Minimally Invasive Coronary Artery Bypass Grafting
Dual-Center Experience in 450 Consecutive Patients

Joseph T. McGinn, Jr, MD; Saif Usman, MD; Harry Lapierre, MD; Vijayasimha R. Pothula, MD; Thierry G. Mesana, MD, PhD; Marc Ruel, MD, MPH

Background—Minimally invasive coronary artery bypass grafting (MICS CABG) is a novel coronary operation that does not require infrastructure and is potentially available to all cardiac surgeons. It aims at decreasing the invasiveness of conventional CABG while preserving the applicability and durability of surgical revascularization. We examined the feasibility and safety of MICS CABG in the first large series of this operation to date.

Methods and Results—All myocardial territories are accessed via a 4- to 6-cm left fifth intercostal thoracotomy. An apical positioner and epicardial stabilizer are introduced into the chest through the subxyphoid and left seventh intercostal spaces, respectively. The left internal thoracic artery is used to graft the left anterior descending artery, and radial artery or saphenous vein segments are used to graft the lateral and inferior myocardial territories. Proximal anastomoses are performed directly onto the aorta or from the left internal thoracic artery as a T-graft. In the first 450 consecutive MICS CABG procedures at our 2 centers, mean age was 62.3 ± 10.7 years and 123 patients were female (27%). The average number of grafts was 2.1 ± 0.7, with complete revascularization in 95% of patients. There were 34 patients in whom cardiopulmonary bypass was used (7.6%), 17 conversions to sternotomy (3.8%), and 10 reinterventions for bleeding (2.2%). Perioperative mortality occurred in 6 patients (1.3%).

Conclusions—MICS CABG is feasible and has excellent procedural and short-term outcomes. This operation could potentially make multivessel minimally invasive coronary surgery safe, effective, and more widely available. (Circulation. 2009;120[suppl 1]:S78–S84.)

Key Words: bypass coronary disease surgery

An optimal way of performing revascularization for coronary artery disease (CAD) has not yet been identified. Although percutaneous coronary interventions (PCIs) are particularly appropriate for acute ischemic presentations and focal CAD, their long-term durability does not match that of surgical revascularization. On the other hand, coronary artery bypass grafting (CABG) surgery is associated with major morbidity in ≈15% of patients, which includes septicemia, infection, stroke, reoperation, hemorrhage, low cardiac output, new-onset hemodialysis, and adult respiratory distress syndrome. Furthermore, atrial fibrillation is seen in up to 50% of patients after CABG. Chronically, poststernotomy patients not uncommonly experience decreased physical functioning, and up to 30% of CABG patients still report pain 1 year after operation.

The thoracic invasiveness of CABG has not decreased since the operation was introduced >40 years ago. With the exception of a few specialized centers at which total endoscopic coronary artery bypass is performed in very selected patients, no operation has eliminated the sternotomy and decreased the invasiveness of CABG while preserving key principles of complete revascularization and wide applicability for multivessel or diffuse CAD.

Minimally invasive CABG (MICS CABG) is a surgical procedure based on the anatomic relations between the left internal thoracic artery (LITA), the coronary arteries and their branches, the apex of the heart, and the ascending aorta. The goal of the MICS CABG operation is to allow the surgeon to perform, within a patient’s closed anterior thorax, a revascularization configuration equivalent to that of a regular CABG operation while keeping the procedure minimally invasive, without a sternotomy, and in many cases without the use of cardiopulmonary bypass (CPB). We hereby report on our dual-center experience of 450 consecutive patients treated with this cardiac surgical modality.

Methods

Patient Population

Between 2005 and 2008, 450 patients with CAD referred for CABG underwent MICS CABG at the Staten Island University Hospital or...
Table 1. Preoperative Patient Characteristics (N=450)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>SIUH/UOHI</th>
<th>Age, y</th>
<th>Men/women</th>
<th>Ethnicity, n*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>369/81</td>
<td>62.3±10.7 (range, 37–88)</td>
<td>327/123</td>
<td>White 405 (90.0%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Black 15 (3.3%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hispanic 11 (2.4%)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Asian 15 (3.3%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Height, cm 170.7±10.0 (range, 149–198)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Weight, kg 84.5±19.4 (range, 44–163)</td>
</tr>
<tr>
<td>CCS angina class, n</td>
<td>I</td>
<td>80 (17.8%)</td>
<td></td>
<td>Tobacco use, n 265 (58.4%)</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>156 (34.7%)</td>
<td></td>
<td>Cerebrovascular disease, n 41 (9.1%)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>139 (30.9%)</td>
<td></td>
<td>Peripheral vascular disease, n 40 (8.9%)</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>68 (15.1%)</td>
<td></td>
<td>Chronic pulmonary disease, n 66 (14.7%)</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>68 (15.1%)</td>
<td></td>
<td>Chronic renal insufficiency, n 42 (9.3%)</td>
</tr>
<tr>
<td></td>
<td>Prior PCI</td>
<td>159 (35.3%)</td>
<td>80 (17.8%)</td>
<td>Prior CABG, n 7 (1.6%)</td>
</tr>
</tbody>
</table>

CCS indicates Canadian Cardiovascular Society; SIUH, Staten Island University Hospital; UOHI, University of Ottawa Heart Institute.

*Unknown in 4 patients.

Attention is given on history and physical examination to the detection of possible left subclavian artery stenosis. In cases where such suspicion exists, Doppler, computed tomography, or angiographic examination of the left subclavian–LITA axis is warranted. If use of a radial artery is contemplated, then the ulnar pulse and Allen test must be compatible with its safe use. If pulmonary disease, if suspected, is also investigated, because tolerance of single-lung ventilation greatly facilitates the conduct of the operation.

**Operative Procedure**

Patients may be given paravertebral thoracic (T2–T3) blockade. Intubation is performed either with a double-lumen endotracheal tube or with a regular endotracheal tube and a left bronchial blocker to selectively deflate the left lung. Transesophageal echocardiography is routinely used to monitor cardiac function, as well as to help position guide wire–guided femoral venous and arterial cannulas, should CPB be used.

Patients are positioned in a 15° to 30° right lateral decubitus position, with the right arm extended to allow harvest of the radial artery, if applicable. The patient is draped to allow access to the left groin and right thigh/leg for femoral cannulation and saphenous vein harvest, respectively. A 4- to 6-cm incision is made in the left fifth intercostal space, started at the midclavicular line, and extended laterally (Figure 1). In obese patients, the incision can be made slightly larger, and exposure is facilitated by use of a soft-tissue retractor (CardioVations, Edwards Lifesciences, Irvine, Calif). A Finochietto or Thoratrak (Medtronic, Minneapolis, Minn) rib spreader is inserted, and an incision in the pericardium is performed ~1 to 2 cm anterior to the left phrenic nerve, extended cephalad to the level of the left atrial appendage and anterocaudally toward the diaphragmatic reflection. Pericardial retraction stitches are inserted and used in combination with finger mobilization of the left ventricular apex to evaluate the coronary artery targets, after which the heart is returned to its normal position. In patients who experience arterial oxygen desaturation (ie, SaO2 <90% on FiO2 1.0) on single-lung ventilation, reestablishment of double-lung ventilation with smaller tidal volumes and posterior packing of the left lung with 2 wet sponges allows for correction of the hypoxemia while maintaining adequate exposure.
is positioned, and a silicone elastomer (Silastic) occluder is placed.

Venous CPB (without aortic cross-clamping) is used.

During support including low-dose vasopressors, femoral arterial and venous CPB (I-Flow, Lake Forest, Calif) is implanted into the thoracotomy. The anterior pectoralis muscle fascia is closed with No. 0 polyglactin 910. The subcutaneous tissues and skin are closed in the usual fashion.

Postoperative Management and Evaluation
Postoperatively, patients are started on daily enteric-coated acetylsalicylic acid 325 mg on the day of operation. Unless contraindi-
cated, antihyperperfusion medications are resumed on the first postop-
erative day. All patients are treated with medical therapy as with conventional CABG via sternotomy, including aspirin, β-blockers, and anticholesterol agents. Patients undergoing MICS CABG with a radial artery graft are prescribed a dihydropyridine calcium channel blockers for 6 months.

In the present series, all patients were followed up for a minimum of 30 days after discharge from the hospital. Death was defined as mortality occurring within 30 days of operation or at any time during hospitalization. Stroke was defined as a permanent, new, focal neurologic deficit occurring either intraoperatively or postoperatively. Respiratory insufficiency was defined as a cumulative re-
quirement for intubation and ventilation of 72 hours or more at any time during the postoperative stay. New-onset renal failure was defined as the need for temporary or permanent renal dialysis of any type. Transfusion rates were determined by the proportion of patients who received at least 1 transfusion of any blood product, and the mean number of units transfused was derived as the total number of packed red blood cell units transfused divided by the number of patients who received a red blood cell transfusion. A known stenotic or occluded graft was defined as an angiographic graft stenosis of >50% or graft occlusion. Sternal wound infection was defined as drainage of purulent material from the wound and was recorded up to 6 months postoperatively.

Results are reported according to the intent-to-treat principle. Continuous data are expressed as mean±SD and discrete data as numbers (percentage). A log-rank test was used to examine the equality of freedom from late PCI reintervention between patients who had LITA T-grafts and patients who had proximal anastomoses onto the ascending aorta (Stata 10.1, Stata, College Station, Tex).

Operative Characteristics
Of the 450 patients brought to the operating room with the intent to perform MICS CABG, the operation was completed without conversion in 433 (96.2%). Total perioperative mortality occurred in 6 patients (1.3%). Causes of death were multigorgan failure in 3 patients, sepsis in 2, and tamponade in 1.

Table 2 shows the operative characteristics and postoperative results. The mean number of grafts was 2.1±0.7, and 359 patients (79.8%) received 2 or more grafts. Complete revascularization, ie, revascularization of each major myocardial territory subtended by a coronary artery of 1.5 mm or more in diameter with stenosis ≥70%, was achieved in 427 patients (94.9%). Of these, 17 patients had hybrid revascularization during the same hospital stay, with PCI performed either before (n=16) or after (n=1) MICS CABG. Rates of return to the operating room, transfusion, stroke, and atrial

The rib spreader is progressively pulled cephalad and toward the left by using a Rultract Skyhook (Rultract, Cleveland, Ohio) retrac-
tor. With the use of long instruments and a long electrocautery blade, the LITA is taken down from a lateral approach, under direct vision, from the first rib down to the bifurcation. Care is taken at identifying and avoiding the phrenic nerve. Heparin is given intravenously before LITA division.

In the earlier part of the series (ie, first 144 multivessel patients), proximal anastomoses were performed from the LITA in a T-graft configuration with 8-0 polypropylene. All proximal anastomoses were subsequently performed onto the ascending aorta, either by using a proximal connector, or by hand-sewing after the application of a side-biting clamp. To expose the ascending aorta, the pericar-
dium is opened anteriorly and retracted inferolaterally toward the thoracotomy by using several traction sutures and by bringing the retractor in a cephalomedial direction with the Rultract Skyhook. A 6-mm incision is made in the left seventh intercostal space to allow retractor in a cephalomedial direction with the Rultract Skyhook. A 6-mm incision is made in the left seventh intercostal space to allow

Figure 2. Left anterolateral thoracotomy presentation of the ascending aorta for partial clamping and hand-sewn proximal anastomoses. With the use of incremental steps for mediastinal retraction and aortic mobilization (see text), the aorta can rou-
tinely be brought within direct view and reach of the surgeon for the safe performance of hand-sewn proximal anastomoses. AA indicates ascending aorta; RVOT, right ventricular outflow tract.

The aorta can be dissected from the pulmonary artery, and an open gauze tube or occluded graft was defined as an angiographic graft stenosis of 1.5 mm or more in diameter with stenosis ≥70%, was achieved in 427 patients (94.9%). Of these, 17 patients had hybrid revascularization during the same hospital stay, with PCI performed either before (n=16) or after (n=1) MICS CABG. Rates of return to the operating room, transfusion, stroke, and atrial...
fibrillation were low. Excellent wound healing was noted in nearly all patients (Figure 3), with only 1 incident of superficial chest wound infection. Pleural complications were observed almost exclusively in the left thorax.

Procedural Adoption of MICS CABG
Figure 4 displays the surgeon-specific procedural adoption rates of MICS CABG at the 2 centers from which this report originates. Overall, MICS CABG was performed in 450 of 1404 (32.1%) nonemergent coronary bypass patients throughout the study period, and this proportion increased to 142 of 283 patients (50.2%) in 2008.

Mid-Term Reintervention
Mid-term follow-up is available for the series’ first 300 initial patients, 2 mid-term graft failures occurred in the remaining 128 patients who had proximal anastomoses onto the aorta, and both involved saphenous vein grafts (P=0.1 versus LITA T-grafts). No reintervention for graft failure occurred in the 28 patients (from the initial 300) who underwent a single LITA–left anterior descending coronary artery (LAD) operation. Patients with multivessel CAD beyond the initial 144 have all been managed by performing proximal anastomoses onto the aorta.

Discussion
The main finding of this report is that multivessel coronary revascularization can be performed minimally invasively in a large number of patients, with wide applicability and excellent procedural outcomes. In our dual-center series of 450 patients, 2 mid-term graft failures occurred in the remaining 128 patients who had proximal anastomoses onto the aorta, and both involved saphenous vein grafts (P=0.1 versus LITA T-grafts). No reintervention for graft failure occurred in the 28 patients (from the initial 300) who underwent a single LITA–left anterior descending coronary artery (LAD) operation. Patients with multivessel CAD beyond the initial 144 have all been managed by performing proximal anastomoses onto the aorta.

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Mid-Term Reintervention
Mid-term follow-up is available for the series’ first 300 patients to a mean of 19.2±9.4 months (maximum, 39 months). In this period, 10 MICS CABG patients (3.0%) required PCI, 8 of whom developed problems with LITA T-grafts (of 144 patients), with stenosis or occlusion involving either the side graft or the LITA. Also from those 300

Table 2. Operative Characteristics and Postoperative Results (N=450)

<table>
<thead>
<tr>
<th>No. of grafts, n</th>
<th>2.1±0.7 (range, 1–4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 graft</td>
<td>91 (20.2%)</td>
</tr>
<tr>
<td>2 grafts</td>
<td>241 (53.6%)</td>
</tr>
<tr>
<td>3 grafts</td>
<td>111 (24.7%)</td>
</tr>
<tr>
<td>4 grafts</td>
<td>7 (1.6%)</td>
</tr>
<tr>
<td>Use of automated proximal anastomotic device, n</td>
<td>7 (1.6%)</td>
</tr>
<tr>
<td>Use of CPB, n*</td>
<td>34 (7.6%)</td>
</tr>
<tr>
<td>Conversion to sternotomy, n</td>
<td>17 (3.8%)</td>
</tr>
<tr>
<td>Bleeding</td>
<td>5 (1.1%)</td>
</tr>
<tr>
<td>Poor exposure</td>
<td>4 (0.9%)</td>
</tr>
<tr>
<td>Hemodynamic instability</td>
<td>6 (1.3%)</td>
</tr>
<tr>
<td>LITA injury</td>
<td>2 (0.4%)</td>
</tr>
<tr>
<td>Return to operating room, n</td>
<td>12 (2.7%)</td>
</tr>
<tr>
<td>Bleeding</td>
<td>10 (2.2%)</td>
</tr>
<tr>
<td>Graft revision</td>
<td>2 (0.4%)</td>
</tr>
<tr>
<td>Perioperative transfusion, n</td>
<td>96 (21.3%)</td>
</tr>
<tr>
<td>No. of units</td>
<td>3.2±3.4 (range, 1–20)</td>
</tr>
<tr>
<td>New-onset Q waves, n</td>
<td>5 (1.1%)</td>
</tr>
<tr>
<td>Known stenotic or occluded graft, n</td>
<td>4 (0.9%)</td>
</tr>
<tr>
<td>Stroke, n</td>
<td>2 (0.4%)</td>
</tr>
<tr>
<td>Respiratory insufficiency, n</td>
<td>26 (5.8%)</td>
</tr>
<tr>
<td>New-onset renal failure, n</td>
<td>12 (2.9%)</td>
</tr>
<tr>
<td>New-onset atrial fibrillation, n</td>
<td>111 (24.4%)</td>
</tr>
<tr>
<td>Pneumothorax, n</td>
<td>14 (3.1%)</td>
</tr>
<tr>
<td>Length of stay, days</td>
<td>5.9±3.4 (range, 1–86)</td>
</tr>
<tr>
<td>Death, n</td>
<td>6 (1.3%)</td>
</tr>
<tr>
<td>Wound infection, n</td>
<td>4 (0.9%)</td>
</tr>
<tr>
<td>Chest, superficial</td>
<td>1 (0.2%)</td>
</tr>
<tr>
<td>Chest, deep</td>
<td>0</td>
</tr>
<tr>
<td>Lower limb</td>
<td>3 (0.7%)</td>
</tr>
<tr>
<td>Pleural effusion, n</td>
<td>41 (9.1%)</td>
</tr>
</tbody>
</table>

*All patients received a graft to the circumflex coronary system.
patients undergoing MICS CABG during a period of 3.5 years, we observed a low incidence of perioperative morbidity and mortality and high procedural success with regard to applicability and revascularization completeness. Furthermore, this report includes our entire experience, including our initial one, thus suggesting that this procedure may be implemented and developed without the occurrence of a significant “learning curve” with respect to morbidity and mortality.

**MICS CABG Versus CABG**

The present findings are significant in that for >40 years since the introduction of CABG, no diffusible change has occurred to decrease the invasiveness of the operation, and attempts at minimally invasive, multivessel surgical revascularization have succeeded in only low numbers and at highly specialized centers. Although a cost-effectiveness analysis was not performed, MICS CABG does not involve any significant infrastructure acquisition or additional operational costs, thereby potentially facilitating implementation of this new modality at other centers.

To our knowledge, this also constitutes the first large report wherein a minimally invasive multivessel CABG approach compares favorably with the results of the “gold standard” CABG operation. Modern results of conventional CABG include an operative mortality of 2.5%–20 and a 5.2% rate of revascularization within 18 months after the initial procedure. It is important to caution, however, that MICS CABG remains a new technique in need of external validation, that its results might not be generalizable to all centers, and that surgical selection bias may have favored the inclusion of patients more likely to benefit from a sternal-sparing CABG approach. In the present study, >50% of patients had 2-vessel disease; in a related geographic area, Hannan et al found 2-vessel CAD in 30% of CABG and in 75% of PCI patients with multivessel CAD. Therefore, referral patterns may have selected a number of patients for MICS CABG who had less severe CAD or who might otherwise have received PCI.

**MICS CABG Versus MIDCAB**

The MICS CABG operation is quite different from a minimally invasive direct coronary artery bypass (MIDCAB) operation, itself associated with excellent results but restricted to the performance of a single LITA-LAD graft. First, MICS CABG is a multivessel operation that allows for complete revascularization in the presence of 3-vessel or diffuse CAD. Second, the MICS CABG thoracotomy is more lateral and often smaller, allowing for rib spreading with less risk of costochondral or rib injury and for use of the space normally occupied by the left lung (deflated during the procedure) to work within the chest. Third, the LITA can readily be harvested, skeletonized or not, over its entire length, ie, from the level of the subclavian vein down to the bifurcation, as in a conventional CABG operation, thus allowing for optimal selection of the LAD anastomotic site as well as for avoidance of a possible steal phenomenon from LITA side branches. Fourth, all coronary arteries and their relations can be visualized and identified because the pericardium is opened widely. Fifth, the MICS CABG operation allows for proximal anastomoses to be routinely performed onto the ascending aorta.

**MICS CABG Versus Other Multivessel Minimally Invasive Techniques**

There have been other previous reports of nonsternotomy, off-pump CABG for multivessel CAD. These may be broadly classified as 3 types of interventions: robotic approaches, bilateral MIDCAB-based approaches, and single thoracotomy approaches. Previous series have involved fewer patients than in the present study, and to date, few if any approaches have combined minimal invasiveness, wide applicability for multivessel disease, and preservation of the standard CABG anatomic configuration.

Among robotic approaches, Bonatti et al and Schachner et al reported on 85 patients who underwent totally endoscopic coronary artery bypass with the daVinci telemanipulation system between 2001 and 2006. The mean CPB time was 114 minutes, and the aortic endooclusion time was 65 minutes. There was a significant learning curve, including injury to the LITA in 6%. In an experience involving 12 centers, totally endoscopic coronary artery bypass was performed in 98 patients requiring single-vessel LAD revascularization. Average CPB time was 117 minutes, cross-clamp time was 71 minutes, and overall freedom from reintervention or angiographic failure at 3 months was 91%. Multivessel robotics was used by Srivastava et al in 150 patients, with a mean number of grafts per patient of 2.6. In their experience, all coronary arteries could be reached by the use of bilateral internal thoracic arteries, with the use of in situ or composite grafts.

Other multivessel alternatives include bilateral MIDCAB or endo-ACAB, for which Vassiliades reported, in 52 patients, the use of bilateral thoracoscopic internal thoracic artery harvesting followed by a right-sided thoracotomy to reach anterior coronary vessels, including the right coronary artery and the LAD. However, bilateral thoracotomy incisions were necessary to also reach posterolateral vessels, and no grafting of the posterior interventricular branch could be performed.

With respect to thoracotomy approaches, techniques including complex arterial configurations have been previously reported in up to 27 patients. In 2 other publications, single-center thoracotomy multivessel grafting with a configuration similar to that in the present series was reported in as many as 255 patients. Although the thoracotomies were larger (allowing central cannulation via the right atrial appendage and aorta) and used external sternotomy off-pump CABG instruments through the incision, the authors noted good results, including low mortality and an incidence of atrial fibrillation that ranged between 5.5% and 8%.

**Selection of Patients for MICS CABG**

Preoperative assessment of prospective MICS CABG patients is important to identify those with an unsuitable anatomy; those with peripheral, ascending aortic, or subclavian artery disease; or those who are unlikely to tolerate single-lung ventilation. Mild to moderate thoracic hyperinflation is not a contraindication to MICS CABG, as it is often associated
with very good exposure. On the other hand, several considerations may be important for surgeons who are beginning to perform MICS CABG. Patients with severe cardiac hypertrophy, especially when concentric in distribution and associated with diastolic dysfunction, may not allow for adequate exposure of the lateral and inferior coronary arteries, and CPB assistance or conventional CABG may be a better option for these patients. Patients with previous chest trauma or rib fractures on the left side should not be offered MICS CABG early in one’s experience. Early attempts at grafting the circumflex coronary distribution should preferably include patients who have at least 1 well-developed marginal branch target. Finally, as with standard off-pump surgical revascularization, patients with significant ischemia or instability associated with manipulation of the heart should be treated with pump assistance or, if unsuitable, with sternotomy and on-pump CABG.

Limitations
This report is observational and bias in the selection of patients is likely, especially in the earlier part of the experience. Even in the last year of the present series, nearly 50% of our CABG patients still underwent CABG via sternotomy owing to a number of logistical, surgical, and patient selection reasons. Selection bias may therefore have remained throughout the study period and favored the selection of patients who were more likely to benefit from the avoidance of a sternotomy.

Mid-term follow-up is incomplete and ongoing; therefore, no inference can be made regarding the late durability of this revascularization procedure. On the other hand, MICS CABG has evolved to allow for a graft configuration that is anatomically similar to conventional CABG, and chronic-phase results could be equivalent, provided that all technical aspects of the minimally invasive procedure are mastered. Although no adverse events were observed, the use of peripheral CPB occurred in nearly 8% of patients in this series and should be considered to carry an inherent risk of complications.

Conclusions
In this large cohort of adult patients undergoing MICS CABG, applicability, revascularization completeness, morbidity profile, and safety were excellent and were maintained despite rapid procedural adoption. This suggests that a novel minimally invasive surgical alternative to CABG exists, may be widely applicable, and might be associated with at least as good procedural outcomes. However, randomized, controlled trials will be necessary to compare MICS CABG with CABG with respect to survival, long-term patency, and physical functioning.

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References


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