EVOLVING TECHNOLOGY

COMPUTER-ENHANCED "ROBOTIC" CARDIAC SURGERY: EXPERIENCE IN 148 PATIENTS

Friedrich W. Mohr, MD, PhD
Volkmar Falk, MD, PhD
Anno Diegeler, MD, PhD
Thomas Walther, MD, PhD
Jan F. Gummert, MD, PhD
Jan Bucerius, MD
Stefan Jacobs, MD
Rüdiger Autschbach, MD, PhD

Objective: A computer-enhanced instrumentation system was used in 148 patients to minimize access in cardiac surgical procedures.

Methods: The da Vinci telemanipulation system (Intuitive Surgical, Mountain View, Calif) provides a high-resolution 3-dimensional videoscopic image and allows remote, tremor-free, and scaled control of endoscopic surgical instruments with 6 degrees of freedom. By April 2000, the system had been used in 131 patients for coronary artery bypass grafting and 17 patients for mitral valve repair. In the coronary bypass group, the system was used in one of three ways: (1) to take down the internal thoracic artery followed by a minimally invasive direct coronary bypass procedure (n = 81); (2) to perform the anastomosis between the internal thoracic artery and the left anterior descending coronary artery in standard-sternotomy coronary bypass (n = 15); or (3) for total endoscopic coronary artery bypass grafting to anastomose the left internal thoracic artery to the left anterior descending on the arrested heart (n = 27) or the beating heart (n = 8). In 17 patients with non-ischemic mitral valve insufficiency the mitral valve was repaired. Closed-chest cardiopulmonary bypass with cardioplegic arrest (Port-Access technique; Heartport, Inc, Redwood City, Calif) was used for arrested-heart total endoscopic coronary bypass and mitral valve repair.

Results: The da Vinci system allows for precise tissue handling and enables the endoscopic performance of cardiac surgical tasks that require a high degree of dexterity (coronary anastomosis, mitral valve repair). No technical mishaps have occurred. The internal thoracic artery was successfully taken down in 79 of 81 patients in the group undergoing minimally invasive coronary bypass and, after a steep learning curve, is currently performed in less than 40 minutes. The postoperative patency rate is 96.3%. Total endoscopic coronary bypass was completed in 22 of 27 cases with 95.4% patency as demonstrated by angiography at 3 months' follow-up. Closed-chest endoscopic beating-heart bypass grafting was successfully performed in 2 out of 8 patients with the use of a new endoscopic stabilizer. In the group having mitral valve repair, primary endoscopic computer-enhanced repair was successfully completed in 14 of 17 patients; three others had to be changed to a standard endoscopic technique, including 1 who required valve replacement. At 3 months' follow-up, 1 additional patient underwent early reoperation for recurrent mitral insufficiency. Overall early and late mortality in this cohort of 148 patients was 2.0% and was not related to the use of the system.

Conclusion: In conclusion, computer-enhanced endoscopic cardiac surgery can be performed safely in selected patients. Internal thoracic artery take-

From the Department of Cardiac Surgery, Heart Center, University of Leipzig, Leipzig, Germany.

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down is now routinely performed with good results. Total endoscopic coronary bypass is feasible on the arrested heart but does not offer a major benefit over the minimally invasive direct approach because cardiopulmonary bypass is still required. The early clinical experience with closed-chest beating-heart bypass grafting outlines the limitations of this approach despite some procedural success. (*J Thorac Cardiovasc Surg* 2001;121:842-53)

Traditionally, coronary artery bypass grafting (CABG) and mitral valve surgery have been performed through a sternotomy, an approach that provides optimal access to all cardiac structures and the great vessels. Cardiopulmonary bypass (CPB) and cardioplegic arrest have long been regarded as necessary adjuncts, providing a bloodless and motionless operating site and offering great comfort and safety for the surgeon. The rise of catheter-based interventions for myocardial revascularization that are associated with no surgical trauma, no anesthesia, and an instant recovery have challenged the surgical approach for coronary artery disease. As a result, off-pump techniques for multivessel revascularization and single-vessel revascularization through a minithoracotomy (minimally invasive direct coronary artery bypass; MIDCAB) have evolved and are performed with excellent results.¹⁻³ At the same time methods for closed-chest CPB with cardioplegic cardiac arrest were developed to provide a platform for endoscopic cardiac surgery.⁴ Whereas videoscopic techniques for mitral valve repair found a rapid and widespread use,^{5,6} endoscopic CABG proved more difficult and was not feasible given the limitations of standard endoscopic instruments (Table I). While 6 degrees of freedom are required to allow free orientation in space, standard endoscopic instruments with only 4 degrees of freedom reduce dexterity substantially. Working through a fixed entry point causes the operator to reverse motions (fulcrum effect) while at the same time shear forces on the instrument shaft require higher handle forces, leading to muscle fatigue.⁷ Motion transmission is dependent on the ratio of internal and external instrument shaft length, again due to pivoting at the body entry point.⁸ In addition, human cognitive and motor skills to accomplish tasks deteriorate with visual-motor incompatibility that is commonly associated with endoscopic surgery (misalignment of camera viewing and instrument orientation).⁹ Computer-enhanced instrumentation systems have been developed to overcome these limitations.¹⁰⁻¹² With the introduction of these systems, endoscopic CABG and mitral valve repair have become possible.¹³⁻¹⁵ This arti-

cle summarizes the single-institution results with the da Vinci telemanipulation system (Intuitive Surgical, Mountain View, Calif).

Methods

The study was presented to and approved by the local ethics committee of the University of Leipzig. All patients were informed about the experimental nature and the potential risks of the procedure. It was clearly stated that operating times would be prolonged as compared with a standard approach and that the likelihood of conversion was high. Written informed consent was obtained from all patients.

The Intuitive da Vinci system was approved as an investigational device by the regional government "Regierungspräsidium Leipzig"; meanwhile, the system has received CE mark (European Commission) approval.

Telemanipulation system. The da Vinci computer-enhanced instrumentation system consists of two major parts, an input device (surgeons console) and an output device (manipulator). The console houses the display system, the input handles, the user interface, and the electronic controller. The tool handles are serial link manipulators that act both as high-resolution input devices, reading the position, orientation, and grip commands from the surgeon, and as haptic displays. The image of the surgical site is transmitted to the surgeon through a high-resolution stereo display. The system projects the image of the surgical site atop the surgeon's hands (via mirrored overlay optics), while the controller transforms the spatial motion of the tools into the camera frame of reference. Thereby the system restores hand-eye coordination and provides a natural correspondence in motions.

The user interface allows the surgeon to control camera positioning while keeping the slave tool tips in the operator's view, to reposition the masters in their work space, and to focus the endoscope. Orientational alignment is always provided, and positional alignment can be changed to allow repositioning of the master handles independent of the instrument tips. Motion scaling and tremor filtering further enhance precision. The electronic controller is capable of fully interconnected control of 48 degrees of freedom at update rates exceeding 1000 cycles per second.¹⁶

The second subsystem is the patient side cart, consisting of fully sterilizable tools, the tool manipulators, the camera manipulator, the surgical endoscope, and the assistant's user interface. The end-effectors are fully sterilizable instruments

Table I. Limitations of endoscopic tools as opposed to the da Vinci computer-enhanced instrumentation system

	Conventional endoscopic instruments	da Vinci telemanipulator
Degrees of freedom	4	6
Tremor filter	No	Yes
Motion transmission	1:1	1:1 to 5:1
Hand-eye alignment	Poor (camera viewing direction/instrument orientation misalignment)	Natural
Fulcrum effect	Reversed motion	Not effective
Force ratio (handle/tip)	Large/abnormal/not linear	Programmable/linear
Indexing	Not possible	Possible
Ergonomics	Unfavorable	Favorable

Table II. Preoperative, intraoperative, and postoperative data for MIDCAB group with computer-enhanced endoscopic ITA takedown

Preoperative data	
N	81 (22 female, 69 male)
Age (y)	62.8 ± 9.7
CAD	×1 (52), ×2 (14), ×3 (15)
LAD pathology	Stenosis > 75% (57), LAD occlusion (24)
Status post MI (No.)	26
Status post PTCA/stent (No.)	17
Ejection fraction (%)	61 ± 13
CCS class	2.1 ± 0.5
Intraoperative data	
ITA takedown (min)	48.3 ± 26.3 last 20 patients: 35.4 ± 7.7
Anastomosis (min)	17.8 ± 6.8
Operating room time (min)	217 ± 75
Patency* (%)	96.3
Postoperative data	
ICU (h)	20.1 ± 11.4
Hospitalization (d)	10.7 ± 4.2

CAD, Coronary artery disease; LAD, left anterior descending coronary artery; MI, mitral insufficiency; PTCA, percutaneous transluminal coronary angioplasty; CCS, Canadian Cardiovascular Society; ITA, internal thoracic artery; ICU, intensive care unit.

*Patency includes intraoperative failures (2) and postoperative occlusion (1) at postoperative angiogram (3-6 days).

that attach interchangeably to the two manipulators (automated instrument recognition) and provide a total of 6 degrees of freedom (plus tool function) inside the body. Three manipulators drive the two instruments and the endoscope. In turn, these manipulators are positioned around the body by three passive multiple-link arms mounted to a fixed base. In an emergency, the arms can be removed from the patient in seconds.

Endoscopic CABG. In the beginning of this experience, according to the study protocol, the device was used for only part of the procedure. This stepwise approach acknowledges the fact that two learning curves are expected to influence the initial results of this new endoscopic cardiac procedure: working in a total endoscopic environment with limited exposure and different anatomic landmarks and using a computer-enhanced instrumentation system. By April 2000, the da Vinci system had been used in operations on 148 patients. In a group of 81 patients with single-vessel disease undergoing a MID-

CAB procedure, the ITA was harvested endoscopically with the system (Table II). In 15 patients undergoing multiple-vessel revascularization through a sternotomy, the anastomosis of the internal thoracic artery (ITA) to the left anterior descending coronary artery (LAD) was performed with the system.¹³ Twenty-seven patients underwent a total closed-chest approach for ITA-LAD grafting (total endoscopic coronary artery bypass; TECAB) on the arrested heart. In 8 patients TECAB was attempted on the beating heart. For the TECAB group, only patients with an indication for a single-vessel revascularization of the LAD and normal left ventricular function were included. Among the exclusion criteria were all known contraindications for using the Port-Access technique (Heartport, Inc, Redwood City, Calif). In addition, patients with left ventricular dilatation or diffuse disease of the target vessel were excluded. Other contraindications for thoracoscopic ITA takedown were extensive pleural symphysis or intolerance of single lung ventilation because of pulmonary disease. Demographic data of the TECAB group are given in Table III.

The technique of TECAB grafting has been described in detail by our group.^{11,13} In brief, patients were placed in a supine position with the left side of the chest slightly elevated and the left arm lowered. After deflation of the left lung, a 30° scope angled up was inserted at the fourth intercostal space in the anterior axillary line. Continuous carbon dioxide insufflation was used. The instrument ports were created at the third and sixth intercostal spaces above the anterior axillary line. The ITA was dissected as a pedicle from the first rib to the sixth intercostal space by means of a low-energy cautery (Fig 1). The distal end of the ITA was skeletonized, with the concomitant veins and fascia left intact to provide countertraction (Fig 2). After removal of pericardial fat, a pericardial window in the region of the LAD was created and the target vessel marked by a clip close to the chosen anastomotic site. After full heparinization, an angled vascular clamp (Scanlan, St Paul, Minn) was inserted to temporarily occlude the ITA, which still in situ was then clipped, cut, and trimmed for the anastomosis. Femoro-femoral bypass and closed-chest cardioplegic arrest were initiated by means of the Port-Access system as described elsewhere.¹⁷ Access to the groin was facilitated by moving the left manipulator arm out of the operating field during placement of the EndoClamp catheter (Heartport). Monitoring for the EndoClamp catheter included transesophageal echocardiography and transcranial Doppler ultrasonography.^{18,19} The procedure was continued using the

same ports as for ITA takedown but switching the scope to a 30° downward angle. The ITA was detached and approximated to the anastomotic site with a stay suture. The LAD was dissected and an arteriotomy was made. A running 8-0 double-armed suture (7 cm) was used to perform the anastomosis (Fig 3). An angiogram was performed in the operating room during rewarming and before discharge.

TECAB grafting on the beating heart. After our initial experience with a canine model for computer-enhanced beating-heart TECAB,²⁰ a new endoscopic stabilizer based on the EndoWrist principle (Intuitive) was developed (Fig 4). By adding cleats onto the pads of the stabilizer, we were able to anchor silicone rubber bands, achieving coronary occlusion by adapting a technique commonly used in off-pump revascularization. For an initial trial, a second console was added, yielding two more manipulator arms and thus providing assistance. The video signal of the primary surgeon's console was fed into the assistant's console; camera position was controlled from the primary console.²¹ After an initial trial, beating-heart TECAB was then performed with the same setup (single console, three manipulator arms) and the same ports as described for TECAB on the arrested heart. The stabilizer was inserted through a fourth port in a subxiphoid position.

Total endoscopic mitral valve surgery. Patients with comorbid factors were excluded from the study. Only patients with a mitral abnormality amenable to repair were included (Carpentier segmental leaflet pathology: P2 [n = 8]; P2,3 [n = 5]; P2,A2 [n = 3]; A1 or 2 [n = 1]). As a result, relatively young (58 ± 9 years) predominantly female (n = 9) patients were included. The degree of mitral valve insufficiency was 2 in 2 patients, 3 in 13, and 4 in 2 patients (left ventricular end-diastolic diameter, 57 ± 7 mm; left atrium, 61 ± 9 mm; New York Heart Association class, II [n = 10], III [n = 7]). The technique of computer-enhanced endoscopic mitral valve surgery can be summarized in brief as follows: After femoro-femoral bypass was initiated with Port-Access cannulation, a lateral, small 3- to 4-cm minithoracotomy was made in the right fourth intercostal space and a soft tissue retractor was placed. The pericardium was opened manually and four traction stay sutures were placed to enhance exposure. After endoaortic balloon clamping, the left atrium was opened and the valve exposed by means of the Heartport left atrial retractor. Once sufficient exposure was achieved, the telemanipulator was placed from the patient's left. The 3-dimensional videoscope was inserted through the incision while the instruments were inserted through two additional trocars in the second and sixth intercostal spaces in the midaxillary line. Mitral valve repair was then performed remotely from the surgical console in the other room. Selection of appropriate ring size was based on the preoperative transesophageal echocardiographic measurement of the free length of the anterior leaflet (longitudinal view) and by intraoperative endoscopic measurements using custom-made sizers. There was a preference for more flexible ring types (Carpentier-Edwards Physio and Cosgrove-Edwards; Baxter Healthcare Corporation, Irvine, Calif) because ring suturing was facilitated. So that sutures could be tied under tension, a technique of sliding instrument square knots was applied.¹⁴ Short (6 cm) single-armed sutures were

Table III. Preoperative, intraoperative, and postoperative data for TECAB group

Preoperative data	
N	27 (7 female, 20 male)
Age	62 ± 8
CAD	$\times 1$ (22), $\times 2$ (4), $\times 3$ (1)
LAD pathology	Stenosis > 75% (20), LAD occlusion (7)
Status post MI (No.)	15
Status post PTCA/stent	11
Ejection fraction (%)	64 ± 10
Intraoperative data	
ITA takedown (min)	64 ± 64
Anastomosis (min)	27 ± 13
Operating room time (min)	347 ± 95
Patency* (%)	95.4
Postoperative data	
ICU (h)	15.5 ± 6.4
Hospitalization (d)	9.4 ± 2.9

CAD, Coronary artery disease; LAD, left anterior descending coronary artery; MI, mitral insufficiency; PTCA, percutaneous transluminal coronary angioplasty; ITA, internal thoracic artery; ICU, intensive care unit.

*Patency rate of completed cases (n = 22) at 3-month follow-up angiography.

used both for leaflet repair (Premio 4-0; Peters, Bobigny Cedex, France) and for ring implantation (Tevdek II 2-0; Genzyme Biosurgery, Fall River, Mass). Annular sutures were placed in a counterclockwise fashion beginning at the right fibrous trigone. Because of the small field of view, continuous suturing requiring long suture lines was avoided. Although in general sutures were tied after each stitch (thereby providing maximum countertraction for the following suture placement), placement of the last three sutures toward the aortic commissure was completed before the preceding suture was tied. For recovering lost needles, an endoscopic tool with a bendable shaft and a strong magnet at the tip was developed. After completion of the repair and testing of the valve, the end-effectors were withdrawn and the left atrium was closed manually with standard endoscopic instruments (Heartport).

Results

Endoscopic left ITA-LAD anastomosis through a sternotomy. The results for this group of 15 patients, in brief, are as follows: Mean time for performing the anastomosis was 16 ± 11 minutes and all anastomoses were patent. The postoperative course was uneventful except in 1 hypertensive patient who died of a massive hemorrhagic stroke that occurred on the third postoperative day.

MIDCAB with computer-enhanced ITA takedown. The results are given in Table II. Time for endoscopic ITA takedown has constantly improved and is now in the range of 25 to 40 minutes. In 2 patients the ITA was discarded for occlusion (n = 1) or low flow (n = 1), so that the overall success rate for endoscopic ITA takedown is currently 97.5% (79/81). In these 2 patients a sternotomy

Fig 1. Endoscopic view during ITA takedown. The graft has been harvested as a pedicle.

Fig 2. In situ dissection of distal ITA. Concomitant veins are clipped.

was performed and a vein graft placed on the beating heart. Transit time flow measurements and intraoperative angiograms were performed in almost all patients, documenting graft patency in the operating room. According to the protocol, a postoperative angiogram was performed between postoperative days 3 and 6 and revealed patency in all but 1 ITA graft (78/79). This patient was subsequently reoperated on (sternotomy, vein graft).

Thus, overall immediate postoperative graft and optimal anastomotic patency rate was 96.3% (78/81). Two patients required re-exploration for bleeding. In 1 patient, a side branch was identified as the cause; in the other patient, no obvious bleeding source was found. One patient had a stroke postoperatively and is currently undergoing a neurologic rehabilitation program. Three patients had transient atrial fibrillation. One patient in this

Fig 3. Anastomosis performed endoscopically on the beating heart.

Fig 4. Endoscopic stabilizer with cleats to anchor silicone rubber bands.

group required an extensive endarterectomy of the LAD after an uneventful ITA takedown. Despite a patent graft and an uneventful immediate postoperative period, the patient died on postoperative day 7 of an unknown cause (autopsy denied). At 6 months' follow-up (completed in 58/79 patients by April 2000), all patients were free from angina.

TECAB on the arrested heart. Total closed-chest left ITA–LAD grafting through 3 or 4 ports was

achieved on the arrested heart in 22 of 27 patients by April 2000. A substantial learning curve was associated with the procedure, which is reflected in long operating times of from 3.5 to 8 hours (Fig 5). Despite a clear trend toward shorter procedure times, the overall time far exceeds that required for a standard MIDCAB approach, and that remains a major concern.

The decrease of procedural times for the arteriotomy (including LAD dissection) and anastomosis are shown

Fig 5. Procedural times reflecting overall learning curve for TECAB. Note that all intraoperative conversions occurred in the first half of this series.

Fig 6. Procedural time for arteriotomy (including dissection of the artery, puncturing by sharp scalpel, and enlarging the cut by scissors) and performance of the anastomosis in closed-chest bypass grafting on the arrested heart (TECAB).

in Fig 6. The rate of conversion to a minithoracotomy or sternotomy, either intraoperative ($n = 4$) or postoperative ($n = 1$), was 18.5% (5/27). All conversions were electively performed in the first half of this series. Reasons for intraoperative conversion were bleeding from the anastomosis, unintended grafting of a large diagonal branch, and torsion of the pedicle. One patient was converted postoperatively for ITA side branch bleeding. There was no mortality and all patients were

discharged with an angiographically patent graft and a good functional result. At 3 months' follow-up angiography, all grafts except one were patent (3 months' patency rate 95.4%). This patient underwent an uneventful reoperation through a sternotomy. One patient required treatment for recurrent left lower lobe atelectasis.

TECAB on the beating heart. With the aid of an active and articulating stabilizer, sufficient endoscopic

Table IV. *TECAB grafting (left ITA to LAD) on the beating heart*

No.	Operation	Conversion	Termination	Reason
1	BH-TECAB	MIDCAB*	Complete	Occlusion at level of anastomosis. Revision of anastomosis
2	BH-TECAB	MIDCAB*	Complete	Angiographically low flow. Revision of anastomosis
3	BH-TECAB	MIDCAB,* CPB	Stabilization	Ventricular fibrillation after stabilization before LAD occlusion
4	BH-TECAB	—	Complete	
5	BH-TECAB	—	Complete	
6	BH-TECAB	MIDCAB*	Anastomosis	Heavily calcified LAD, anastomosis not possible. Conversion to MIDCAB, endarterectomy of LAD, vein patch, ITA grafting
7	BH-TECAB	MIDCAB*	Anastomosis	Septal branch bleeding
8	BH-TECAB	MIDCAB*	Stabilization	Insufficient space for placement of stabilizer

TECAB, Total endoscopic coronary artery bypass; BH, beating heart; MIDCAB, minimally invasive direct coronary artery bypass; CPB, cardiopulmonary bypass; LAD, left anterior descending coronary artery; ITA, internal thoracic artery. *Elective conversion.

stabilization was achieved in 4 of 8 patients. By means of proximal and distal silicone rubber slings that were attached to the stabilizer, complete occlusion of the LAD was achieved. The addition of an assisting instrument provided countertraction during suturing and facilitated performance as compared with earlier trials. In 4 patients the anastomosis was performed on the beating heart in 24 to 49 minutes. Total LAD occlusion times were in the range of 38 to 65 minutes. Intraoperative angiography revealed graft occlusion in 1 patient and a low-flow graft in another patient, necessitating conversion to a MIDCAB and revision of these grafts. Whereas in the first case the anastomosis was clearly stenotic, in the second case a 2-mm probe was easily passed through the anastomosis. After revision, both grafts were patent. In the other 2 patients, angiography showed excellent runoff and widely patent anastomoses. In another 4 patients the operation could not be completed for the reasons listed in Table IV. From these data it is obvious that the choice of the anastomotic site becomes the crucial step in closed-chest beating-heart CABG. In 1 patient with LAD occlusion, back-bleeding from a large septal branch made suturing impossible. In another patient, in whom stabilization and occlusion were readily achieved, heavy calcification of the vessel necessitated an extensive endarterectomy and thus conversion to a MIDCAB operation. In 1 patient the stabilizer could not be placed because of limitations in intrathoracic space. One patient with a type C 95% proximal LAD lesion had ventricular fibrillation shortly after first placement of the stabilizer but before LAD occlusion. The system was withdrawn and emergency CPB initiated through the right groin, which was dissected for cannulation in all patients before the procedure as an additional safety measure. The patient was converted (lateral thoracotomy) and grafting was performed on the fibrillating heart through

Table V. *Intraoperative and postoperative data for computer-enhanced mitral valve repair*

Intraoperative data	
OR time (min)	201 ± 53
CPB time (min)	162 ± 31
Clamp time (min)	89 ± 18
Postoperative data	
ICU stay (h)	19 ± 8
Hospitalization (d)	10 ± 5

OR, Operating room; CPB, cardiopulmonary bypass; ICU, intensive care unit.

a left thoracotomy. Despite successful revascularization, the postoperative course was complicated by a severe anterior myocardial infarction from which the patient died on the sixth postoperative day. All other patients in this group had an uneventful postoperative course and were discharged between postoperative days 6 and 8.

Mitral valve repair. Fourteen of 17 valves were successfully and completely repaired by means of the da Vinci system. In 3 patients the operation had to be completed with the use of conventional endoscopic Heartport instruments for various reasons. Results are summarized in Table V. Different repair techniques such as quadrangular resection, sliding plasty, chordal transfer, shortening and replacement, Whooler-plasty, Alfieri-plasty, and annular decalcification ring implantation were all accomplished from the control room using a surgical console with the high-resolution 3-dimensional image without major tactile feedback. Both partial and complete flexible rings were implanted with interrupted sutures. In 1 patient with complex leaflet abnormalities and insufficient exposure because of a small left atrium, the repair was completed manually. In 1 patient insufficient repair necessitated mitral valve replacement that was then performed through the same small incision, but manually. According to the

preoperative dynamic transesophageal echocardiographic assessment and on the basis of the length of the anterior leaflet, the most commonly used ring size was 28 mm. Intraoperative transesophageal echocardiography demonstrated no ($n = 13$) or only minor residual regurgitation ($n = 3$). One patient mentioned above with Barlow disease had grade 2 mitral insufficiency after mitral valve repair and underwent immediate endoscopic valve replacement.

The postoperative course was complicated by confusion ($n = 2$), reintubation for respiratory insufficiency ($n = 1$), and prolonged chest tube drainage due to a persistent pneumothorax in a patient with lung adhesions ($n = 1$). In 1 patient with primarily successful mitral valve repair, a torn out ring caused acute onset of mitral insufficiency on postoperative day 3 and necessitated endoscopic mitral valve replacement. At reoperation, all sutures were intact but two were torn out of the annulus, most likely because of extensive tension. At 1 to 6 months of follow-up (complete in 17/17 patients as of April 2000), all patients are alive with normal valve function and are free from recurrent myocardial insufficiency.

Discussion

This report updates our experience with a computer-enhanced instrumentation system for endoscopic ITA takedown, TECAB, and mitral valve repair. Despite the heterogeneity of this patient cohort, some observations relevant to the use of the system are communicated. After extensive trials in animals and cadavers,²² a prototype of the system was introduced into clinical practice in May 1998.²³ Beginning in December 1998, the system was used in a total of 148 patients. During this period, the system was operated by the hospital staff and worked without any relevant mechanical failures. Time for setup is well within the range of 10 to 20 minutes (median time 16 minutes in 22 TECAB patients).¹³ There were 3 deaths in the series (2.0%), none related to the use of the system. Clearly the EndoWrist technology enhances intracorporeal dexterity, rendering knot-tying and suturing relatively easy. Optimized hand-eye alignment, indexing, and tremor filtering all greatly facilitate tissue handling. The high-resolution 3-dimensional image display provides a detailed view of all anatomic details, allowing for precise tissue manipulation. However, some restrictions of thoracoscopic surgery still apply, despite all these advantages over conventional endoscopic instruments. The rib cage defines a rigid boundary for thoracoscopic work and limits the work space and the insertion angles that define the ease of manipulation. This can cause singularities (loss of 1 degree of freedom by using

one link to compensate for an unfavorable insertion angle) and thus impair performance. Depending on the individual's anatomy, collisions may occur between the manipulator arms or the manipulator arms and the shoulder or lower rib cage of the patient. Usually collisions occur only during the very proximal or the very distal part of the ITA dissection because the manipulator arms then work parallel to each other. However, it was usually not necessary to change ports. Rather, a different scope was used (leading to a different viewing angle that helped to resolve some collisions with the camera arm), or dissection was performed with the nondominant hand. In addition, longer tipped instruments were developed, which help to avoid collisions due to subsequent changes of the angle and distance of the instrument toward the tissue. Despite its limitations, TECAB grafting that has been attempted in the past with only minor success²⁴ has now become feasible. With the use of the ZEUS system (Computer Motion, Inc, Goleta, Calif), robot-assisted coronary anastomoses were performed on the arrested heart with good patency results in a long-term calf model.²⁵ However, the ITA was harvested through a minithoracotomy with conventional instruments. Clinically, the system has been used in 5 patients for endoscopic CABG. Although the anastomosis was performed through ports, manual assistance was provided through a minithoracotomy.²⁶ Damiano and associates¹² reported on 10 patients in whom the left ITA-LAD anastomosis was performed through a sternotomy by means of the ZEUS system. In 8 patients the anastomosis was successfully performed. Reichenspurner and colleagues²⁷ also reported on the performance of computer-assisted coronary anastomosis on the beating heart using manual assistance and a conventional stabilizer. The da Vinci system was used for ITA harvesting in MIDCAB patients as well as for coronary anastomoses in patients undergoing a sternotomy.¹³ Endoscopic ITA harvesting is now routinely performed and allows the thoracotomy incision for the MIDCAB procedure to be decreased. This is in accordance with other studies of thoracoscopic ITA harvesting, which demonstrated that the minithoracotomy incision can be tailored for the anastomosis, rather than for ITA harvest. The thoracoscopic approach (irrespective of the computer-enhanced instrumentation system) allows a smaller chest incision and may reduce the pain that usually results from the extensive spreading necessary for a direct takedown.²⁸ Early patency is currently 96.3%, which resembles the early patency rate with our MIDCAB program in 1997.²⁹

With increased clinical experience and experimental trials (cadaver and animal studies), it became obvious

that ITA-LAD grafting could be performed without the need for a thoracotomy (TECAB procedure). The first 2 successful cases were subsequently performed in June 1998³⁰ and were followed by larger series in a number of centers.¹³

Natural tissue attachments provide enough countertraction for the procedure to be performed unassisted as solo surgery through 3 ports. Careful patient positioning and port placement are crucial. Although all patients in the TECAB group had a good outcome with a good functional result, refinements in the procedural flow were and are required. With the described technique, the incidence of conversion is decreasing as is the overall procedure time.

In terms of access, this is currently the least invasive procedure for CABG. Although the surgical trauma is reduced in the absence of a thoracotomy, CPB and cardioplegic cardiac arrest are still required. Given the known side effects of CPB, and in the light of a very successful and noninvasive surgical alternative, namely, the MIDCAB procedure, the benefit of the TECAB operation for the patient is currently not evident. We therefore focused on developing an approach for endoscopic CABG on the beating heart. After development of a low-profile endoscopic stabilizer, an initial animal trial demonstrated the feasibility of this approach.²⁰ By means of a more sophisticated stabilizer that allows for free angulation inside the chest, stabilization of the target vessel was improved. At the same time, coronary occlusion was achieved by designing the stabilizer to feature locking slits to hold silicone rubber tapes. Despite stabilization, there is some residual motion. Due to the mechanical design of the manipulators and end-effectors, residual system inertia may thus become an issue during beating-heart procedures. Both in the clinical trial as well as in this animal study, bleeding presents a major problem in beating-heart TECAB grafting. A new generation of tools featuring irrigation channels was therefore developed. These instruments only became available during the study but showed great potential to provide a bloodless field. The anastomosis could be sutured on the beating heart in an unassisted fashion, but the procedure was performed with more comfort once an assisting tool driven by a second console became available. In these cases, an assistant worked remotely from a second console driving an electronic version of the stabilizer and an assisting instrument (forceps). This experimental setup demonstrated the potential benefit of multiple robotic arms that could also be operated by one surgeon provided the human-machine interface would allow an intuitive control algorithm for multiple arm operation. Clearly, beat-

ing-heart surgery not only will minimize the overall trauma of the procedure but also will lead to a major decrease in procedure time, as no time for cannulation, reperfusion, and rewarming is required. However, the technique of closed-chest beating-heart CABG has not fully evolved and currently works only under the best of circumstances. In 1 patient, ventricular fibrillation occurred during the procedure and necessitated emergency conversion and initiation of CPB. The reason for the triggering event remains speculative, but it could be that the combination of carbon dioxide insufflation and mechanical stabilization may increase the likelihood of ischemic complications even without temporary vascular occlusion. As outlined in Table IV, limited exposure is one reason for conversion. A large septal branch may lead to substantial bleeding from the anastomotic site, rendering an endoscopic anastomosis impossible. The lack of tactile feedback may lead to impaired decision making in terms of defining the best spot for the anastomosis. If the target vessel is opened in a largely calcified segment, suturing becomes difficult and time consuming. We have therefore developed an endoscopic Doppler method to detect the target vessel and to outline disease-free segments that are amenable for anastomosis. Furthermore, endoscopic Doppler ultrasonography may aid in ITA harvesting in case the vessel is covered by fat or muscle.³¹ The endoscopic stabilizer, although providing articulation, will need further refinement and allow for easier placement. Alternatives to the currently applied method for vascular occlusion are also to be developed. Application of multimodal 3-dimensional image visualization and manipulation systems that allow modeling of the range of motion of the robotic arms in an individual patient data set (computed tomographic scan, electrocardiogram-gated magnetic resonance imaging) may help to optimize port placement and minimize the risk of collisions in the future. A virtual cardiac surgical planning platform that will allow surgeons to examine the topology of a patient's thorax for planning of endoscopic cardiac procedures has recently been introduced by Chiu and colleagues.³² A similar system, including a 3-dimensional reconstruction of coronary angiograms that will be fused with the intraoperative videoscopic image, is currently being developed at the French Institute National de Recherche en Informatique et en Automatique.³³

Mitral valve repair. The versatility of the end-effectors enabled complex intracardiac repairs including chordal transfers and shortening and sliding plasty, as well as annular decalcification. The use of a rib spreader was abandoned because of some collisions that occurred between the end-effectors and the retractor blade. As a

result, the right instrument can be placed more cephalad and below the scope, which solves the problem of unintended enlargement of the atriotomy by the tool coming in too low. Recently we have started to use the Chitwood clamp for aortic clamping through a separate stab incision in the posterior axillary line. No collisions between the clamp and the manipulator arms were encountered. Although not yet a total endoscopic approach, the technique of computer-enhanced mitral valve repair may offer some potential benefits over the standard endoscopic approach using conventional instruments. Among those are the freedom to orient the instrument tip relative to the tissue, yielding optimal angles for tissue manipulation. Intracardiac knot-tying is easily accomplished. Future design of mitral valve rings with preloaded sutures may further facilitate the procedure.

In conclusion, some cardiac procedures can be performed in selected patients by means of current computer-enhanced telemanipulation systems. ITA take-down is now routinely and safely performed with very good results. Total endoscopic single-vessel bypass grafting to the LAD is feasible on the arrested heart but does not offer a major benefit over the MIDCAB approach because CPB is still required. Experimentally, endoscopic beating-heart CABG can be performed with good functional results. The early clinical experience with this approach clearly outlines its limitations despite some procedural success. Mitral valve repair can be performed safely using the system, but the numbers are too small to render a comparison to manual endoscopic mitral valve repair meaningful. It is expected that with further refinements and the development of adjunct technologies, the technique of computer-enhanced endoscopic cardiac surgery will evolve in specialized centers and may prove beneficial for selected patients; as yet, it is in an investigational stage and should be carefully evaluated.

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Address for reprints: Friedrich W. Mohr, MD, Klinik für Herzchirurgie, Universität Leipzig, Herzzentrum, Russenstraße 19, 04289 Leipzig, Germany (E-mail: mohf@medizin.uni-leipzig.de).

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Discussion

Dr Alain F. Carpentier (*Paris, France*). I rise to congratulate Dr Mohr. We have had a similar experience, although we have treated only 26 patients, about half of them for coronary artery disease, including the first cases of TECAB done by Dr Berrebi. It may be interesting also to add that Dr Fabiani recently did the very first totally endoscopic replacement of the abdominal aorta; that is to say, this technology is useful not only for cardiac and thoracic surgery but also for abdominal surgery.

This is a very demanding technology. At the beginning there is a learning curve, and one has to proceed very wisely, but the technology can be learned.

The only limitation for the moment is loss of tactile feedback. Dr Mohr, how do you think we could improve this particular point, as well as the strength of the instrument? This is particularly important for mitral valve disease, which requires more strength than is needed for coronary artery disease.

Dr Mohr. Thank you. I think this is an obvious conflict. The surgeon is always demanding a change for the next day, and technicians and engineers are not able to make such changes immediately.

They focused on coronary bypass surgery for many reasons, and it would be helpful to have tactile feedback in coronary operations. However, I think the improved visualization overcomes many of the drawbacks of not having tactile feedback. For CABG surgery it may not really be necessary. For mitral valve surgery, I think tactile feedback would be very helpful. However, major technical changes will be required, and I do not know how long those changes will take.

The development of different instruments for mitral valve surgery is absolutely necessary. Some of the rings must also be changed. We have made some changes together with Professor Camp on the Physio rings. I have used many Carpentier rings in this series, and I think there will be great progress in the future.