Robotic total endoscopic double-vessel coronary artery bypass grafting—state of procedure development

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Objective: Robotic total endoscopic coronary artery bypass grafting (TECAB) has been under development for 10 years. With increasing experience and technological improvement, double-vessel TECAB has become feasible. The aim of the present study was to compare the current outcomes of single- and double-vessel TECAB.

Methods: Between 2001 and 2011, 484 patients underwent TECAB by 4 surgeons at 2 institutions. The median patient age was 60 years (range, 31-90), and the median European System for Cardiac Operative Risk Evaluation was 2 (range, 0-13). Single-vessel (n = 334) and double-vessel (n = 150) procedures were performed using the da Vinci, da Vinci S, and da Vinci Si robotic systems.

Results: Compared with the single-vessel procedure, double-vessel TECAB required a longer operative time (median, 375 minutes; range, 168-795; vs median, 240; range, 112-605; $P < .001$) and had an increased conversion rate to a larger thoracic incision (31/150 [20.7%] vs 31/334 [9.3%]; $P < .001$). The median ventilation time was 10 hours (range, 0-288) for double-vessel versus 8 hours (range, 0-278) for single-vessel procedures ($P = .006$). The hospital stay was comparable, with 6 days (range, 2-27) for double-vessel TECAB and 6 days (range, 2-33) for single-vessel TECAB ($P = .794$). Perioperative mortality was 0.3% (1/334) with single-vessel TECAB and 2.0% (3/150) with double-vessel TECAB ($P = .090$). Freedom from major adverse cardiac and cerebral events at 5 years was similar after double- and single-vessel TECAB (73.5% vs 83.1%, $P = .150$). The 5-year survival was 95.8% and 93.9% ($P = .708$).

Conclusions: Double-vessel TECAB appears feasible and reproducible. The operative times were longer and the conversion rates to a larger thoracic incision were greater than with single-vessel TECAB. Also, the post-operative ventilation time was longer. Other perioperative morbidity and mortality and the recovery time and long-term clinical outcomes, however, were comparable. (J Thorac Cardiovasc Surg 2012;144:1061-6)

Double-vessel total endoscopic coronary artery bypass grafting (TECAB) represents a second generation of closed-chest coronary bypass grafting procedures. With application of robotic technology, the procedures are performed using ports, without the need for thoracotomy. After an initial phase in which only single-vessel coronary artery bypass grafting procedures were performed using robotics, some groups reported successful first case reports of double-vessel TECAB.^{1,2} A first small series was published by our group in 2007.³ To date, little information is available on the intraoperative performance, perioperative

results, and long-term outcomes of double-vessel TECAB. We, therefore, analyzed a series of 150 double-vessel TECABs and compared these with a series of single-vessel TECABs performed during the same study period.

METHODS

From 2001 to 2011, 334 single-vessel and 150 double-vessel TECAB procedures were performed using the da Vinci, da Vinci S, and da Vinci Si robotic systems (Intuitive Surgical, Inc, Sunnyvale, Calif). The operations were performed at the Innsbruck Medical University and the University of Maryland Medical Center by 4 console surgeons (J.B., T.S., N.B., and E.L.). The demographic data for the whole study population are listed in Table 1, and the procedures performed are listed in Table 2.

General Surgical Technique

All operations were performed with the patients under general anesthesia with double-lumen tube intubation. The patients were placed in the supine position with the left or right chest slightly elevated. Percutaneous defibrillator patches were placed preoperatively.

Ports were placed under ipsilateral lung collapse. A camera port was inserted into the left fifth intercostal space, and instrument ports were inserted into the third and seventh intercostal spaces. Assistance ports were created in the subcostal region for the EndoWrist (Intuitive Surgical, Inc) endostabilizer and in the parasternal region for transthoracic assistance. The internal thoracic artery (ITA) was harvested using a pedicled technique during the early phase of our series and was skeletonized during the later

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Abbreviations and Acronyms

CABG = coronary artery bypass grafting
 ITA = internal thoracic artery
 TECAB = total endoscopic coronary artery bypass grafting

phases. For revascularization of the right coronary artery territory ports were placed on the right side of the chest, mirroring the left-sided port placements. During the very last phase of our experience, the right coronary artery system was also approached from the patient's left side. For exposure of the lateral and back walls of the heart, the endoscopic stabilizer was used. All anastomoses were created using a short, double-armed 7-0 polypropylene suture.

The arrested heart technique for TECAB has been previously described, and videos of this procedure are available on [OR-LIVE.com](http://www.orlive.com) (available from: <http://www.orlive.com/umm/videos/tecab-totally-endoscopic-coronary-artery-bypass>) and the Minimally Invasive Robotic Association Web site (available from: <http://www.miraweb.org/video.htm>).⁴ The procedures were performed using remote-access heart–lung machine perfusion and ascending aorta balloon occlusion for cardioplegia. For creation of bypass grafts on the beating heart, a suction stabilizer was used, as described previously.⁵ The target vessel was encircled with Silastic tapes, and shunts were used during the later phase of our series. Also during the later phase, patients were cannulated prophylactically, and the heart–lung machine was used in cases of significant space constraints, for exposure of the back wall of the heart, or in the case of hemodynamic instability. We described this cannulation technique in 2009.⁶

TABLE 1. Demographic data

Variable	Single-vessel TECAB	Double-vessel TECAB	P value
Patients (n)	334	150	
Age (y)	60 (31-90)	61 (38-83)	.178
Men	233 (69.8%)	117 (78.0%)	
Women	101 (31.2%)	33 (22.0%)	.150
Height (cm)	172 (137-196)	173 (142-188)	.766
Weight (kg)	80 (48-158)	80 (41-180)	.393
BMI (kg/m ²)	27 (18-47)	28 (14-46)	.379
CVI	23 (7.0%)	21 (14.0%)	.012
Peripheral vascular disease	22 (6.6%)	9 (6.0%)	.492
Dialysis	8 (2.4%)	0 (0.0%)	.05
Preoperative creatinine	0.98 (0.56-12.0)	0.94 (0.48-2.0)	.082
Prophylactic IABP	14 (4.2%)	7 (4.7%)	.802
Previous myocardial infarction	91 (27.2%)	61 (40.7%)	.002
LVEF (%)	60 (20-88)	60 (25-80)	.125
STS risk score (%)	0.59 (0.18-0.99)	0.57 (0.18-0.62)	.448
EuroSCORE			.136
Median	2	2	
Range	0-13	0-7	
Mean ± SD	2.17 ± 2.24	2.35 ± 1.94	
Learning curve cases	113 (33.8%)	105 (70.0%)	.001

Data presented as n (%) or median (range), unless noted otherwise. *TECAB*, Total endoscopic coronary artery bypass grafting; *BMI*, body mass index; *CVI*, chronic venous insufficiency; *IABP*, intra-aortic balloon pump; *LVEF*, left ventricular ejection fraction; *STS*, Society of Thoracic Surgeons; *EuroSCORE*, European System for Cardiac Operative Risk Evaluation.

Definitions

The first 20 cases of a new procedure variation for a single surgeon were defined as the learning curve cases and were documented as such. Of the 334 single-vessel TECAB cases and 150 double-vessel TECAB cases, 112 (33.5%) and 105 (70.0%) were a part of a single surgeon's learning curve, respectively ($P < .001$). The operative time was defined as the interval from skin incision to skin closure. Conversion was defined as the need to open the chest through a larger incision such as sternotomy or thoracotomy because of technical difficulties or inadequate intraoperative revascularization.

Statistical Analysis

The data were collected prospectively, entered into an institutional review board-approved database, and analyzed using the IBM SPSS, version 19.0 (IBM Corp, Armonk, NY), statistical software package. Continuous variables are presented as medians and ranges and categorical variables as absolute values and percentages. Comparisons between single- and double-vessel TECAB were done using the Mann Whitney-*U* test for continuous variables and the χ^2 test or Fisher exact test for categorical variables, as appropriate. Long-term survival and freedom from adverse events were calculated using the Kaplan-Meier method. For comparison between groups, we used the log-rank test.

RESULTS

Of all the procedures, 303 of 334 single-vessel TECAB and 119 of 150 double-vessel TECAB were completed total

TABLE 2. Procedures performed

Variable	Arrested heart	Beating heart
Single vessel		
LITA to LAD	234	75
LITA to Dg	8	
LITA to OM	6	1
RITA to LAD	3	2
RITA to RCA	3	
LITA to LAD (from right side)	1	
RITA to LAD (from right side)	1	
Total	256	78
Double vessel		
RITA LAD + LITA Dg/OM/Cx	62	14
LITA to LAD/LAD jump	34	3
RITA to LAD, LITA Y-graft to PDA	5	
LITA to LAD, RITA Y-graft to PDA	4	1
LITA to LAD, RITA to RCA (from right)	3	
RITA to LAD, LITA Y-graft to RCA (from right)	5	
LITA to LAD, RITA Y-graft to OM	2	
LITA to LAD, SVG to RCA (from right)	3	
LITA to LAD, SVG to Dg	1	2
LITA to LAD, SVG to OM	1	3
LITA to OM/ramus jump	1	
RITA/RA composite to Dg/OM	1	
LITA to LAD, RITA to Dg		3
LITA to LAD/Dg jump		2
Total	122	28

LITA, Left internal thoracic artery; *LAD*, left anterior descending artery; *Dg*, diagonal branch; *OM*, obtuse marginal branch; *RITA*, right internal thoracic artery; *RCA*, right coronary artery; *Cx*, circumflex artery; *PDA*, posterior descending artery; *SVG*, saphenous vein graft.

endoscopically (Table 3). The operative times are also listed in Table 3. The operative times were consistently longer for the completely endoscopic double-vessel TECAB procedures.

The postoperative results are listed in Table 4. In-hospital mortality was 0.3% (1/334) for single-vessel TECAB and 2.0% (3/150) for double-vessel TECAB ($P = .090$). When the single-surgeon learning curve cases were excluded from the analysis, the hospital mortality was 0.5% (1/221) for single-vessel TECAB and 0.0% (0/45) for double-vessel TECAB ($P = .831$) and the mortality was less than predicted using both the Society of Thoracic Surgeons risk score and the European System for Cardiac Operative Risk Evaluation.

The ventilation time was 2 hours longer for double-vessel TECAB, and a trend toward an increased rate of postoperative pulmonary infections was noted in patients undergoing double-vessel TECAB. With double-vessel TECAB, patients required, on average, 2 U of blood compared with the 1 U needed perioperatively with single-vessel TECAB. No significant difference was seen in the hospital length of stay. Patients in both groups had a quick return to normal activities, and no differences were seen between patients after single- and double-vessel TECAB with respect to this endpoint.

The 5-year survival was 93.9% after single-vessel TECAB and 95.8% after double-vessel TECAB ($P = .708$; Figure 1). Freedom from angina showed a trend in favor of single-vessel TECAB, but the difference was not statistically significant (Figure 2). The freedom from major adverse cardiac and cerebral events at 5 years was approximately 10% lower after double-vessel TECAB (Figure 3). However, this difference also did not reach statistical significance.

DISCUSSION

Our series of 150 double-vessel TECAB operations has demonstrated that increasingly complex endoscopic

TABLE 4. Postoperative results

Variable	Single-vessel TECAB	Double-vessel TECAB	P value
Patients (n)	334	150	
Revision for bleeding	21 (6.3%)	7 (4.7%)	.317
Packed red blood cells	1 (0-28)	2 (0-27)	.002
Intra-aortic balloon pump	4 (1.2%)	2 (1.3%)	.602
Atrial fibrillation	50 (15.0%)	21 (13.8%)	.336
Ventilation time (h)	8 (0-278)	10 (0-288)	.006
Pneumonia	10 (3.0%)	10 (6.7%)	.055
Venoarterial ECMO	0 (0.0%)	1 (0.7%)	.310
CVVH	3 (0.9%)	4 (2.7%)	.138
Transitory ischemic attack	0 (0.0%)	2 (1.3%)	.096
Stroke	6 (1.8%)	1 (0.7%)	.307
Intensive care unit stay (h)	21 (11-389)	39 (12-480)	.047
Hospital stay (d)	6 (2-33)	6 (2-27)	.846
Hospital mortality	1 (0.3%)	3 (2.0%)	.091
Observed/expected mortality ratio			
EuroSCORE	0.15	1.00	
STS risk score	0.51	3.51	
Interval to activities (d)			
Walking outside	7 (3-180)	7 (3-90)	.556
Household work	17 (4-360)	17 (7-120)	.205
Driving	21 (5-90)	21 (5-60)	.372
Full activity, including sports	50 (10-365)	44 (7-720)	.954

Data presented as n (%) or median (range). TECAB, Total endoscopic coronary artery bypass grafting; ECMO, extracorporeal membrane oxygenation; CVVH, continuous venovenous hemofiltration; EuroSCORE, European System for Cardiac Operative Risk Evaluation; STS, Society of Thoracic Surgeons.

coronary artery bypass surgery is feasible and reproducible. Compared with single-vessel TECAB, the procedure appears technically more demanding, as reflected by the longer operative times and greater conversion rate. Additionally, this complexity results in postoperative morbidity, such as increased blood transfusion requirements and greater ventilation times. However, the hospital stay was similar and patients recovered equally quickly after single- and double-vessel TECAB. No difference was seen in long-term outcomes, and we found only a slight trend favoring single-vessel TECAB with respect to freedom from symptoms and major adverse cardiac and cerebral events.

Patient Selection

We chose a relatively low-risk cohort with a predicted mortality of 2% according to the European System for Cardiac Operative Risk Evaluation and a predicted mortality of 0.5% according to Society of Thoracic Surgeons risk score. Patients undergoing double-vessel TECAB had had previous myocardial infarcts more frequently and had a greater incidence of cerebrovascular disease than did patients undergoing single-vessel TECAB. Patients requiring dialysis underwent only single-vessel TECAB to avoid long, complex procedures in this specific risk group. Also, only 1

TABLE 3. Intraoperative results

Variable	Single-vessel TECAB	Double-vessel TECAB	P value
Patients (n)	334	150	
Conversion to larger thoracic incision	31 (9.3%)	31 (20.7%)	.001
Any intraoperative technical problem	110 (32.9%)	66 (44.0%)	.019
Operative time (min)			
Including angiography	285 (112-690)	402 (183-1050)	<.001
Surgery	240 (112-650)	375 (168-795)	<.001
Aortic dissection	3 (0.9%)	1 (0.7%)	.634
Upper/lower extremity ischemia	2 (0.6%)	1 (0.7%)	.602

Data presented as n (%) or median (range). TECAB, Total endoscopic coronary artery bypass grafting.

FIGURE 1. Cumulative survival in patients after single- and double-vessel total endoscopic coronary artery bypass grafting (TECAB).

of 3 operations in the single-vessel group was a learning curve case, but 70% of the double-vessel cases were within a single surgeon's learning curve. The perioperative mortality was 0% and 0.5% for single- and double-vessel TECAB, respectively, after these learning curves were overcome.

FIGURE 2. Cumulative freedom from angina in patients after single- and double-vessel total endoscopic coronary artery bypass grafting (TECAB).

FIGURE 3. Cumulative freedom from major adverse cardiac and cerebral events (MACCE) in patients after single- and double-vessel total endoscopic coronary artery bypass grafting (TECAB).

Operative Technique

The present series has demonstrated that a variety of total endoscopic coronary artery bypass grafting (CABG) procedures can be performed. Both arterial and venous grafts can be used, and beating heart and arrested heart approaches are feasible. The first double-vessel TECAB was reported by Kappert and colleagues¹ in 2000, in which a right ITA to the left anterior descending artery and left ITA to the obtuse marginal branch were placed using an arrested heart technique. The beating heart version of this procedure was first described in 2004.²

We performed our initial double-vessel TECABs using the arrested heart technique, because we believed a completely unloaded and flaccid heart would better facilitate rotation and access to the side and back walls of the heart. We described a specific exposure technique for accessing the circumflex coronary artery system in 2006.⁷ In select beating heart cases, exposure of the side and back walls of the heart was enhanced by unloading the left ventricle "on pump."^{6,8}

Our study has also demonstrated that sequential or so-called jump grafts can be performed reproducibly in the closed chest. The group from Frankfurt, Germany introduced this sequential endoscopic bypass grafting technique in 2002 and published a preliminary series.⁹ We also showed that Y-grafts have become a part of the armamentarium of robotic endoscopic coronary surgeons. Balkhy and colleagues,¹⁰ in their recent series of 120 patients undergoing TECAB using automated anastomotic connectors, also

performed sequential grafts and Y-graft constructs. Because the performance of aortocoronary bypass grafts is difficult in the completely endoscopic setting, we regard the development of sequential and Y-grafts as a major step in procedure development.

Operative Times and Conversion Rates

Our data have revealed that double-vessel TECAB has significantly increased operative time requirements compared with single-vessel procedures. The double-vessel operative time was about 6 hours; however, ideal cases can be performed in only 4 hours. Few data are available regarding the time requirements for double-vessel TECAB performed by other groups. Dogan and colleagues⁹ reported an operative time of 7 hours for sequential left ITA to left anterior descending artery and diagonal branch bypasses during a learning curve period. The earliest TECAB reports on double-ITA grafting reported an operative time of 6 hours for arrested heart and 5.5 hours for beating heart procedures.^{1,2} In their 2010 report, Srivastava and colleagues¹¹ reported a time of 5 hours, 20 minutes for double-vessel beating heart TECAB and approximately 3 hours for single-vessel procedures.

Because of the complexity of double-vessel TECAB operations, a greater rate of conversion to a larger thoracic incision was expected when we started our program. Significant conversion rates have been reported in other intricate robotic procedures, such as Whipple operations and endoscopic cystectomy for bladder cancer.^{12,13} Our conversion rate of 20.7% for double-vessel TECAB was comparable to the conversion rates described in early single-vessel TECAB series, which were in the 20% range.^{9,14,15} A decrease in the conversion rate to about 5% has been described for single-vessel TECAB as one progresses beyond the learning curve,⁶ and we expect to see this decrease with double-vessel TECAB as well.

Postoperative Course

More postoperative clinical events occurred after double-vessel TECAB than after single-vessel TECAB. However, our first 150 double-vessel TECAB cases represented our early experience and 70% of the cases were within the learning curve. In contrast, one third of our single-vessel TECABs were learning curve cases. Dogan and colleagues,⁹ in 2002, also reported longer intensive care unit and hospital stays for patients undergoing total endoscopic left anterior descending artery and diagonal branch sequential grafts. This too, however, was a very early learning curve experience.

We chose a threshold of 20 cases to define our learning curve. From our experience, both the time needed to complete a specific procedural task (eg, ITA harvesting, anastomotic suturing) and the total operative time began to improve significantly after the first 20 cases. Nevertheless,

a triple digit number of cases is likely needed to achieve a steady state in terms of consistent task-specific and total operative times. Moreover, only with this many cases, can one attain a high level of comfort.

Morbidity after double-vessel TECAB mainly affected the respiratory system. Prolonged periods of single-lung ventilation most likely contributed significantly to this finding. Patients undergoing double-vessel TECAB received, on average, 2 U of blood perioperatively. We have recently illustrated that the causes for blood transfusions after arrested heart TECAB are multifactorial.¹⁶ It can be anticipated that with additional technical improvements, the blood transfusion requirements in double-vessel TECAB will likely decrease. An additional contributor to morbidity with double-vessel TECAB is addressed by our recent finding that a clear correlation exists between the operative times and conversion to a larger incision.¹⁶ Hence, improving operative times and avoiding the technical problems that lead to these conversions will be imperative in decreasing perioperative morbidity as we move forward.

Concerning mortality, our results did seem to meet the current quality standards, because they were in line with the mortality rates reported in contemporary studies. For example, in their series of 68 double-vessel and 139 single-vessel TECABs, Srivastava and colleagues¹¹ observed no mortalities in nonconverted cases. Balkhy and colleagues,¹⁰ in a mixed series of single- and double-vessel TECABs, reported an overall 30-day mortality of 0.8%. Risk scores were unavailable from either study, however, and in the latter study, 10 very early learning curve cases were excluded. A significant decrease in mortality was observed in our present series after the initial learning curve had been overcome.

Early Rehabilitation Phase

Our data have shown that after both single- and double-vessel TECAB, patients are able to return to their normal activities more quickly than those undergoing traditional coronary bypass surgery through sternotomy. Patients returned to full activity levels—including sports—within 6 to 7 weeks, far shorter than the 10-week period of sternal precautions usually recommended after standard CABG. Kon and colleagues¹⁷ previously demonstrated similar findings after robotically assisted coronary bypass surgery through minithoracotomy. Our Innsbruck team has also shown that after TECAB, patients have advantages with respect to postoperative rehabilitation compared with those who underwent sternotomy and those converted to sternotomy.¹⁸ We believe these quality of life data justify the investment of longer operative times and the technical challenges of robotic surgery.

Intermediate-Term Results

Currently, no published data are available on the intermediate- or long-term results after multivessel TECAB. Our

double-vessel TECABs resulted in the same 5-year survival as was observed for our single-vessel procedures. Moreover, our intermediate-term results have demonstrated that our freedom from angina and freedom from major adverse cardiac and cerebral events were comparable to the results seen after open CABG reported in classic comparative trials such as the Arterial Revascularization Therapies Study, thereby further demonstrating that multivessel robotic interventions are safe in the intermediate term.¹⁹

CONCLUSIONS

Having performed 150 double-vessel TECAB procedures, this operation appears to be reproducible and safe. The technical performance and perioperative results, at present, are slightly inferior to the postlearning curve results for single-vessel TECAB. However, the intermediate-term freedom from symptoms and freedom from adverse events seem to be comparable to the results seen for single-vessel TECAB and meet the standards of open CABG using the traditional sternotomy approach. The learning curve effects are visible.

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