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Comparison of Economic and Patient Outcomes With Minimally Invasive Versus Traditional Off-Pump Coronary Artery Bypass Grafting Techniques

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Abstract

Background—Minimally invasive coronary artery bypass grafting (miniCABG) decreases in-hospital morbidity versus traditional sternotomy CABG. We performed a prospective cohort study (NCT00481806) to assess the impact of miniCABG on costs and metrics that influence quality of life after hospital discharge.

Methods—One hundred consecutive miniCABG cases performed using IMA grafting ± coronary stenting were compared with a matched group of 100 sternotomy CABG patients using IMA and saphenous veins, both treating equivalent number of target coronaries (2.7 vs. 2.9), off-pump. We compared perioperative costs, time to return to work/normal activity, and risk of major adverse cardiac/cerebrovascular events (MACCE) at 1 year: myocardial infarction (elevated troponin or EKG changes), target vessel occlusion (CT angiography at 1 year), stroke, or death.

Results—For miniCABG, robotic instruments and stents increased intraoperative costs; postoperative costs were decreased from significantly less intubation time (4.80 ± 6.35 vs. 12.24 ± 6.24 hours), hospital stay (3.77 ± 1.51 vs. 6.38 ± 2.23 days), and transfusion (0.16 ± 0.37 vs. 1.37 ± 1.35 U) leading to no significant differences in total costs. Undergoing miniCABG independently predicted earlier return to work after adjusting for confounders ($t = -2.15$; $P = 0.04$), whereas sternotomy CABG increased MACCE (HR, 3.9; 95% CI, 1.4 –7.6), largely from lower target-vessel patency.

Conclusions—MiniCABG shortens patient recovery time, minimizes MACCE risk at 1 year, and showed superior quality and outcome metrics versus standard-of-care CABG. These findings occurred without increasing costs and with superior target vessel graft patency.

Coronary artery bypass grafting (CABG) provides a distinct survival advantage over medical therapy in certain patient subgroups. Although CABG typically involves the placement of several bypass grafts, it is believed that the survival benefit is derived mainly by grafting the left internal mammary artery (LIMA) onto the left anterior descending (LAD) artery.[1] The LAD is accessible for grafting with the LIMA without requiring a full sternotomy using a technique called minimally invasive direct coronary artery bypass (MIDCAB) grafting. It has

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been reported that the MIDCAB procedure is superior to stenting with regard to the need for repeated intervention, and yields equivalent LIMA graft patency and fewer perioperative complications when compared with conventional CABG performed via a sternotomy.[2] MIDCAB is not offered at most surgical centers due to the technical difficulty of the procedure, the risk of prolonged rib pain and the limited number of patients are candidates for single vessel LIMA to LAD grafting. It has been proposed that the da Vinci surgical robot (Intuitive Surgical, Mountain View, CA) helps to address these disadvantages by avoiding the need for extensive rib retraction to access and harvest a long length of IMA conduit.[3,4] The robot enables minimally invasive harvest of both the right and left IMA, thus providing the benefits of having 2 of these gold standard conduits without the risk of provoking a sternal infection. The addition of percutaneous coronary intervention (PCI) and intracoronary stenting creates a minimally invasive hybrid strategy (mini-CABG) that is suitable for a broader spectrum of patients referred for surgical revascularization.[3,5]

A potential concern regarding mini-CABG from the perspective of the hospital and/or payer is its direct or variable cost relative to the gold standard of a median sternotomy approach. The use of a robot ± intracoronary stent(s) lead to significantly higher intraoperative costs compared with using a sternal saw and autologous conduits for conventional sternotomy CABG.[6] We have previously demonstrated that mini-CABG can decrease in-hospital morbidity.[6] The purpose of this study was to identify the effect of miniCABG on in-hospital costs and its effect on patient outcomes through 12 months, in comparison to the results of traditional off-pump CABG performed via a median sternotomy.

METHODS

Patient Selection

The institutional review board provided approval for this prospective, observational study of patients undergoing the surgical revascularization at this institution between January 2005 and June 2007 (UMB IRB 25350, clinical trial registration number NCT00481806). All patients provided informed consent before enrollment.

Inclusion criteria for enrollment into the mini-CABG group included the presence of multivessel coronary artery disease (CAD) involving anterior and lateral coronary branches that were deemed suitable targets for grafting via a mini-thoracotomy. If additional coronary lesions were present, they were evaluated by 2 cardiologists (B.R., D.Z.) and deemed suitable for PCI/stenting. Hemodynamically unstable patients and those who could not be provided with a complete revascularization were excluded. Other exclusion criteria included severe pulmonary and vascular disease, decompensated heart failure, significant arrhythmia, and allergic to radiographic contrast. One hundred consecutive miniCABG cases performed using IMA grafting ± coronary stenting that met the inclusion/exclusion criteria were analyzed.

A group of 100 sternotomy CABG patients using IMA and saphenous veins was selected as a comparison control group from a cohort of 307 patients undergoing off-pump coronary artery bypass (OPCAB) surgery using a median sternotomy approach during the study period. The matching criteria included risk factors for outcomes of surgical revascularization that influence the propensity to perform mini-CABG (Table 1), which was used to create a propensity score derived from a logistic regression model.[7] A computer algorithm was then used to obtain one-to-one matching of the propensity scores for each miniCABG patient with its closest match from the OPCAB cohort.

Surgical Procedure

MiniCABG was performed using the da Vinci S robot (Intuitive Surgical) with instruments telemanipulated via a robotic console. The camera port was entered in the left fifth intercostal space, 4 cm at the anterior axillary line, and the right and left robotic ports were inserted through the third and seventh intercostal spaces. Continuous carbon dioxide insufflation was initiated at 8 to 10 mm Hg pressure. The LIMA ± RIMA was dissected using a skeletonized technique. The distal anastomoses of the in situ IMA grafts were completed through a small thoracotomy on the beating heart using a suction based stabilizer (Octopus 4.3; Medtronic, Inc, Minneapolis, MN). When PCI was performed concurrently (ie, hybrid procedure), intraoperative angiography was used to confirm patency of the bypass grafts. Anesthesia management was directed towards extubation in the OR for miniCABG patients and a “fast track” protocol for extubation of OPCAB patients within 6 hours of arrival to the intensive care unit.

The OPCAB control group was approached via median sternotomy. Conduits included the LIMA, saphenous vein, which was harvested endoscopically (VasoView6; Guidant Systems, Inc., Minneapolis, MN), and radial artery, which was harvested using an open technique. The proximal aortosaphenous anastomoses were performed first using a partial occluding aortic clamp and distal anastomoses were performed on the beating heart.

Blood flow and flow waveform were measured in each graft using transit time ultrasound (Medistim, Inc.). Those grafts with flow <10 mL/min and PI >5 (n = 1 OPCAB, n = 1 miniCABG) or with a stenotic anastomotic appearance on intraoperative angiography (n = 1 miniCABG) underwent revision of the distal anastomosis with improvement in parameters in each case.

PCI Procedure

In those requiring the hybrid approach, PCI procedure was performed immediately after completion of LIMA grafting. Access was achieved via the femoral artery through the use of 6F guiding catheters. The use of pre- and postdilation was left to the discretion of the operator. Drug-eluting stents were implanted in all patients consisting of the Cypher sirolimus-eluting stent (Cordis Corporation, Miami Lakes, FL) and the Taxus Paclotaxel-eluting stent (Boston Scientific, Inc., Natick, MA). This simultaneous hybrid procedure can be viewed through a surgical webcast.[8]

Unfractionated heparin was given intraoperatively to obtain a kaolin-based ACT >300 seconds and heparin level >2 IU/mL according to heparin-protamine titration assay (HMS heparin assay cartridges, Medtronic, Inc.). In all patients, aspirin (325 mg p.o. daily) was given preoperatively and within 6 hours postoperatively. Heparin was reversed with protamine only in patients that did not undergo PCI. For patients undergoing PCI, a loading dose of 300 mg of clopidogrel was given postoperatively upon arrival to the intensive care unit (ICU) followed by 75 mg daily thereafter. GPIIb/IIIa antagonists were not used. Blood lost intraoperatively was salvaged by a cell saver device, washed, and retransfused in both groups.

Clotting Assay

Citrated (3.2%) blood samples were collected pre- and post-operatively for analysis by thrombelastography. Whole blood was stimulated with kaolin within the TEG analyzer (TEG Hemoscope, Niles, IL) and the maximum amplitude (MA) was determined, a parameter, which is dependent on number of platelets and its functional interaction with fibrin.[9]

Clinical Outcomes

Perioperative outcomes were monitored including length of surgery, hospital and ICU lengths of stay, intubation time, intraoperative blood loss, and transfusion requirements. Major

postoperative complications within 30 days were defined as acute myocardial infarction (Q-wave or troponin I >5 times of normal), bypass graft failure, symptom-driven need for revascularization, clinically evident stroke, 30-day mortality, acute renal failure (oliguria and serum creatinine level >2.0 mg/dL or the requirement of dialysis), reoperation for bleeding, severe infection including mediastinitis or septicemia, and prolonged ventilation requiring greater than 24 hours of ventilatory support.

Graft patency was determined at discharge and at 6 to 12 months by blinded review of a 16 detector row, CT angiography (CTA) scan (420 milliseconds rotation, 100- to 150-mL contrast agent IV at 5 mL/s) using retrospective ECG gating. Two patients in each group were excluded due to elevated creatinine. Patency was defined as any flow through the entire graft regardless of the presence of stenosis (ie, Fitzgibbon A/B). The graft was classified as nonpatent if a stump was seen or if there was no contrast in an area known by operative report to contain a graft (ie, Fitzgibbon O), as previously described by our group.[10]

Demographics, preoperative risk factors, medications, intra-, and post-operative data on complications were prospectively recorded onto Teleform case report forms (TELEform Elite; Cardiff Software Ltd, Vista, CA), electronically scanned and imported into a relational database. In addition, patients were interviewed by phone at 3 months and 1 year to assess major adverse cardiac and cerebrovascular events (MACCE), the amount of time required for incisional pain to resolve, and the length of time taken to return to work or normal activities. MACCE included myocardial infarction, stroke, graft failure, and cardiac related death. Patient satisfaction with the overall surgical experience was assessed using a semiquantitative scale of 1 to 6, with 1 being very dissatisfied and 6 being very satisfied, an assessment tool previously validated by our group.[6]

Cost Analysis

Cost data were retrieved for each patient from the hospital's database (McKesson Horizon Performance Manager, San Francisco, CA) and represent actual resource consumption. Mean total costs were calculated from intraoperative costs (OR time, supplies including stent cost and robotic disposables, medications, labs, radiology, and other services) and postoperative costs (ICU, room, medications, labs, radiology, physical therapy, and other tests). Preoperative and indirect cost (eg, administration, utilities, and hospital maintenance) were not included in the analysis.

The analysis was performed with and without including the institutional cost for the da Vinci S robotic system of $1,480,000 with a maintenance fee of $139,000/yr. To account for amortization of cost for this technology, an additional $4309/patient was added based on an assumption of 100 robotic cases/yr and a 5-year lifespan of the robotic system.

Patients were classified as high or low risk according to the All Patient Refined Diagnosis Related Groups (APR-DRG) clinical model developed by 3M Health Information Systems and by the European System for Cardiac Operative Risk Evaluation (EuroSCORE).[11] Total margin was defined as the regulated approved revenue adjusted for actual collections less total expense. The procedure's hospital efficiency ratio was calculated as the actual versus expected cost of care.

Statistical Analysis

The primary end point of this study was to compare the costs and hospital profit margins between the miniCABG versus sternotomy OPCAB groups, stratified according to patient risk. A secondary end point was to analyze the effect of performing mini-CABG on metrics that influence quality of life after hospital discharge such as MACCE, time to return to work/full

activities (≥1 month), time for pain to resolve (≥2 weeks), and the patient's overall satisfaction with the procedure (score = 6).

Continuous variables were expressed as a mean ± SD and were examined using the 1-way analysis of variance (ANOVA). Categorical variables were compared by means of Welch *t* tests. Comparison of MACCE curves was performed using log-rank test. A *P* value ≤0.05 was considered statistically significant. Multiple correspondence analysis was performed as an exploratory technique to identify those comorbidities and other risk factors that have a significant influence on clinical outcomes. Logistic regression analysis was used to determine variables with an independent effect. Statistical analyses were performed using the InStat (GraphPad, San Diego, CA) and XLSTAT statistical software packages.

RESULTS

Group Characteristics

Preoperative risk factors, comorbidities, medications, and EuroSCORE were similar between the 2 groups, as shown in Table 1. There was also no significant difference between groups in the logistic EuroSCORE for patients categorized by APR-DRG as either extreme or class 4 risk (17.0 ± 24.4, n = 21, vs. 14.2 ± 8.3, n = 18; *P* = NS) versus the other classes (ie, 1–3) risk (5.8 ± 6.4 vs. 4.1 ± 2.1%; *P* = NS). The mean number of stents placed in the miniCABG group was 0.7 ± 0.7 with a diameter of 3.0 ± 0.4 mm and length of 32.1 ± 17.8 mm. The mean number of grafts for miniCABG and OPCAB patients was 1.9 ± 0.4 and 2.9 ± 0.8, respectively. All patients underwent LAD grafting using an IMA graft. Non LAD targets were grafted in miniCABG patients with the other IMA in 58 cases (30 diagonal, 18 ramus, 10 OM) and RA in 34 cases (20 diagonal, 12 OM, 2 ramus) and in OPCAB patients with 150 SVG (55 OM, 50 PDA, 36 ramus, 9 diagonal) and 38 RA (20 OM, 8 PDA, 8 ramus, 2 diagonal).

Thirty-Day Outcomes

Compared with OPCAB, patients undergoing miniCABG showed significantly shorter times for intubation and less ICU and hospital lengths of stay (Table 2). The percentage of patients in each group that met the fast-track extubation goal was 59% in the miniCABG group (ie, OR extubation) versus 41% of the OPCAB group (ie, extubation within 6 hours) (*P* = 0.03). The miniCABG group showed less intraoperative blood loss and packed red blood cell (PRBC) transfusion requirements (Table 2) and significantly better preservation in clot strength (ie, TEG-MA) assessed immediately postoperatively (1% vs. 10% decline from baseline; *P* = 0.001).

As shown in Table 3, the aggregate rate of major complications during the postoperative period was significantly higher in the OPCAB than miniCABG group (37% vs. 12%; *P* = 0.031). Readmission within the first 30 days was required in the miniCABG group due to a pleural effusion (3 patients) and stent thrombosis (1 patient) and in the OPCAB group due to respiratory complications (4 patients), recurrent angina (2 patients), mediastinitis (2 patients), and fever (one patient). On multivariate analysis, only group assignment (ie, mini-CABG versus OPCAB), and not baseline comorbidities or other risk factors, was found to have a significant effect on whether the patient experienced a major postoperative complication.

One-Year Outcomes

At 1-year follow up, 78% of patients completed CT angiography and 100% of alive patients completed the phone interview. The miniCABG group showed 1 cardiac-related mortality, 1 stroke, 1 IMA graft stenosis and 1 stent thrombosis. The OPCAB group showed 4 cardiac deaths, 2 strokes, and 20 cases of SVG failure. As a result, the incidence of MACCE was 26%

in the OPCAB group compared with 4% after miniCABG (HR, 3.9; 95% CI, 1.4–7.6; P = 0.008) (Fig. 1).

Compared with the OPCAB group, miniCABG was more frequently associated with the highest level of satisfaction after surgery (76.5% vs. 42.9% with a score of 6; P = 0.035). They also had a shorter duration of postoperative incisional pain (13.1 ± 10.9 vs. 26.6 ± 31.4 days), but the difference versus OPCAB patients did not reach statistical significance. MiniCABG patients returned to work and/or normal activities in a significantly shorter period of time than OPCAB patients (44.2 ± 33.1 vs. 93.0 ± 42.5 days; P = 0.016). Multiple correspondence analysis identified OPCAB, female gender, COPD, cerebrovascular disease, previous revascularization, and history of arrhythmia as predictors of ≥1 month to return to work. Multivariate, forward stepwise, logistic regression analysis showed that only assignment to OPCAB predicted longer return to work (standardized coefficient 0.59; CI, 0.48 –1.72; χ^2 = 11.7).

Cost Analysis

MiniCABG incurred significantly higher cost for operative supplies, OR time, and radiology service compared with OPCAB (P = 0.016, 0.004, and <0.001, respectively) but significantly less costs during the postoperative course attributed to drugs, labs, and ICU stay (P = 0.002, 0.026, and <0.001, respectively) (Table 4). Without incorporating the amortization of initial capital outlay and ongoing service costs of the robot for the miniCABG group, there were no significant differences in total in-hospital costs between groups. Allocating these robotic expenses resulted in a significant increase in total costs for the miniCABG group ($7218 increase vs. OPCAB; P = 0.001).

For the entire cohort, the miniCABG versus OPCAB groups were found to have nearly identical cost efficiency ratios (0.97 ± 0.13 vs. 0.95 ± 0.19; P = NS) and total margins ($8768 ± 12,581 vs. $9496 ± 13,946; P = NS). Reanalysis with the groups stratified according to risk revealed that miniCABG had a significantly more favorable cost efficiency (0.62 ± 0.16 vs. 0.81 ± 0.17; P <0.05) and profit margin (25,132 ± 6086 vs. 15,653 ± 8141; P = 0.01) than OPCAB for patients at extreme (ie, class 4) risk.

DISCUSSION

Although OPCAB has not been broadly adopted, the continued decline in hospital reimbursement for CABG provides incentive for re-examining the cost advantages of off-pump techniques[12] and whether evolution in practice towards miniCABG will enhance or roll-back this benefit. The mini-CABG strategy was first introduced about a decade ago in response to patient demands for less invasive surgery and has been documented to accelerate postoperative recovery and improve early quality of life by our group[6] and others.[13–15] Admittedly, performing multiple surgical grafts via a small thoracotomy can be a technical challenge in many patients. Robotics and PCI/stenting provide critical tools for being able to reliably treat multivessel disease with this approach and avoid the adverse consequences of incomplete revascularization.[16] An unresolved concern has been that the additional costs incurred by these adjuvant technologies make miniCABG prohibitively expensive relative to conventional CABG.

The main finding of our study was that total hospital costs were not significantly increased in the miniCABG group compared with an OPCAB control group matched for risk factors likely to effect perioperative resource utilization. Although the price of stents and robotic instruments increased intraoperative costs for miniCABG, this was offset by reduced postoperative expenses due to less transfusions, shortened ICU, and hospital stay. Given that hospital reimbursement for CABG in the state of Maryland is fixed among risk groups and not

influenced by whether PCI or robotics were used, the resulting profit margins were similar between groups. It is not possible to formally conclude that costs were statistically equivalent between groups; more than 300 patients in each treatment group would have been required to demonstrate such equivalence. However, this analysis does demonstrate that enabling technology for alternative and less invasive techniques can be implemented in pursuit of improved patient outcomes without unduly compromising the economic resources of the hospital.

Of note, we excluded the expense of the robot from the cost analysis of our miniCABG cohort because, at our center, the robot was a pre-existing capital expense used by other services besides cardiac surgery. Allocating the amortized capital and service expenses related to the robot into the analysis increased total costs for miniCABG by nearly $8000/patient over the OPCAB group. These data suggest that the purchase of a robot for the sole purpose of creating a mini-CABG program is not likely to be profitable for the hospital. This is particularly true during the early phase of the “learning curve” for this procedure, which is associated with longer OR times and a greater risk of intraoperative conversion to on-pump CABG, factors that reverse the cost advantages of OPCAB.[17,18]

IMA harvesting thoracoscopically instead of robotically is an alternative technique that might have reduced intraoperative costs and improved cost effectiveness. In a series of over 600 patients undergoing thoracoscopic IMA harvest, Vassiliades et al[19] reported excellent results with single IMA harvest. However, only a small minority (5%) underwent procurement of bilateral IMA. According to the authors, BIMA harvesting via ports placed on both sides of the chest is a lengthy and cumbersome procedure, whereas harvest via a unilateral approach can be quite technically challenging in many patients. IMA dissection on the side of the chest contralateral to the port sites requires the thoracoscopic instruments to be manually manipulated at their furthest extent across the mediastinum. Precise manipulation of the instruments can be further hindered by a hyperinflated right lung, a large beating heart, increased mediastinal adiposity, and thick subcutaneous fat, features that have minimal influence the robotic approach. In light of the well-described advantages of using BIMA grafts for CABG, the reluctance of even the most experienced thoracoscopic surgeons to routinely harvest both IMA highlights an important advantage of our robotic-assisted miniCABG approach.

Another limitation of the overall potential economic impact of our analysis is that it was based on hospitalization costs alone. We did not collect data on resource use for outpatient treatment during this study. If miniCABG is associated with lower morbidity compared with OPCAB, this would likely be reflected in lower outpatient treatment and medication use for patients undergoing miniCABG. If and/or when policies for hospital reimbursement become adjusted in recognition of the improved postoperative outcomes for mini-CABG, the cost effectiveness of this procedure is likely to improve relative to OPCAB.

In prior reports, miniCABG has been reserved for highly selected, low risk patients with multivessel CAD.[4,13–15] When minimally invasive surgery has been described for those at extreme perioperative risk, coronary revascularization has often been limited to the LAD (ie, MIDCAB procedure).[20] Our experience suggests the miniCABG strategy is feasible for complete multivessel revascularization in all patients with suitable coronary anatomy, even those at the most extreme perioperative risk. In fact, this highest risk subgroup seems to derive more clinical benefit from avoiding the sternotomy than lower risk patients, just as OPCAB has been shown to provide maximal benefit in those at highest risk for complications due to the use of CPB.[21,22] Avoiding postoperative complications in patients at extreme risk (ie, ARP-DRG class 4) with the miniCABG approach translates into a greater cost efficiency for this procedure compared with OPCAB. As a result of higher reimbursements for this class 4

risk category, miniCABG was associated with an average profit of more than $25,000, a 65% greater margin than derived when similar risk patients underwent OPCAB. Because this extreme risk subgroup consumes more healthcare resources than all others, our findings suggest that a viable miniCABG program is an important tool for containing costs at tertiary referral centers that are exposed to large number of these patients. Paradoxically, almost all miniCABG programs are currently located in community hospital settings and not in academic, tertiary referral centers.

Randomized trials have demonstrated relatively modest differences in morbidity and mortality for off- versus on-pump CABG.[23] In the minds of many cardiac surgeons, these differences do not justify broad adoption of beating heart techniques. As a result, OPCAB has been limited to <20% of all CABG procedures performed per year and miniCABG is offered in only 10 centers in the United States on a routine basis. Unique impediments to miniCABG include the belief that there are too few candidates because of unsuitable coronary anatomy and concern that graft patency will be compromised by the difficulty of performing anastomoses on a beating heart through a small incision.[24] Our protocol addressed these concerns. Both the right and left IMA are accessible for harvest by the robot, providing 2 “gold standard” bypass grafts with patency results that far exceed other conduits.[25] This limits concerns about competitive flow from the native coronary artery that would exist if the radial artery were used as a conduit in this cohort. Blood flow was assessed in all grafts intraoperatively after the distal anastomosis and revised if necessary. Finally, we limited surgical grafting in miniCABG patients mainly to coronary targets located on the anterior and lateral myocardium and used PCI/stenting for inferior-lateral lesions as described by others.[26] We feel that these measures expanded the number of patients suitable for miniCABG and minimized the chance that technical defects in the grafts influenced our results.

The OPCAB group had a significantly higher risk of MACCE during the first postoperative year than the mini-CABG group. This was largely attributed to a 20% rate of SVG failure during this time period after OPCAB versus 1 failed IMA graft in the miniCABG group. These data suggest that minimally invasive techniques need not lead to imprecise IMA graft anastomoses nor to a decrement in early graft patency and are consistent with published series showing that bilateral IMA grafts provide long-term patency rates of >90% and lower risk of MACCE.[25] In addition, our findings highlight that the use of coated stents provides an option for early revascularization that is likely to be highly competitive to all grafts other than the IMA. However, the long-term consequences of the risk of thrombosis in coated stents remain to be clarified.[27] It is important to note that those patients in the miniCABG group that underwent PCI received postoperative clopidogrel and aspirin, whereas OPCAB patients received aspirin alone. A reduction in MACCE after miniCABG may be related to this aggressive antithrombotic regimen and not from surgical technique. However, mini-CABG patients showed less blood loss and PRBC transfusion requirements and significantly better preservation in postoperative clot strength as measured by TEG. This emphasizes that even if antithrombotic agents were mainly responsible for the rate of postoperative MACCE, the use of a thoracic versus sternal incision still influenced the safety (and therefore, efficacy) of this more aggressive antithrombotic therapy.

Commonly, studies of the hybrid approach have described the performance of PCI and surgery in a staged fashion and in different operative settings.[26,28] Typically, when the “culprit lesion” leading to symptoms is within the LAD, surgery is performed first while PCI takes priority for symptomatic right coronary artery or left circumflex lesions. In our study, a specially designed operating room enables CABG and PCI procedures to be completed simultaneously in a single setting, eliminating this logistical conflict regarding which sequence proves to be optimal and allowing immediate assessment of LIMA patency by intraoperative angiography. Because of their expense, few operating rooms are equipped with a robot and angiographic facilities, which

limits the widespread applicability of our findings. However, as the hybrid approach evolves in cardiac surgery and other surgical fields, it is likely that more centers would become equipped with these technologies.[29]

This study was not a randomized comparison of these 2 surgical techniques; thus the possibility of bias exists. We attempted to minimize this possibility in several ways. First, we included consecutive miniCABG patients in the study, rather than targeting certain patients for analysis. Second, a third party statistician analyzed the outcome data in the 2 groups while unaware of which group was miniCABG versus OPCAB. Third, we closely matched the OPCAB control group to the characteristics of the miniCABG group to minimize the influence of variables that may have confounded the analysis. Finally, all surgery in both groups was performed by a single surgeon, which reduced surgical variability and made the groups more comparable. Another important limitation is that 1-year follow-up angiography was only obtained in 78% of the enrolled patients. Therefore, we cannot exclude the possibility of selection biases affecting our findings, a limitation that is inherent in trials that require patients to undergo follow-up procedures with potential adverse effects (eg, contrast nephropathy). A final limitation is that many important drivers of hospital costs and patient satisfaction are often influenced by subjective judgments (eg, extubation times, length of stay, and red blood cell transfusions). It is possible that enthusiasm for miniCABG biased the management of these variables and therefore the differential in costs and satisfaction. We believe the risk of this type of bias was minimized by the fact that our study was performed in the context of declining reimbursements and numbers of referrals for CABG, which creates a strong incentive to limit costs and improve patient satisfaction regardless of the approach. Finding reduced postoperative costs for the miniCABG group is notable given that OPCAB currently represents the best available evidence-based approach to save costs in the treatment of patients requiring surgical revascularization.

CONCLUSIONS

The miniCABG strategy is a unique example of a healthcare innovation that cuts across existing disciplines to best meet the needs of patients. In exchange for increasing intraoperative costs relative to OPCAB, the use of robotic assistance ± PCI during miniCABG provide 3 advantages: (1) broaden the number of candidates requiring multivessel revascularization that are suitable for a minimally invasive approach, (2) reduce postoperative costs, and (3) improve quality of life metrics immediately after surgery and through the first postoperative year. Although the long-term value of this strategy compared with the conventional approach remains to be investigated, concerns over hospital costs should not deter from its use in appropriate candidates.

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References

1. Caracciolo EA, Davis KB, Sopko G, et al. Comparison of surgical and medical group survival in patients with left main coronary artery disease: long-term CASS experience. Circulation 1995;91:2325–2334. [PubMed: 7729018]
2. Diegeler A, Thiele H, Falk V, et al. Comparison of stenting with minimally invasive bypass surgery for stenosis of the left anterior descending coronary artery. N Engl J Med 2002;347:561–566. [PubMed: 12192015]
3. Katz MR, Van Praet F, de Canniere D, et al. Integrated coronary revascularization: percutaneous coronary intervention plus robotic totally endoscopic coronary artery bypass. Circulation 2006;114 (suppl 1):I473–I476. [PubMed: 16820621]

4. Subramanian VA, Patel NU, Patel NC, et al. Robotic assisted multivessel minimally invasive direct coronary artery bypass with port-access stabilization and cardiac positioning: paving the way for outpatient coronary surgery? Ann Thorac Surg 2005;79:1590–1596. [PubMed: 15854938]
5. Murphy G, Angelini G. Hybrid coronary revascularization in the era of drug-eluting stents. Ann Thorac Surg 2004;78:1861–1867. [PubMed: 15511503]
6. Kon Z, Reicher B, Brown E, et al. Simultaneous hybrid coronary revascularization reduces postoperative morbidity compared to procedures utilizing only coronary artery bypass grafting. JTCVS 2008;135:367–375.
7. D'Agostino RB Jr. Tutorial in biostatistics: propensity score methods for bias reduction in the comparison of a treatment to a non-randomized control group. Stat Med 1998;17:2265–2281. [PubMed: 9802183]
8. Available at: http://www.or-live.com/umm/1713.
9. Oshita K, Az-ma T, Osawa Y, et al. Quantitative measurement of thromboelastography as a function of platelet count. Anesth Analg 1999;89:296–299. [PubMed: 10439733]
10. Poston RS, Gu J, Brown JM, et al. Endothelial injury and acquired aspirin resistance as promoters of regional thrombin formation and early vein graft failure after coronary artery bypass grafting. J Thorac Cardiovasc Surg 2006;131:122–130. [PubMed: 16399303]
11. Nashef SAM, Roques F, Gauducheau ME, et al. European system for cardiac operative risk evaluation (Euro SCORE). Eur J Cardiothorac Surg 1999;16:9–13. [PubMed: 10456395]
12. Puskas JD, Williams WH, Mahoney EM, et al. Off-pump vs conventional coronary artery bypass grafting: early and 1-year graft patency, cost, and quality-of-life outcomes: a randomized trial. JAMA 2004;291:1841–1849. [PubMed: 15100202]
13. Srivastava S, Gadasalli S, Tijerina O, et al. Planned simultaneous beating-heart totally endoscopic coronary artery bypass (TECAB) and percutaneous intervention in a single operative setting. Innovations 2006;1:239–242.
14. Damiano RJ Jr, Ehrman WJ, Ducko CT, et al. Initial United States clinical trial of robotically assisted coronary artery bypass grafting. J Thorac Cardiovasc Surg 2000;119:77–82. [PubMed: 10612764]
15. Mohr FW, Falk V, Diegeler A, et al. Computer enhanced coronary artery bypass surgery. J Thorac Cardiovasc Surg 1999;117:1212–1214. [PubMed: 10343274]
16. Jones EL, Weintraub WS. The importance of completeness of revascularization during long-term follow-up after coronary artery operations. J Thorac Cardiovasc Surg 1996;112:227–237. [PubMed: 8751484]
17. Oehlinger A, Bonaros N, Schachner T, et al. Robotic endoscopic left internal mammary artery harvesting: what have we learned after 100 cases? Ann Thorac Surg 2007;83:1030–1034. [PubMed: 17307454]
18. Shiga T, Apfel CC, Wajima Z, et al. Influence of intraoperative conversion from off-pump to on-pump coronary artery bypass grafting on costs and quality of life: a cost-effectiveness analysis. J Cardiothorac Vasc Anesth 2007;21:793–799. [PubMed: 18068054]
19. Vassiliades TA Jr, Reddy VS, Puskas JD, et al. Long-term results of the endoscopic atraumatic coronary artery bypass. Ann Thorac Surg 2007;83:979–984. [PubMed: 17307445]
20. Sunderdiek U, Kalweit GA, Marx R, et al. Minimally invasive coronary artery bypass grafting in high-risk patients. Late follow-up with assessment of left internal mammary artery graft patency and flow by exercise transthoracic Doppler echocardiography. Cardiovasc Surg 2003;11:389–395. [PubMed: 12958550]
21. Al-Ruzzeh S, Nakamura K, Athanasiou T, et al. Does off-pump coronary artery bypass (OPCAB) surgery improve the outcome in high-risk patients?: a comparative study of 1398 high-risk patients. Eur J Cardiothorac Surg 2003;23:50–55. [PubMed: 12493504]
22. Demaria RG, Carrier M, Fortier S, et al. Reduced mortality and strokes with off-pump coronary artery bypass grafting surgery in octogenarians. Circulation 2002;106(suppl 1):I5–I10. [PubMed: 12354700]
23. Puskas J, Cheng D, Knight J, et al. Off-pump versus conventional coronary artery bypass grafting: a meta-analysis and consensus statement from the 2004 ISMICS consensus conference. Innovations 2005;1:3–27.

24. Robicsek F. Robotic cardiac surgery: time told! J Thorac Cardiovasc Surg 2008;135:243–246. [PubMed: 18242242]

25. Lytle BW, Blackstone EH, Loop FD, et al. Two internal thoracic artery grafts are better than one. J Thorac Cardiovasc Surg 1999;117:855–872. [PubMed: 10220677]

26. Cohen HA, Zenati M, Smith AJ, et al. Feasibility of combined percutaneous transluminal angioplasty and minimally invasive direct coronary artery bypass in patients with multivessel coronary artery disease. Circulation 1998;98:1048–1050. [PubMed: 9736589]

27. Pfisterer M, Brunner-La Rocca HP, et al. Late clinical events after clopidogrel discontinuation may limit the benefit of drug-eluting stents: an observational study of drug-eluting versus bare-metal stents. J Am Coll Cardiol 2006;48:2584–2591. [PubMed: 17174201]

28. Izzat MB, Yim AP, Mehta D, et al. Staged minimally invasive direct coronary artery bypass and percutaneous angioplasty for multivessel coronary artery disease. Int J Cardiol 1997;62:S105–S109. [PubMed: 9464593]

29. Friedrich GJ, Jonetzko P, Bonaros N, et al. Hybrid coronary artery revascularization: logistics and program development. Heart Surg Forum 2005;8:E258–E261. [PubMed: 16112939]

Discussions

Dr. Gus J. Vlahakes (Boston, Massachusetts): In the recent decade, the practice of coronary bypass surgery has been under intense competition from cardiologists who can offer patients nonsurgical means of managing coronary disease. This has significantly changed the professional landscape of our surgical specialty and has accelerated the search for better and less morbid means of achieving excellent surgical revascularization for patients with this disease.

In an attempt to decrease the impact of surgical revascularization on patients, various techniques have entered the practice to permit the surgical end to be achieved in a less morbid fashion. For the majority of patients, it is the morbidity and temporary disability produced by sternotomy and the potential effects of cardiopulmonary bypass that contribute to the morbidity and potential complications associated with cardiac surgery. Efforts to decrease the impact of traditional bypass surgery include conducting revascularization without the use of cardiopulmonary bypass or use of small incisions in lieu of a full sternotomy. Although small-incision access to the heart has been demonstrated before, a limiting factor has been the ability to fully mobilize internal mammary artery conduits off of the chest wall. The authors used a novel robotic technique to achieve this end with endoscopic visualization and robotic manipulators to mobilize the mammary pedicles throughout their length.

The authors report superb results, and when compared with off-pump surgery via median sternotomy, in their prospective study involving well-selected patients, the authors showed a clear decrement in surgical morbidity. They also included an important analysis of the overall impact of each type of procedure on their patients and the now all-important financial impact of the 2 methodologies. Although hospital stay and morbidity associated with use of robotic surgery are reduced, the authors demonstrated that the device, given its capital and maintenance costs when amortized over the course of the device’s lifetime, can add substantially to the cost of a procedure.

Robotic techniques were introduced in other surgical fields such as urology. The acquisition of a surgical robot remains a major expenditure for a hospital, which must be carefully and persuasively presented to financial decision-makers. The use of surgical robots in cardiac surgery is not new. They have been adapted for use in cardiac surgery, most notably the experience of Chitwood and coworkers, who accumulated an impressive series of mitral valve repairs performed using a surgical robot and an appropriately tailored surgical technique.

In the current report, the surgical robot is not being used for cardiac per se, but has been used for thoracoscopically guided internal mammary pedicle mobilization. As an alternative to those surgeons who do not have access to a surgical robot, and as a potential means of decreasing the cost associated with the procedure as you have described, might a surgeon mobilize the internal mammary pedicle using thoracoscopy and traditional thoracoscopic instruments with the addition of a harmonic scalpel? Do you actually need the robot to achieve the type of procedure you are describing, and if not, could this be a way to obviate the substantial cost as documented in your manuscript.

Using the thoracotomy approach, you used for distal anastomoses in the miniCABG group, which vessels would you suggest are most easily accessible for distal anastomosis and which are not? Does the approach permit sequential anastomoses to be constructed?

How do you manage the mammary artery crossing the front of the chest? Is it placed inside the pericardium to reduce risk in the event that future cardiac surgery is needed, and how do you manage patients with this technique that have diffuse disease?

In many institutions, the length of an ICU stay, particularly after CABG, is generally 1 day. In your manuscript, you described a mean ICU stay slightly in excess of 2 days. Do you have any insights as to why patients are staying this long, particularly when intubation times are averaging approximately 12 hours?

Do you use any adjunctive measures for pain management such as epidural catheters?

We are learning from accumulating data regarding patients who have undergone percutaneous interventions, particularly with drug-eluting stents, that these are not the panacea for coronary artery disease that they were originally suggested as by early clinical studies. We now understand patients are often committed to a very long course of potent antiplatelet drugs, and the incidence of stent thrombosis remains. You elected to use an interesting approach to hybrid procedures incorporating both bypasses placed by minimal access approaches and stenting. Do you think that anything is lost with respect to the patient’s long-term prognosis and safety from long-term events by not having full revascularization by surgical means?

Dr. Alden H. Harken (Oakland, California): First, it seems that you had the opportunity to do a randomized prospective study yet you chose to do a matched control study. We always worry that patients are really not matched. Can you convince us that they really were comparable patients?

Second, I was surprised that you are using a unit and a half of blood for all of the patients in your CABG group. Several previous studies discussed our reluctance to give blood. It seems like somehow those patients are sicker than the ones we normally see.

Third, in your return-to-work metric, you indicate that these were determined after adjusting for confounders. Could something possibly be hidden in that adjustment for confounders?

Finally, I was surprised that you could obtain permission to perform an angiogram at a year. That is a wonderful opportunity to look at graft patency, if that is indeed, what you are able to do? You were able to get patients to come back and perform an angiogram; I doubt we could get that permission through our IRB. However, it is my impression that this would be the first study demonstrating that an endovascular angioplasty/stent technique was actually more durable than a surgically placed graft. Is that correct, and could you amplify on that?

Dr. Julie A. Freischlag (Baltimore, Maryland): I have a question about your patient satisfaction survey. Did you use an authenticated instrument administered by a noninterested individual to

look at this? And, did you ask the surgeon whether or not he was satisfied using any survey instrument, too, because these procedures are actually very stressful for our cardiac surgeons, and were they Safford as well?

Dr. W. Scott Melvin (Columbus, Ohio): Could you briefly describe your financial analysis? There have been very few studies in the last 8 years since the robot has been available that demonstrate superior or even equivalent cost. It is an expensive platform technology with a significant yearly maintenance cost. Can you explain the finances for us?

Dr. Robert S. Poston, Jr. (Baltimore, Maryland): In regards to Dr. Vlahakes' point about the acquisition cost of the robot, the analysis that I presented suggesting that the robot is cost neutral did not include the amortization of the purchase cost of the robot. However, we did include the instrument costs and the extra costs from prolonged times in the operating room. We did not include the cost of the robot because other services such as urology and GYN use it. If the question was whether a hospital should buy the robot for the sole purpose of supporting a robotic CABG program, then it would be important to include the amortization and maintenance costs of the robot to perform an adequate analysis. We performed that analysis and found that robotic cases were $8,000 more expensive, making it significantly less cost effective than open sternum CABG.

Regarding the question as to whether a thoracoscopic approach could be used instead of the robot, I think that is possible. Tom Vassiliades and others at Emory mastered this technique and reported good results from it, but they have not used it frequently for harvesting bilateral mammaries. The ability to harvest bilateral IMAs without the risk of compromising the healing of the sternotomy is a compelling reason for miniCABG that is lost with the thoracoscopic approach.

Regarding the technical details about which conduits to use on which targets and the concern that the RIMA to the LAD might be a contraindication for future sternotomy reoperations if necessary. Obtaining "buy-in" from the cardiologists toward taking the RIMA across the chest to the LAD is very important, because this is a straightforward procedure as compared with other options. The LIMA is then used to graft a lateral wall coronary target. An important technical issue is whether you get the RIMA adequately skeletonized to reach the LAD target without having to use the distal, more muscular, spastic portion of this arterial vessel. With regards to the concern about resternotomy, the point of using BIMA grafts is to not have a reoperation be a relevant issue. Using bilateral mammaries in CABG should create less than 5% risk of ever needing any further cardiac surgery.

With regards to the fact that our control group experienced a longer than expected ICU stay, I think that is just a matter of patient flow in our particular ICU, which is in an academic institution. In addition, our groups had EuroSCORE mortality risks of around 10% so an ICU length of stay of less than 2 days is fairly predictable.

Pain management strategies are critical. The thoracotomy tends to be a more painful incision than the sternotomy because the ribs are more heavily innervated. However, the pain resolves faster. MiniCABG patients stopped taking pain meds at around 2 weeks as compared with patients in the sternotomy group who, on average, took pain meds until the sternum healed at about 6 weeks. Early management strategies like intercostal nerve blocks, the On-Q pain pump are also very helpful. Epidurals are possible but are more complicated because it is a high thoracic epidural. However, I think that would be an excellent option if you could cope with the postoperative hemodynamics of low SVR.

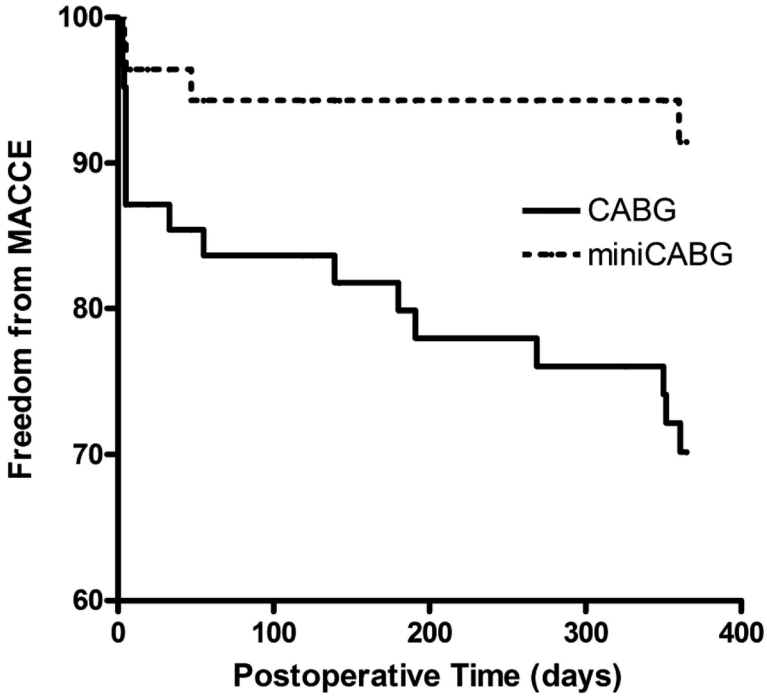

FIGURE 1.

Freedom from major adverse cardiac and cerebrovascular events was more common over the first postoperative year in the minCABG group compared with the OP-CAB group (4 vs. 26% risk at 1 year; $P < 0.01$).

TABLE 1

Clinical Demographics of Patients

	MiniCABG (n = 100)	OPCAB (n = 100)	*P*
Age (yr)	61.8 ± 9.4	66.2 ± 10.1	NS
Gender (M)	72.0%	63.3%	NS
BMI	29.9 ± 9.7	28.4 ± 6.7	NS
Risk factors			
Current smoker	29%	33%	NS
Family history of CAD	40%	40%	NS
Diabetes	32%	43%	NS
Dyslipidemia	76%	86%	NS
Hypertension	80%	80%	NS
Comorbidities			
Chronic lung disease	14%	10%	NS
PVD	28%	26%	NS
Renal failure	4%	0%	NS
Mean LVEF (%)			
Good (>50%)	52%	50%	
Moderate (35%–50%)	28%	27%	
Poor (<35%)	20%	23%	
History of CV disease			
No. diseased vessels	2.8 ± 0.5	2.8 ± 0.4	NS
Left main disease	47%	43%	NS
Previous MI	48%	56%	NS
Congestive heart failure	13%	26%	NS
Preoperative medications			
Beta blocker	84%	80%	NS
ACE inhibitor	36%	46%	NS
Aspirin	88%	86%	NS
Statin	82%	80%	NS
Logistic EuroSCORE (%)	10.5 ± 18.1	10.7 ± 11.9	NS

BMI indicates body mass index; CAD, coronary artery disease; MI, myocardial infarction; LVEF, left ventricular ejection fraction; ACE, angiotensin-converting enzyme; NS, nonsignificant.

TABLE 2

Perioperative Outcomes

	Robotic Hybrid (n = 100)	OPCAB (n = 100)	*P*
Length of surgery (h)	5.8 ± 1.2	4.1 ± 0.9	<0.001
Hospital LOS (d)	3.77 ± 1.51	6.38 ± 2.23	<0.001
ICU LOS (h)	21.9 ± 9.3	50.6 ± 27.3	<0.001
Intubation time (h)	4.80 ± 6.35	12.24 ± 6.24	<0.001
Intraop. blood loss (mL)	547 ± 366	1230 ± 945	0.001
PRBC transfusion (U)	0.16 ± 0.37	1.37 ± 1.35	<0.001

LOS indicates length of stay; PRBC, packed red blood cell; NS, nonsignificant.

TABLE 3

Postoperative Complications

	MiniCABG (n = 100)	OPCAB (n = 100)	*P*
Major complications	12 (12%)	37 (37%)	0.031
Mortality	0	2	NS
Myocardial infarction	1	7	NS
Stroke	0	2	NS
Need for revascularization	1	1	NS
Major infection	0	2	NS
Renal failure	3	5	NS
Reoperation for bleeding	1	6	NS
Prolonged ventilation	6	12	NS
Atrial fibrillation	12	20	NS
30-d readmittance	4	9	NS

NS indicates nonsignificant.

TABLE 4

Summary of Cost Analysis

	MiniCABG (n = 100)	OPCAB (n = 100)	*P*
Intraop. cost ($)			
Drugs	201 ± 80	164 ± 121	NS
Supplies	10,606 ± 3073	6933 ± 2152	0.016
Labs	411 ± 146	416 ± 73	NS
OR time	3161 ± 606	1765 ± 499	0.004
Radiology	952 ± 573	68 ± 51	<0.001
Other services	358 ± 330	474 ± 258	NS
Total	14,890 ± 3211	9819 ± 2229	<0.001
Postop. cost ($)			
Drugs	304 ± 168	503 ± 221	0.002
Labs	95 ± 58	140 ± 60	0.026
Radiology	201 ± 295	180 ± 95	NS
Non-ICU	626 ± 473	594 ± 761	NS
ICU	2119 ± 1014	4287 ± 1345	<0.001
PT	183 ± 111	233 ± 68	NS
Other tests	213 ± 237	425 ± 538	NS
Total	3741 ± 1214	6361 ± 1656	<0.001
Total hospital cost	18,631 ± 3450	16,180 ± 2777	NS
+ Cost of robot*	23,398 ± 3333	16,180 ± 2777	0.001

*Allocation of institutional cost for the robotic surgical system ($4309 per robotic case).

OR indicates operating room; ICU, intensive care unit; PT, physical therapy.