Feasibility, safety, and efficacy of totally endoscopic coronary artery bypass grafting: Multicenter European experience

Didier de Cannière, MD, PhD,^a Gerhard Wimmer-Greinecker, MD, PhD,^b Romuald Cichon, MD,^c Vassilios Guliemos, MD,^c Frank Van Praet, MD,^d Usha Seshadri-Kreaden, MSc,^f and Volkmar Falk, MD, PhD^e

Dr de Cannière

See related editorials on pages 559 and 562.

From the Departments of Cardiac Surgery at Erasme University Hospital, Brussels, Belgium,^a Klinikum der Johann Wolfgang Goethe Universität, Frankfurt am Main, Germany,^b Dresden Herzzentrum, Dresden, Germany,^c Onze Lieve Vrouweziekenhuis, Aalst, Belgium,^d and Leipzig Heart Institute, University of Leipzig, Leipzig, Germany,^e and from Intuitive Surgical Inc, Sunnyvale, Calif.^f

This study was sponsored by Intuitive Surgical Inc, the manufacturer of the da Vinci robotic surgical system used by the five centers contributing to this report. U.S.-K. is a full-time employee of Intuitive Surgical.

Received for publication Sept 27, 2005; revisions received May 16, 2006; accepted for publication June 9, 2006.

Address for reprints: Didier de Cannière, MD, PhD, Chief of Cardiac Surgery, Erasme University Hospital, Department of Cardiac Surgery, 808 Route de Lennik, 1070 Brussels, Belgium (E-mail: didier.decanniere@ulb.ac.be).

J Thorac Cardiovasc Surg 2007;134:710-6
0022-5223/\$32.00

Copyright © 2007 by The American Association for Thoracic Surgery

doi:10.1016/j.jtcvs.2006.06.057

Objective: The invention of robotic systems has begun a new era of endoscopic cardiac surgery. Reports on totally endoscopic coronary artery bypass grafting are limited, however, and data regarding feasibility, safety, and efficacy are needed to determine this technique's position in the therapeutic armamentarium. This study describes the largest multicenter experience in the literature with robotic totally endoscopic coronary artery bypass grafting specifically addressing procedural feasibility, safety, and efficacy.

Methods: Between September 1998 and November 2002, a total of 228 patients with coronary artery disease were scheduled for totally endoscopic coronary artery bypass grafting with the da Vinci Surgical System (Intuitive Surgical Inc, Sunnyvale, Calif.) at five European institutions. Patients underwent totally endoscopic coronary artery bypass grafting with either an on-pump (group A, n = 117) or an off-pump approach (group B, n = 111). Patients underwent postoperative angiography or stress electrocardiography and were followed up for 6 months.

Results: Procedural feasibility was demonstrated through the completion of 164 successful totally endoscopic cases. Sixty-four patients (group C, 28%) had conversion to nonrobotic procedures. Conversion rates decreased with time. The overall procedural efficacy, as defined by angiographic patency or lack of ischemic signs on stress electrocardiography, was 97%. The incidence of major adverse cardiac events within 6 months was 5%.

Conclusion: Both on- and off-pump totally endoscopic coronary artery bypass grafting are feasible, with a conversion rate that diminishes with increasing experience. Conversion does not adversely affect outcome and thus constitutes a safe alternative. Although target vessel reintervention may be slightly higher than that reported for open coronary artery bypass grafting, graft patency and major adverse cardiac events for both approaches are comparable to those reported in the Society of Thoracic Surgeons database, demonstrating the safety and efficacy of the totally endoscopic coronary artery bypass grafting procedure.

The continuous refinement of coronary artery bypass grafting (CABG) has led to a mature and efficient procedure that provides excellent long-term results for selected patients, with low mortality.^{1,2} Standard CABG, however, is associated with significant invasiveness and large social, direct, and indirect costs.³ These limitations mandate further improvement. A novel procedure that uses robotic technology has been recently introduced into the operating room, enabling the performance of endoscopic coronary surgery.⁴ This procedure potentially offers the benefits of endoscopic surgery: avoidance of an aggressive chest incision, minimal

Abbreviations and Acronyms

CABG	= coronary artery bypass grafting
CPB	= cardiopulmonary bypass
ECG	= electrocardiography
MACE	= major adverse cardiac event
STS	= Society of Thoracic Surgeons
TECAB	= totally endoscopic coronary artery bypass grafting

blood–air interface, and minimal risk of infection, with a better cosmetic result and faster recovery and return to routine activity. Robotic surgery represents a major paradigm shift and challenge for the operative team.⁵ It requires the development of new technical skills, communication patterns, and conversion and contingency modalities, as well as overall changes in operative planning.^{6–8} Since the world's first procedure at the end of 1998, only limited patient numbers have been reported from single-center series.

This report describes the largest multicenter experience to date with robotic totally endoscopic CABG (TECAB). It specifically addresses feasibility, safety, and efficacy while discussing the potential value and limitations of TECAB.

Materials and Methods

Between September 1998 and November 2002, a total of 228 patients aged 18 to 80 years (59.2 ± 10.1 years) with significant symptomatic coronary artery disease were selected to undergo TECAB with the da Vinci Surgical System (Intuitive Surgical Inc, Sunnyvale, Calif) at five European institutions. The patients were categorized into three groups: on-pump TECAB (group A, 1.9 ± 0.8), off-pump TECAB (group B, 1.9 ± 0.8), and conversions (group C, 2.0 ± 0.8). A conversion was defined as the need for an incision (sternotomy or minithoracotomy) before the completion of the endoscopic anastomosis. A reintervention, even during the same operative session, after the completion of the anastomosis has been regarded as a major adverse cardiac event (MACE). All patients underwent 6-month postoperative follow up. In considering patients suitable for a robotic operation, the following exclusion criteria were applied: evidence of severely calcified left anterior descending coronary artery, contraindications for peripheral cannulation (group A), morbid obesity, decompensated congestive heart failure, and acute renal failure.

Overall, the vast majority (90%) had single-vessel disease, with the target vessel for revascularization being the left anterior descending coronary artery in 86%, a diagonal branch in 3%, and the right coronary artery in 1%. The remaining patients received either a sequential left internal thoracic graft to the diagonal and left anterior descending arteries (6%) or a double thoracic graft to the left anterior descending artery and the circumflex artery, diagonal, or right coronary artery (4%). Sixty percent had a history of percutaneous intervention to the left anterior descending artery before TECAB, whereas 15% underwent TECAB as a part of a hybrid procedure. All institutions completed the majority of their

on-pump TECAB experience (group A) before proceeding to their off-pump TECAB experience (group B) and performed at least 30 cases. In group A, the left internal thoracic artery was harvested, the pericardium was opened, and the target vessel was identified before femoral cardiopulmonary bypass was instituted. The operative techniques have been described previously.^{9,10} In group A, the CABG was performed under endoaortic balloon clamping and cardioplegic arrest, with a running suture to anastomose the thoracic conduit to the target vessel. In group B, an endoscopic stabilizer was inserted through a subxyphoid port after the thoracic harvesting and pericardial opening for stabilization of the target vessel and performance of the anastomosis on the beating heart.

All the operations were performed after obtaining written informed consent from the patient, in accordance with the ethics committees of each participating institution.

Feasibility, Efficacy, and Safety Assessment

The feasibility of the procedure was assessed by the ability to successfully complete TECAB without the need for conversion to any kind of open-chest procedure. The rate, reasons, and evolution of conversions are described in [Tables 1](#) and [2](#) and in [Figure 1](#). The efficacy of the procedure was measured by postoperative angiography, stress electrocardiography (ECG), or both. Angiographic efficacy was defined with a modified FitzGibbon criteria of less than 50% stenosis of the distal anastomosis for a patent graft. A clinically negative stress test result for ECG, defined by the absence of angina and ST-wave changes, was used as a surrogate measure for graft patency. Procedural safety was measured by the incidence of MACEs within a 6-month postoperative period. MACE variables included all-cause mortality, myocardial infarction, and target vessel reintervention. Perioperative incidence of MACE was compared with that in a matched cohort from the Society of Thoracic Surgeons (STS) National Database for open chest procedures performed for isolated single-vessel disease between 2000 and 2002. To assess longer term recurrence of MACEs, a random sample of 100 patients was contacted during the reviewing period of the article, at an average follow-up of 3.5 years.

Data Collection, Entry, and Analysis

Data were abstracted from medical charts and covered a 6-month follow-up period for completion of the study. Clinical information was verified against medical records by three independent monitors. Once entered in a database and verified for accuracy, the data were accessed and analyzed with SAS (SAS Institute, Cary, North Carolina) statistical software.

Statistical Methods

The study was designed and powered to achieve an overall procedural efficacy of 94%, with a lower limit of the 95 percent confidence interval of at least 90%. All analyses were conducted according to an intent-to-treat principle. The data provided from the STS National Database used for perioperative comparisons of MACE frequency were based on a custom query of a patient population undergoing sternotomy CABG for isolated single-vessel disease. Patients were matched on the basis of age, sex, and preoperative risk factors. Although this comparison is provided as a baseline reference, it is not possible to draw meaningful statis-

TABLE 1. Intended totally endoscopic coronary artery bypass grafting procedures and conversions to alternate surgical modes and incisions

Intended total procedures	Nonconverted (TECAB)	Total converted	Conversion mode			
			Thoracotomy		Sternotomy	
			Arrested heart	Beating heart (MIDCAB)	Arrested heart (CABG)	Beating heart (OPCAB)
Group A (n = 117)	90 (77%)	27 (23%*)	6 (5.1%†)	14 (12%†)	4 (3.4%†)	3 (2.5%†)
Group B (n = 111)	74 (66.7%)	37 (33.3%*)	—	34 (30.6%‡)	3 (2.7%‡)	—
TECAB (n = 228)	164 (72%)	64 (28%)	—	—	—	—

All data represent numbers and percentages of patients. *TECAB*, Totally endoscopic coronary artery bypass grafting; *MIDCAB*, minimally invasive direct coronary artery bypass grafting; *CABG*, on-pump coronary artery bypass grafting; *OPCAB*, off-pump coronary artery bypass grafting. *No statistically significant difference was seen in conversion rates between group A and group B ($P = .08$). †This is the percentage of attempted procedures among group A. ‡This is the percentage of attempted procedures among group B.

tical comparisons because of demographic differences of the two populations. Patients who did not undergo postoperative angiography or stress ECG were excluded from the efficacy analysis. Categorical variables are expressed as number and percentage of patients and were analyzed with the Fisher exact test or χ^2 test for association, with or without continuity correction.

Continuous variables were compared with a two-sample *t*-test. A log-rank test was used to compare Kaplan–Meier curves of freedom from MACE.

TABLE 2. Conversion reasons by procedure type

Reason for conversion	Conversions		
	Group A	Group B	Total
Total conversions	27	37	64
Cannulation	15	—	15 (23.4%)
Balloon failure (rupture or migration)	9	—	9 (14.1%)
Iliofemoral condition	6	—	6 (9.4%)
Patient conditions	3	22	
Inability to locate and dissect LAD	3	8	11 (17.2%)
Ventricular tachycardia	—	1	1 (1.7%)
Inadequate LITA flow	—	1	1 (1.7%)
Hemodynamic instability	—	3	3 (4.8%)
Calcified LAD	—	7	7 (11%)
Body habitus	—	2	1 (1.7%)
Bleeding	6	8	
Anastomotic site	6	6	12 (18.8%)
LITA	—	1	1 (1.7%)
Right ventricle	—	1	1 (1.7%)
Inadequate stabilization	—	6	6 (9.4%)
da Vinci System failure	1	1	2 (3.4%)
Threshold of time on CPB reached	1	—	1 (1.7%)
Wrong target vessel	1	—	1 (1.7%)

All data represent numbers and percentages of patients. *LAD*, left anterior descending coronary artery; *LITA*, left internal thoracic artery; *CPB*, cardiopulmonary bypass.

Results

A total of 228 subjects were intended to undergo TECAB. One hundred sixty-four patients underwent completion of a totally endoscopic operation, whereas 64 patients (28%), denoted as group C, had intraoperative conversion to an alternate (nonrobotic) technique for completion of the procedure. The total numbers of patients, stratified by group and conversion mode, are shown in Table 1. There were no significant differences in conversion rate between groups A and B. The individual reasons for conversion among patients in group A and B are explained in Table 2. Most conversions in group A were due to cannulation, whereas conversion in group B occurred as the result of inadequate stabilization, inappropriate patient conditions, or bleeding at the anastomosis. The evolution of the conversion rates through discrete 6-month time intervals for the study period is shown in Figure 1. Twelve patients were unavailable for follow-up within the 6 month period.

Figure 1. Operation period represents 6 discrete 8-month intervals in which on-pump (group A) and off-pump (group B) conversion rates are shown. Numbers in histogram represent total number of cases performed during period.

TABLE 3. Procedure efficacy as measured by angiography and stress electrocardiography

Patient group	Patients with angiography or stress test	Efficacy			Patients not assessed
		Per angiography	Per stress test	Per both angiography and stress test	
Group A (n = 90)	78	61/62 (98.4%)*	23/23 (100%)	84/85 (98.8%)	12
Group B (n = 74)	63	35/38 (92.1)†	24/25 (96)	59/63 (93.6)	11
Overall (A + B)	141	100	48	148	23
Group C (n = 64)	44	15/17 (88.2)‡	28/28 (100%)	43/44 (97.7%)	20

*Among 55 patients, 62 grafts were assessed. †Among 38 patients, 38 grafts were assessed. ‡Among 15 patients, 17 grafts were assessed. Mean CCSC score among 15 group A patients: preoperative, 1.9 ± 0.8 ; postoperative, 0.02 ± 0.2 . Mean CCSC score among 15 group B patients: preoperative, 1.9 ± 0.8 ; postoperative, 0.05 ± 0.2 . Mean CCSC score among 15 group B patients: preoperative 2.0 ± 0.8 , postoperative 0.06 ± 0.3 .

The efficacy of the TECAB procedure, as measured by the FitzGibbon definition of patency (<50% stenosis), was 96%, described in Table 3 for patients without conversion. Postoperative angiographic controls were not systematically performed except in the case of hybrid procedures. One hundred grafts were assessed in 93 patients who did not have conversion; 17 grafts were assessed in 15 patients who had conversion (group C). Among patients who did not undergo angiography, 48 had completed a stress ECG test. The overall efficacy of TECAB as assessed by stress test alone was 98%. The combined procedural efficacy, as defined for patients having had either test, was 97% for all patients undergoing TECAB. In patients who had conversion, the combined procedural efficacy was 97.7%. There were no statistically significant differences in procedural efficacy across the three groups.

The safety of the TECAB procedure is depicted in a series of Kaplan–Meier curves in Figure 2 for on- and off-pump procedures. There was no statistical differences in the 6-month freedom from MACE between groups A and B ($P = .64$), groups A and C ($P = .09$), and groups B and C ($P = .26$). The same was true when group B was compared with group C ($P = .26$). Perioperative safety of the proce-

cedure was further compared with open chest procedures from the STS National Database for isolated single-vessel disease between 2000 and 2002. This comparison was stratified by on- and off-pump procedures. Nine of 164 patients without conversion (5%) had a MACE within the 6-month postoperative period. Four of these events happened in group A (4%) and 5 in group B (7%). Among patients who had conversion, 3 of 64 had a MACE (5%). The rates of perioperative target vessel reintervention appear to be higher for all TECAB groups relative to those for open CABG as published in the STS National Database (Table 4); however, statistically meaningful conclusions cannot be drawn.

Overall, 3 patients without conversion (2%) died in the perioperative period. In group A, mortality was 1%. One patient died approximately 10 months after the operation from immunosuppressive therapy complications after kidney transplantation. In group B, mortality was 3%. One patient scheduled for a hybrid procedure died of an acute infarction in the territory of the circumflex artery before the planned percutaneous intervention could be performed. The cause of death and the patency of the left anterior descending artery bypass were confirmed at necropsy. One patient died of major, acute gastrointestinal bleeding with shock and cardiac arrest that led to postanoxic coma after cardiopulmonary resuscitation. Among patients who did not have conversion, mortality was 3%. The overall mortality of the three groups combined was 2.1%, versus a rate of 2.4% for open CABG.

Two patients (1%, 1 in group A and 1 in group B) had a myocardial infarction within 7 days after the operation. Myocardial infarction rates did not statistically differ across groups A and B and did not exceed the rates found with open CABG. Six patients underwent target vessel reintervention in the 6-month postoperative period. Five underwent surgical reintervention; the remaining patient underwent stent placement. Of the reinterventions, 2 occurred in group A, 3 in group B, and 1 in group C (2%, 4%, and 1%, respectively). There was no statistically significant difference in the incidence of target vessel reintervention. At a mean follow up of 3.5 years of 100 randomly selected

Figure 2. Kaplan–Meier curves for 6-month freedom from major adverse cardiac events (MACEs). Log-rank test shows no difference between groups A and B ($P = .64$), nor groups A and C ($P = .26$), nor groups B and C ($P = .09$).

TABLE 4. Major adverse cardiac events by procedure type

	Overall	Group A	Group B	Group C
Patient group				
No.	228	90	74	64
Total/STS National Database*	20:48	11:382	9:106	NA
All cause mortality				
Study, all causes	5 (2.1%)	1 (1.1%)	2 (2.2%)	2 (2.31%)
STS National Database	494 (2.4%)	279 (2.4%)	215 (2.4%)	—
Perioperative (<7 d) myocardial				
Study	2 (0.9%)	1 (1.1%)	1 (1.2%)	—
STS National Database	169 (0.8%)	92 (0.8%)	92 (0.8%)	—
Target-vessel reintervention (<30 d)				
Study	6 (2.6%)	2 (2.2%)	3 (4.1%)	—
STS National Database	60 (0.3%)	26 (0.2%)	34 (0.4%)	—

NA, Not available; STS, Society of Thoracic Surgeons. *Society of Thoracic Surgeons National Database 2000 through 2002 for single-vessel coronary artery bypass grafting on pump (vs A) and off-pump (vs B) with matched risk stratification.

patients, 4 had MACEs: 2 underwent percutaneous coronary intervention of a nontarget vessel, 1 had a myocardial infarction, and 1 had died from an unknown cause. No patient had undergone surgical target vessel reintervention.

Discussion

This study is limited by its retrospective nature and provision of only a 6-month follow up. It represents a multicenter collaboration in which 228 patients underwent TECAB. Its purpose was to demonstrate feasibility, efficacy, and safety of the endoscopic procedure on both the arrested and beating heart. A significant learning curve was observed. Patency rates and 6-month freedom from MACE revealed acceptable results which were comparable to those from the STS National Database. Although the institutions continue to perform TECAB, the period of September 1998 through November 2002 represents that in which the study took place and a sufficient sample size was obtained to study graft patency and safety of the procedure, as requested by the regulatory approval. Although patients in this study may in fact have had longer follow up available, the 6-month time frame was chosen as a reasonable point within which MACEs and graft patency would be assessed.

TECAB represents a new challenge, requiring development of technical ability to work in an endoscopic environment. A conversion strategy and contingency plan therefore must be choreographed to bring the operation back to the surgical standards in case of need.¹¹

In the on-pump group (group A), which required femoral cannulation and endoaortic balloon clamping, 55% of the conversions were related to cannulation issues and were related to neither the da Vinci system nor the endoscopic nature of the operation itself. The management and monitoring of the endoaortic balloon clamp were made awkward in the presence of the da Vinci system and generated significant "strategic" issues, such as the sequence of cannula

insertion and anticoagulation with regard to the robotic steps of the procedure. This contributed to an unexpectedly high rate of conversion for surgical teams with significant endoscopic CABG experience.^{12,13} Such conversions might have been categorized as intraoperative exclusions, never destined to be completed robotically, resulting in a significantly lower conversion rate; however, they are reported as conversions per our intent-to-treat principle and represent an evolutionary process.

In group B, 3 of 4 conversions were related to the target vessel (wall calcification, intramyocardial course, bleeding from the arteriotomy, and inadequate stabilization). It is likely that the small percentage of hemodynamic intolerance in group B (4.8%) was due to a combination of factors specific to this procedure: the coexistence of carbon dioxide insufflation and stabilization, coupled with some degree of hypoxemia in the event of single-lung ventilation with insufficient compensation, and a potentially longer period of target vessel occlusion.¹⁴ With the exception of hemodynamic instability, which may be present in a fixed percentage of cases, other reasons for conversion can be specifically addressed. A significantly improved endoscopic stabilizer has been a considerable asset for the global success of the procedure. Target vessel localization is improving with time with the development of endoscopic skills, and specific navigation software is currently under development to facilitate target vessel identification.¹⁵ Special silicone elastomer snares have been designed to minimize bleeding at the arteriotomy site. Conversion modalities were different in groups A and B (Table 1). Fourteen of 27 conversions in group A were performed off-pump through a lateral thoracotomy, whereas 34 of 37 patients in group B had conversion to a lateral thoracotomy off-pump procedure. This conversion modality, known as robotically enhanced minimally invasive direct coronary artery bypass grafting, is regarded by some authors as the best operation for single left anterior descending revascularization.¹⁶ It is note-

worthy that 54 of the 64 patients with conversions (84%) received a minimally invasive operation. Although the participating centers initially started with on-pump TECAB, this procedure was later abandoned in favor of off-pump TECAB in the case of single-vessel revascularization.

The efficacy of surgical revascularization can be addressed in different ways. The criterion standard is the angiogram demonstrating graft patency, eventually combined with a surrogate assessment of the functional completeness of revascularization confirming the adequacy of the therapeutic plan.¹⁷ The overall rate of TECAB procedural efficacy was 97%. It did not vary significantly between groups A and B, confirming that it is effective and within the expected range for a thoracic to left anterior descending graft.^{18,19} Furthermore, the postoperative outcomes of the patients are unchanged regardless of whether the procedure is endoscopic or converted to an alternate technique.

The specific skills that are required to perform an endoscopic anastomosis on an arrested heart can easily be developed on isolated animal hearts. Training on such models has taken place at each institution. On the other hand, theoretic concerns have been raised about the efficacy of off-pump TECAB.²⁰ The interposition of the robotic system introduces a delay between the surgical gesture and the motion of the telemanipulated instrument. This delay theoretically affects the precision of tasks performed on the beating heart, such as suture placement, so that even with an adequate visualization of the suture line, the quality of the anastomosis might be in question. This theoretic drawback cannot be solved unless perfect stabilization is achieved. It may also be overcome with the venue of anastomotic connectors that are currently under clinical development. The results of off-pump TECAB, however, as addressed through angiographic controls, have been shown to be satisfactory and to fall within the expected range for thoracic grafting.^{18,19} With confidence limits of combined efficacy ranging from 91% to 100%, off-pump TECAB is a viable therapeutic option.

The assessment of procedural safety shows that the incidence of MACE was similar between groups. Direct comparison of the overall incidence of MACE with that in the STS database is difficult because of the unknown multiplicity of coexisting adverse events among patients in the STS database. This comparison is for information purposes until prospective, randomized procedures are available. It needs to be mentioned that it takes place in the learning curve of TECAB, that the STS cohort is matched for the on and off pump cases but includes only single bypasses and that the patients of the TECAB cohort may have been followed up more closely, so that the comparison may be the worse case scenario for TECAB. Mortality and myocardial infarction are not affected by the endoscopic approach versus the STS database. On the other hand, concerns regarding a potentially higher incidence of target vessel reintervention for

endoscopic procedures must be weighed against the benefits of a minimally invasive approach. In the longer term, the place of the totally endoscopic procedures in the therapeutic armamentarium against coronary artery disease will also require comparison to the existing alternatives of CABG such as the robotic-enhanced minimally invasive direct CABG or ACAB.¹⁶

Conclusions

Although endoscopic CABG represents a major paradigm change, leading to difficulties that must not be underestimated, the results of this study demonstrate that on-pump and off-pump TECAB are feasible, with a conversion rate that diminishes with increasing experience. Conversion does not adversely affect outcome and thus constitutes a safe alternative. Although the rate of target vessel reintervention may be slightly higher than that reported for open CABG, graft patency and major adverse cardiac events for both approaches are comparable to those reported in the STS database and demonstrate that TECAB is a safe and effective procedure. Future prospective studies and longer follow-up may address the benefits of successful TECAB with respect to conventional CABG.

Dr de Cannière thanks the Fonds pour la Chirurgie Cardiaque and LIVE for supporting the robotic program at Erasme Hospital.

References

1. Brener SJ, Lytle BW, Casserly IP, Schneider JP, Topol EJ, Lauer MS. Propensity analysis of long-term survival after surgical or percutaneous revascularization in patients with multivessel coronary artery disease and high-risk features. *Circulation*. 2004;109:2290-5.
2. McGovern PG, Jacobs DR Jr, Shahar E, Arnett DK, Folsom AR, Blackburn H, et al. Trends in acute coronary heart disease mortality, morbidity, and medical care from 1985 through 1997: the Minnesota heart survey. *Circulation*. 2001;104:19-24.
3. National Heart, Lung, and Blood Institute. Morbidity and mortality 2002. Chart book on cardiovascular lung and blood diseases. Bethesda (MD): The Institute; 2002.
4. Loop FD. Coronary artery surgery: the end of the beginning. *Eur J Cardiothorac Surg*. 1998;14:554-71.
5. Falk V, Diegeler A, Walther T, Autschbach R, Mohr FW. Developments in robotic cardiac surgery. *Curr Opin Cardiol*. 2000;15:378-87.
6. Dogan S, Aybek T, Andresen E, Byhahn C, Mierdl S, Westphal K, 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.
7. Mohr FW, Falk V, Diegeler A, Walther T, Gummert JF, Bucerius J, et al. Computer-enhanced "robotic" cardiac surgery: experience in 148 patients. *J Thorac Cardiovasc Surg*. 2001;121:842-53.
8. de Cannière D. The totally endoscopic coronary surgery: state of the art. *J Cardiovasc Surg (Torino)*. 2003;44:323-30.
9. Falk V, Fann JJ, Grünfelder J, Daunt D, Burdon TA. Endoscopic computer-enhanced beating heart coronary artery bypass grafting. *Ann Thorac Surg*. 2000;70:2029-33.
10. Kappert U, Cichon R, Schneider J, Gulielmos V, Ahmadzade T, Nicolai J, et al. Technique of totally endoscopic coronary artery surgery on the beating heart. *Eur J Cardiothorac Surg*. 2001;20:765-9.
11. Bonatti J, Schachner T, Bernecker O, Chevtchik O, Bonaros N, Ott H, et al. Robotic totally endoscopic coronary artery bypass: program development and learning curve issues. *J Thorac Cardiovasc Surg*. 2004;127:504-10.

12. Schwartz DS, Ribakove GH, Grossi EA, Schwartz JD, Buttenheim PM, Baumann FG, et al. Single and multivessel port-access coronary artery bypass grafting with cardioplegic arrest: technique and reproducibility. *J Thorac Cardiovasc Surg.* 1997;114:46-52.
13. Casselman F, Van Slycke S, Wellens F, De Geest R, Gegriek I, Van Praet F, et al. Mitral valve surgery can now routinely be performed endoscopically. *Circulation.* 2003;108 Suppl 1:II48-54.
14. Diegeler A, Thiele H, Falk V, Hambrecht R, Spyranis N, Sick P, 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.
15. Coste-Maniere E, Adhami L, Mourgues F, Carpentier A. Planning, simulation, and augmented reality for robotic cardiac procedures: the STARS system of the ChIR team. *Semin Thorac Cardiovasc Surg.* 2003;15:141-56.
16. Bucerius J, Metz S, Walther T, Falk V, Doll N, Noack F, et al. Endoscopic internal thoracic artery dissection leads to significant reduction of pain after minimally invasive direct coronary artery bypass graft surgery. *Ann Thorac Surg.* 2002;73:1180-4.
17. Diegeler A, Matin M, Falk V, Binner C, Walther T, Autschbach R, et al. Quality assessment in minimally invasive coronary artery bypass grafting. *Eur J Cardiothorac Surg.* 1999;16 Suppl 2: S67-72.
18. Mack MJ, Osborne JA, Shennib H. Arterial graft patency in coronary artery bypass grafting: what do we really know? *Ann Thorac Surg.* 1998;66:1055-9.
19. Tatoulis J, Buxton B, Fuller J. Patencies of 2127 arterial to coronary conduits over 15 years. *Ann Thorac Surg.* 2004;77:93-101.
20. Falk V. Manual control and tracking—a human factor analysis relevant for beating heart surgery. *Ann Thorac Surg.* 2002;74:624-8.