Port placement is crucial in order to find the best position for the instruments. Since the thorax is rigid and the space between the heart and the chest wall is small, there is only very limited working space despite carbon dioxide insuflation. After overcoming initial problems, take down of the ITA is now routinely performed in less than one hour with the telemanipulation system (which is still longer than with conventional instruments). Low energy cautery (15 W) is essential to avoid bleeding complications that are sometimes difficult to manage endoscopically. Preparation of the distal ITA segment (skeletonizing, trimming) is difficult since no assistance is available. Therefore it is best performed in situ as some countertraction is provided by the pedicle. Even simple tasks like placement of a bulldog clamp are sometimes not easily achieved with current telemanipulation systems. Removal of epicardial fat tissue and identification and dissection of the target vessel with no tactile feedback, as well as creating an accurate and precise arteriotomy, are the next major hurdles before the anastomosis can finally be made. In addition, CPB and cardioplegic arrest were required in order to facilitate the anastomosis in patients that would nowadays be operated on with beating heart techniques in one-third of the time.

Although we have been able to perform total endoscopic closed-chest single vessel coronary artery bypass grafting (an operation that may be termed TECABG in the future) in 3 patients up to now (Figure 1) it is still a long way to both endoscopic beating heart surgery or endoscopic multivessel grafting. Procedure development is still at its infancy and it is therefore important to combine all efforts of those who are active in this field. The group that presented this study is again to be congratulated for their important contribution.

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