REVIEW ARTICLE

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Initiation and modification of minimally invasive coronary artery bypass grafting

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Abstract

Minimally invasive coronary artery bypass grafting (MICS CABG) via a small left thoracotomy has been proposed as an alternative to standard coronary artery bypass grafting. However, this technique is still limited to skillful surgeons. Off-pump multi-vessel bypass grafting and the use of bilateral internal thoracic arteries are particularly challenging via a small thoracotomy, while they are widely performed via a full median sternotomy. The purpose of this review is to serve as a guide for the proper introduction of MICS CABG in the current era. We examine the advances, current techniques, outcomes and learning curves of MICS CABG and discuss the safe introduction.

Keywords Coronary artery bypass grafting · Left thoracotomy · Minimally invasive coronary artery bypass grafting

Introduction

Coronary artery bypass grafting (CABG) is still more beneficial than percutaneous coronary intervention (PCI) in patients with multi-vessel disease and diabetes mellitus or with triple-vessel disease [1, 2]. In Japan, off-pump CABG (OPCAB) is widely performed because of its less invasiveness, especially in high-risk patients [3, 4]. The ratio of OPCAB is 55% in elective CABG cases [5, 6], but still 15–20% in Europe and the USA [7, 8]. Furthermore, owing to advancements in OPCAB techniques, its safety and quality have been improved, with an average operative mortality rate of approximately 1% over the past decade [5]. This approach may be the next step in further reducing the invasiveness and thereby providing more benefits to our patients.

Minimally invasive coronary artery bypass grafting (MICS CABG) via small left thoracotomy has several advantages over CABG through median sternotomy in terms of early recovery, less bleeding, and no risk of sternal infection [9, 10]. However, only a few institutions routinely perform MICS CABG due to its technically demanding nature. Therefore, guidance regarding the initiation of MICS CABG without compromising the safety and benefit of surgical revascularization would be helpful.

The aim of this review was to establish proper guidance for the safe introduction of MICS CABG in the current era.

Advances in MICS CABG

Minimally invasive direct coronary artery bypass grafting (MIDCAB) through small anterior thoracotomy was introduced to Japan in the mid-1990s, but did not become a standard procedure for several reasons. First, the full-length harvest of the left internal thoracic artery (LITA) is difficult through its incision, thereby limiting the possible target area. Second, multi-vessel bypass grafting was basically impossible because the proximal anastomosis onto the ascending aorta cannot be performed with this approach. Furthermore, the postoperative wound pain is intense in some cases. As a result, median sternotomy is currently employed in 99.7% of patients who undergo off-pump CABG (OPCAB), according to the annual report of the Japanese Association for Coronary Artery Surgery [11].

In 2005, a new technique for MICS CABG was initiated in North America [12] in which newly developed MICS devices were employed to resolve the above-mentioned issues. The use of a MICS thoracic retractor, heart positioner

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and stabilizer was shown to facilitate the full-length harvest of the LITA through more lateral thoracotomy as compared to MIDCAB. Furthermore, multiple bypass grafting with handsewn proximal graft anastomoses onto the ascending aorta has become feasible, thereby allowing for various bypass graft designs [10].

Patient selection

McGinn et al. stated that absolute contraindications for MICS CABG include emergency surgery with hemodynamic compromise, severe pectus excavatum, and severe pulmonary disease. Relative contraindications include significant left subclavian stenosis, arteriovenous fistula on the patients' left side, redo surgery, morbid obesity, severe left ventricular dysfunction, need for right coronary artery graft with no posterior descending or left ventricular branch target, need for circumflex coronary artery graft with no adequate marginal branch target and absence of femoral pulses bilaterally [12]. A dilated left ventricle with > mild mitral regurgitation may preclude off-pump multi-vessel MICS CABG, especially in patients with a target at the posterolateral wall. CPB assistance with femoro-femoral bypass is useful for securing stable hemodynamics in such patients. The safety of retrograde arterial perfusion should thus be confirmed in patients undergoing multi-vessel MICS CABG. Preoperative contrast CT is important for identifying those with an unsuitable anatomy; those with peripheral, ascending aortic, or subclavian artery disease; or those who are unlikely to tolerate single-lung ventilation. In terms of distal coronary target, diffusely diseased or intramyocardial vessels are unsuitable for MICS CABG.

Surgical techniques of MICS CABG

The detailed methods of MICS CABG have been described in previous studies [12–14]. Single-lung ventilation is performed using a double-lumen endotracheal tube or a bronchial blocker. Full-lung ventilation is also feasible in MICS-CABG procedure. Sixt et al. reported a unique "fan technique" in which multiple pericardial stay sutures (fan sutures) are externalized outside the thorax through minimal incisions lateral of the thoracotomy to keep the left lung from interfering with the surgical view [15]. The patients are positioned in a 15°–30° right decubitus position. The left arm is slightly flexed along the body or extended for radial artery harvest if needed. A 7- to 9-cm skin incision is made in the left fourth or fifth intercostal space, starting at the midclavicular line and extended laterally. Preoperative three-dimensional computed tomography images are useful for selecting the appropriate intercostal space for

thoracotomy. A Thoratrak (Medtronic, Inc., Minneapolis, MN, USA) MICS retractor is then placed and hooked to the Rultract Skyhook (Rultract, Cleveland, OH, USA) retractor to expose the ITA.

The ITA is taken down in a skeletonized or pedicled fashion. For LITA harvest, the Thoratrak retractor is pulled upward. To prevent damage to the ITA, the retractor should be cranked slowly with visual confirmation that the tip of the retractor blade is not touching the ITA. As the middle to distal ITA is covered with the transversus thoracis muscle and is usually invisible from the window incision, the LITA harvesting is started at the 2nd or 3rd intercostal space. Care should be taken in dissecting the LITA distally because it runs closer to the window incision than expected when harvesting from the left thoracotomy. For right ITA (RITA) harvest, the retractor is pulled cephalad and rightward. The right lung is displaced rightward using an Octopus Nuvo stabilizer (Medtronic, Inc.) via a 10-mm subxiphoid incision. In many cases, the RITA can be harvested with direct visualization. Intermittent discontinuation of lung ventilation is helpful, especially for dissecting the proximal part of the RITA.

Next, the pericardium is opened 3 cm anterior to the left phrenic nerve. The incision of the pericardium is extended toward the ascending aorta and the left ventricular apex. Extension of the pericardial incision toward the inferior vena cava allows for further mobilization of the heart. Furthermore, a wide opening of the pericardium allows for visualization of the whole target vessel, which is important, as inadequate visualization of the target vessels may lead to inappropriate anastomosis, especially in LITA-LAD anastomosis.

Handsewn proximal anastomoses are made on the ascending aorta when necessary [14]. The ascending aorta is mobilized toward the thoracotomy using several 2-0 silk stitches on the pericardium near the ascending aorta. The pulmonary artery is displaced leftward and posteriorly using the Octopus Nuvo stabilizer [14]. After dissection between the aorta and the pulmonary artery, a side-biting clamp is placed on the ascending aorta, and proximal anastomosis is performed in the usual fashion. Maintaining relatively low right ventriclar filling and increment of right lung positive end-expiratory pressures makes the ascending aorta more approachable. If the ascending aorta is still too far away, the upper intercostal space can be opened through the same skin incision. Proximal anastomosis can be performed after the completion of distal anastomosis of the LITA to the left anterior descending artery (LAD). After proximal anastomoses are performed, the free flow of the vein/radial grafts should be checked to confirm adequate blood flow.

For distal anastomoses, the stabilizer and heart positioner are placed onto the heart via a subxiphoid incision, the 7th intercostal space, and/or a thoracotomy incision. The whole myocardial territories can be exposed without endoscopic

or robotic assistance. If the target vessel is hidden below the lower rib, the lower intercostal space can be divided through the same skin incision. If the exposure is still inadequate or the hemodynamic status becomes unstable, cardiopulmonary bypass (CPB) is established through the femoral vessels. Anastomoses are made as in regular OPCAB with coronary shunt tubes and a CO_2 blower.

Clinical outcomes and benefits of MICS CABG

A large study from Staten Island University and Ottawa Heart Institute reported the clinical outcomes of consecutive 450 patients in 2009 [12]. The average age was 62.3 ± 10.7 years, and the average number of anastomoses was 2.1 ± 0.7. The operative mortality was 1.3% with an incidence of conversion to sternotomy of 3.8% and reopening for bleeding of 2.2%. Recently, a retrospective study from India reported excellent clinical outcomes in a total of 819 patients who underwent off-pump multi-vessel MICS CABG using bilateral ITAs [16]. The rates for operative mortality and conversion to sternotomy were 0.7% and 0.4%, respectively. The average hospital stay was 3.1 days. A case-matched study between 150 MICS OPCAB and 150 standard OPCAB cases was reported by the same group [9]. The MICS CABG group had a lower incidence of blood transfusions and wound infections than the standard OPCAB group. Although the MICS CABG group had a higher incidence of postoperative pleural effusion, the length of hospital stay was significantly shorter than that of the OPCAB group. Furthermore, the duration to return to full physical activity was much shorter in the MICS CABG group than in the OPCAB group (12 and 36 days, respectively, $P < 0.001$). Rabindranauth et al. conducted another case-matched study (130 MICS CABG patients versus 260 OPCAB patients) and found that the rate of extubation in the operating room was significantly higher in the MICS group than that in the OPCAB group (70.0% and 12.7%, respectively, $P = 0.001$) [17]. Regarding the late clinical outcomes, MICS CABG was associated with a lower 5-year all-cause mortality in 159 patients ≥ 75 years of age with adjustment for confounders [hazard ratio (HR) 0.51, 95% confidence interval (CI) 0.26–0.97, $P = 0.04$] [18].

Only one randomized trial found that off-pump MICS CABG required a longer procedure time than sternotomy OPCAB (4.1 h and 3.3 h, respectively) despite fewer patients being treated with more than 3 grafts (2% and 17%, respectively) [19]. In contrast to other retrospective studies, this study demonstrated a similar duration of hospital and intensive-care unit stay and a worse postoperative pulmonary function in the MICS CABG group with more analgesia required and higher costs during hospitalization, prompting

the authors to conclude that off-pump MICS CABG has no advantages over conventional OPCAB. However, considering the steep learning curve for off-pump multi-vessel MICS CABG (described in the following section), the results may be different if the randomization were focused on MICS CABG and sternotomy CABG without being limited to off-pump procedures.

The clinical benefits of CABG are contingent on the graft patency [20]. In a prospective study, Ruel et al. reported excellent graft patency in 89 patients who underwent MICS CABG with a median number of 3 grafts [21]. The patency was 92% for all grafts and 100% for LITA grafts, as assessed by computed tomography angiography 6 months after the operation.

Learning curve of MICS CABG

At the initiation of MICS CABG, it is important to avoid perioperative adverse events, such as unexpected sternotomy conversion. The University of Ottawa group showed that CPB assistance was useful for ameliorating the learning curve of MICS CABG [22]. They conducted cumulative summation analyses and found that the minimum number of cases required to achieve an acceptable procedure time was smallest when performing CPB-assisted multi-vessel MCIS CABG (16 cases) compared with off-pump single-vessel MICS CABG (66 cases) and off-pump multi-vessel MICS CABG (40 cases), although no significant learning curve effects were noted in terms of postoperative morbidities. Further analyses in a larger patient cohort ($n = 306$) also demonstrated that the first half of the series had a significantly higher incidence of sternotomy conversion than the latter half (5.2% and 1.3%, respectively, $P = 0.05$) as well as a higher rate of repeat revascularization (11% and 2.6%, respectively, $P = 0.03$) [23]. Among those who required repeat revascularization, 52% had graft-associated culprit lesions, and their graftability index (number of grafts/number of diseased vessels) at the initial operation was lower than in those without repeat revascularization, especially in the circumflex system [24]. These studies indicate that a learning curve of MICS CABG exists not only in the procedure time, but also in the quality of coronary revascularization.

Risk factors of sternotomy conversion and cardiopulmonary bypass assistance

Risk factors for the sternotomy conversion and CPB assistance were reported from the University Ottawa group (Table 1) [25]. The risk factors of sternotomy conversion were current smoker, preoperative bradycardia (< 50 beats/

Table 1 Risk factors of sternotomy conversion and predictors of CPB assistance [1]

Risk factors of sternotomy conversion	Predictors of CPB assistance
Current smoker	Diabetes
Preoperative bradycardia (< 50 beats/mins)	3-Vessel disease
	Left circumflex involvement
Low intraoperative ejection fraction	Mild mitral regurgitation
Intolerance for one-lung ventilation	Small targets
Inadequate surgical exposure	
Hemodynamic instability	

CPB cardiopulmonary bypass

mins), low intraoperative left ventricular ejection fraction, intolerance for one-lung ventilation, inadequate surgical exposure, and hemodynamic instability. Bradycardia may increase the ventricular filling and thus can interfere with the surgical exposure. It is also associated with hemodynamic instability due to an impaired systolic function. Of note, elective CPB assistance was used in 24% of patients, and the flexible use of CPB contributed to the low rate (1%) of emergent CPB conversion, which is known to be associated with an increased perioperative mortality in OPCAB. Factors influencing the elective CPB usage were diabetes, triple-vessel disease, left circumflex involvement, mild mitral regurgitation, and small target vessels. Interestingly, less use of coronary shunting was associated with CPB conversion, suggesting that avoiding any myocardial ischemia during anastomosis is important in off-pump MICS CABG. Proper patient selection and flexible CPB usage seems to be important for performing MICS CABG safely in the learning curve period.

How to initiate MICS CABG

Recommended strategies for the initiation of MICS CABG are summarized in Table 2. For the first MICS CABG procedure, off-pump single-vessel CABG is recommended because surgeons can learn techniques of small thoracotomy and LITA harvest with a low risk of unexpected sternotomy or CPB conversion. With experience of single-vessel MICS CABG, multi-vessel MICS CABG can be safely started. Double-vessel bypasses are recommended as the next step, with CPB assistance when necessary. Proper exposure of the target vessels is key. The diagonal branch artery or the high lateral branch artery is generally recommended as the second target vessel because these vessels are close to LAD and do not need aggressive cardiac manipulation. Proximal anastomosis to the ascending aorta seems to be another challenging part in this step. CPB support may not be very helpful aside from aiding in the management of unexpected bleeding. Proper patient selection (e.g., avoiding obese patients) and a thorough preoperative CT evaluation are important. With experience in performing double-vessel MICS CABG, off-pump triple- or more multi-vessel MICS CABG will be able to be completed comfortably. Operating on patients with small or diffuse targets, severe triple-vessel disease, left ventricular dysfunction, mitral regurgitation of moderate or greater severity, significant bradycardia, or a current smoking habit should be avoided during the learning curve period of multi-vessel MICS CABG. Intraoperatively, the use of coronary shunting is recommended.

Table 2 Recommended steps for initiation of MICS CABG

Procedure	Unsuitable candidates	Techniques to be focused on for the next step
1st step: Off-pump single-vessel MICS CABG		Small thoracotomy LITA harvest
2nd step: Off-pump or CPB-assisted double-vessel MICS CABG	Candidates with risk factors of conversion sternotomy	Handsewn anastomoses on the ascending aorta
3rd step: Off-pump or CPB assisted multi-vessel MICS CABG	Candidates with risk factors of conversion sternotomy	Exposure for the whole territory Exposure with off-pump style
4th step: Off-pump multi-vessel MICS CABG	Candidates with risk factors of conversion sternotomy/CPB use	Exposure with off-pump style
Final step: Alternative to OPCAB		RITA harvest (in situ or free graft)

CPB cardiopulmonary bypass, *LITA* left internal thoracic artery, *MICS CABG* minimally invasive coronary artery bypass grafting, *OPCAB* off-pump coronary artery bypass grafting, *RITA* right internal thoracic artery

How to modify MICS CABG

The quality and benefits of CABG should not be compromised when performing MICS CABG. Along with the high OPCAB ratio in Japan, bilateral internal thoracic arteries (BITAs) are used in 40.7% of patients who undergo isolated elective CABG [6]. Strategies for achieving high-quality coronary revascularization should be performed whenever possible, even in minimally invasive procedures. Careful indications for MICS CABG with consideration of the predictors of CPB assistance would be helpful for avoiding unexpected CPB conversion. The use of various heart positioners may also be helpful [26].

In terms of the BITA usage in MICS CABG, several reports have described the feasibility of RITA harvesting with endoscopic devices and/or robot assistance [27, 28]. However, robotic assistance is costly and comes with a steep learning curve. Nambiar et al. reported the clinical outcomes of 819 off-pump MICS CABG cases with BITAs harvested under direct visualization. In addition to an intercostal retractor, both a Thorac-Pro ITA retractor (Fehling Surgical Instruments Inc., Karlstein, Germany) and Rultract retractor were used for ITA exposure. The RITA was harvested as a free graft and used as a Y composite graft connected to the LITA. The free RITA can also be used as an aorto-coronary bypass conduit. A retrospective study from Japan showed excellent early clinical outcomes of V-composite grafting of the free RITA anastomosed to the proximal part of the aorto-coronary bypass conduit (RA or SVG) [29]. Recently, Kikuchi et al. reported the in situ use of an RITA in MICS CABG [30]. The feasibility of RITA harvesting with direct visualization through left thoracotomy can be predicted by preoperative CT. For example, in patients whose RITA runs deep into the intercostal spaces, this vessel would be barely visible via left thoracotomy (Fig. 1). Endoscopic assistance may therefore aid in the visualization of the RITA in such cases.

Conclusions

MICS CABG has been successfully initiated at several centers, and its clinical results have been reported in increasing numbers of publications [26, 31, 32]. Although MICS CABG is associated with a steep learning curve and longer operation time, its benefits due to avoiding sternotomy outweigh that drawback. Furthermore, with the development of MICS devices, multi-vessel MICS CABG with all arterial bypass grafts has become possible [30, 32, 33]. MICS CABG will likely become widely adopted as an important option for treating coronary artery disease.
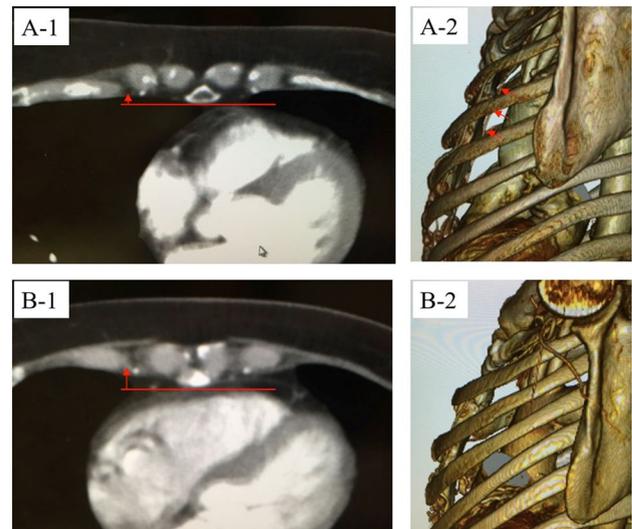

Fig. 1 Preoperative enhanced computed tomography. **a-1** When the right internal thoracic artery is close to the bottom level of the sternum, it is expected to be visible through a left small thoracotomy. The red arrow indicates the distance between the right internal thoracic artery and the bottom level of the sternum. **a-2** 3D images precisely give surgeon's view. The red arrows indicate the right internal thoracic artery. **b-1** When the vessel is far from the bottom level of the sternum (red arrow shows the distance), **b-2** it is expected to be barely visible

Compliance with ethical standards

Conflict of interest The authors have declared that no conflict of interest exists.

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