Minimally Invasive Cardiac Surgery Defined

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There is no operation as complex, yet as fundamentally unchanged over time, as conventional coronary artery bypass grafting (CABG). This remarkable achievement is attributed to the operation’s adaptability to a wide variety of clinical settings; its reproducibility, although performed by surgeons all across the world; and its proved track record for safety and effectiveness. A monumental effort, however, is currently under way to redefine CABG. This paradigm shift has received a groundswell of support as advances in minimally invasive surgery in other areas, such as arthroscopy, laparoscopic cholecystectomy, and thoracoscopy, combined with an increasing focus on cost containment, have forever changed the milieu of the cardiac surgeon. This review examines the clinical and research issues surrounding minimally invasive CABG from the vantage point of a surgeon-scientist working in the field.

EFFECTIVENESS OF CONVENTIONAL CABG

Excellent long-term results are achieved with conventional CABG employing cardiopulmonary bypass (CPB) and sternotomy. Major studies have documented the operation’s superiority to medical therapy in patients with left main coronary disease and triple-vessel disease with impaired left ventricular function. Conventional CABG employing a left internal thoracic artery bypass graft (LITA) to the left anterior descending coronary artery (LAD) has been demonstrated to improve survival, despite the natural progression of disease in vessels that were not bypassed, or in the bypassed vessel beyond the anastomosis. The durability of conventional CABG reduces the risk for repeated revascularization. In the Bypass Angioplasty Revascularization Investigation, only 8% of patients randomized to surgery required repeated revascularization procedures for recurrent angina (1% had repeated CABG and 7% had percutaneous transluminal coronary angioplasty [PTCA]) compared with 54% in the PTCA group (31% had subsequent CABG and 34% had repeated PTCA; 11% had both procedures).

COMPLICATIONS AFTER CONVENTIONAL CABG

The established effectiveness of conventional CABG is offset by significant morbidity and a small but definite risk of death. The operative mortality and major complication figures derived from the Society of Thoracic Surgeons National Database are listed in Table 1. For 1997, in a dataset comprising 161,018 primary CABGs, the overall operative mortality was 2.8%. Major complications included Q-wave myocardial infarction (1.1%), adverse neurological events (5.4%), pulmonary complications (11.2%), acute renal failure (3.1%), and sternal wound infection (1.4%). Importantly, the proportion of patients suffering no complications after primary CABG was only 64.3%. When the incidence of complications is considered in relation to the nearly 800,000 patients worldwide who undergo CABG each year, the magnitude of the problem becomes clear. In a report by the Multicenter Study...
seizures were observed in 3.0%.5 Significantly, adverse served in 3.1% of patients and cognitive dysfunction or outcomes.5 Substantial resources are consumed by such patients. The cost of medical and rehabilitative services based on the 800,000-patient annual projection is estimated to range from $2 billion to $4 billion.5 The most powerful predictor of stroke was the presence of moderate or severe proximal aortic atherosclerosis detected by palpation.5 This provides compelling evidence that most postoperative strokes are caused by cerebral microemboli arising from surgical manipulation of the ascending aorta; for example, during aortic cannulation and initiating CPB, aortic cross-clamping, and partial occlusion clamping.5 Thus, adverse neurological events arising from the surgical manipulation of the aorta significantly increase the mortality, length of hospitalization, and cost of CABG.

By exposing blood to the foreign materials present in the bypass circuit, CPB incites a systemic inflammatory response syndrome mediated by complement activation and cytokine release.6 This in turn promotes neutrophil activation, enhanced capillary permeability, interstitial edema, decreased systemic vascular resistance, and maldistribution of end-organ blood flow.6 Clinically, this syndrome can manifest as postoperative bleeding, pulmonary dysfunction, and acute renal failure.6 The morbidity and cost of CPB have provided an impetus to develop techniques of performing CABG on the beating heart.

Sternotomy closure is accompanied by moderate pain and discomfort, and is infrequently complicated by mediastinitis. However, the occurrence of mediastinitis can adversely affect both short- and long-term survival.7 Only by improving the quality of sternotomy closure or by avoiding sternotomy altogether can the pain and morbidity of sternotomy be eliminated.

GOALS OF MINIMALLY INVASIVE CABG

The clinical effectiveness of the LITA to LAD anastomosis and the significant morbidity associated with conventional CABG provide the background for exploring alternative approaches to surgical revascularization. In general, these approaches have all fallen under the rubric of minimally invasive CABG. The clinical goals of minimally invasive CABG are interrelated, and include (in order of importance): (1) achieving graft patency rates equal or superior to conventional CABG; (2) decreasing incisional pain and discomfort; (3) a more rapid return to normal activity levels; (4) reducing the length of hospital stay; and (5) decreasing cost.

To achieve these clinical goals, 4 technical objectives must be considered. They include (in order of importance): (1) achieving an effective coronary anastomosis; (2) completing active revascularization; (3) avoiding the use of CPB; and (4) avoiding the morbidity of sternotomy.

Achieving an Effective Coronary Anastomosis

The major obstacles to achieving an effective coronary anastomosis are the translational motion of the beating heart, myocardial ischemia, endothelial injury during coronary occlusion, and bleeding arising from the coronary arteriotomy. Ironically, the same problems confronted our surgical forefathers nearly 40 years ago, providing the basis for conventional CABG.

The translational motion of the beating heart results from a complex interplay between its rhythmic pumping action, ventricular loading conditions, and wall compliance, superimposed on slower movements reflecting lung volume changes during the respiratory cycle. Proposed solutions have focused on mechanical and pharmacologic methods of cardiac stabilization. A wide variety of mechanical stabilizers are commercially available. Although subtle differences exist, most are fundamentally compressive- or suction-type devices that are fixed on one end to the operating table or chest wall retractor, with the other end apposed to the epicardial surface. The stabilizer arms are positioned on opposite sides of and parallel to the target coronary artery, thereby physically restraining a localized region of epicardium.8,9 Mechanical stabilizers cause little hemodynamic disturbance unless the heart is physically displaced, and do not cause significant tissue trauma.9,10 There are important limitations, however, to current mechanical stabilizers. Some devices are difficult to deploy and are unwieldy in small incisions. Although benefi-
Table 2. Patient Selection for Beating-Heart CABG*

<table>
<thead>
<tr>
<th>Absolute contraindications to beating-heart CABG:</th>
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<tr>
<td>1. Cosmesis</td>
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<td>2. Peer pressure</td>
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<tr>
<td>3. Marketing and public relations tool</td>
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<table>
<thead>
<tr>
<th>Relative contraindications to beating-heart CABG:</th>
</tr>
</thead>
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<tr>
<td>1. Vessel diameter &lt;1.5 mm</td>
</tr>
<tr>
<td>2. Severe vessel calcification</td>
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<tr>
<td>3. Intramyocardial vessel</td>
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<td>4. Severe cardiomegaly</td>
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* CABG indicates coronary artery bypass grafting.

special for immobilizing the LAD, their stabilizing efficiency is reduced in the posterior circumflex distribution. Whereas the anatomical course of the LAD astride the interventricular septum counterbalances the force exerted by a mechanical stabilizer, the location of the circumflex branches on the ventricular free wall offers negligible support. Indeed, a compressive stabilizer positioned against the ventricular free wall can deform the ventricle and lead to diminished stroke volume without adequate reduction in translational motion. Finally, the proper use of any mechanical stabilizer entails a significant learning curve.

The few published data on graft patency after beating-heart CABG with mechanical stabilizers are limited to the LITA to LAD anastomosis and provide only short-term follow-up. Of 103 patients described by Mack et al.,10 100 (97%) underwent control angiographic evaluation within 96 hours of the procedure.11 Angiographic graft patency was 99%, with perfect graft patency (<50% stenosis in the proximal or distal anastomosis or graft body) present in 91%. In a retrospective study by Calafiore et al.,12 122 patients underwent revascularization through a sternotomy with mechanical stabilization. Sixty-seven patients (54.9%) underwent control angiographic evaluation a mean of 33 days after operation, with perfect graft patency in 98.5%. These favorable results suggest that the LITA to LAD anastomosis on the beating heart can be accomplished with acceptable early graft patency in selected patients when mechanical stabilizers are employed. The current indications for beating-heart CABG are listed in Table 2.

Achieving cardiac stabilization by means of pharmacologic agents is an old concept. Early cardioplegia comprised a mixture of active agents, including magnesium sulfate, potassium citrate, and neostigmine.13 Indeed, magnesium and potassium remain integral components of modern cardioplegia. Yet, because potassium impedes excitation-contraction coupling and prevents electrical pacing, extracorporeal circulatory support became essential. Other agents that provide pharmacologic stabilization decrease wall motion through their negative chronotropic, inotropic, and dromotropic properties, such as β-blockers, calcium channel blockers, and adenosine. Recently, a novel drug combination was introduced that produces controlled periods of ventricular arrest while preserving electrical pacemaker sensitivity, so that pacing can be continued to maintain cardiac output.14 By suspending and resuming electrical pacing on demand, the surgeon creates a completely motionless operative field for the brief period of time (4-8 seconds) required to place a single coronary suture.14 Although promising, the concept of pharmacologic stabilization requires clinical validation.

Beating-heart CABG requires temporary interruption of coronary blood flow to achieve a bloodless operative field. Most surgeons employ a vessel snare (suture or silicone elastomer tape) proximal to the arteriotomy, with or without a second snare placed distally. Interruption of coronary blood flow, however, may cause myocardial ischemia, infarction, or arrhythmia. A proposed solution is the intraluminal coronary shunt. Most shunts are silicone tubes, 10 to 30 mm in length by 1.0 to 3.0 mm in diameter, designed to be inserted through the arteriotomy into the coronary lumen. Besides avoidance of ischemia, shunts also stent the coronary anastomosis open and prevent inadvertent suturing of the back wall. The putative advantages of a shunt, however, are offset by several practical concerns. Shunts are cumbersome to use and may cause endothelial injury if oversized. As bleeding can still occur from diagonal or perforating branches enclosed between snarest, shunts often fail to maintain a bloodless arteriotomy. Because of its small internal diameter, blood flow through a shunt is typically only 30% to 50% of the native coronary flow.15 And finally, with the possible exception of a large, diseased, but patent right coronary artery, the occurrence of significant ischemia, infarction, or arrhythmia with snare occlusion is rare. Thus, for most patients undergoing beating-heart CABG, temporary interruption of blood flow is not associated with significant ischemic injury and intraluminal coronary shunts are generally unnecessary.

Aside from issues related to myocardial ischemia, there is also the concern that snaring of the coronary artery may induce significant mechanical trauma and promote accelerated atherosclerosis. Gundry et al.16 reported that the 7-year patency rate of the LITA to LAD anastomosis in a subgroup of patients who underwent beating-heart CABG was only 42%, compared with 92% in an age-, sex-, and disease severity–matched control group. To reconcile the inferior graft patency rates seen in the beating-heart group, these authors and others have implicated arterial stenosis that developed at sites of previous coronary snare.16,17 Although the link between accelerated atherosclerosis and the use of coronary snare is not clearly established, common sense dictates omitting their use if unnecessary (for example, routine snaring distal to the arteriotomy) and minimizing snare tension to achieve just enough vessel compression to accomplish a precise anastomosis.

Bleeding arising from the arteriotomy obscures precise suture placement during coronary anastomosis. Several techniques have been introduced to improve visualization, including frequent blotting of the arteri-
otomy with an absorbent material, intermittently irrigating with saline solution, intraluminal coronary shunts, and the use of high-flow gas insufflation. Each technique, however, has its limitations. Blotting and irrigating with saline solution provides only temporary and incomplete improvement in visualization, usually requires a second surgical assistant, and may directly traumatize endothelium. The disadvantages of intraluminal coronary shunts are discussed earlier. Although high-flow gas insufflation is effective in maintaining a bloodless field, it can cause profound endothelial cell loss that may predispose to early and late graft failure. 18,19 Significantly, the damage to endothelium is ameliorated by the addition of humidification, producing a mist effect, and by limiting gas flow to less than 10 L/min. 20 The current method of choice to improve visualization of the anastomotic site is humidified gas insufflation.

Achieving Complete Revascularization

A widely accepted principle for success after conventional CAGB is complete revascularization. Minimally invasive approaches that permit complete revascularization include beating-heart CAGB through a sternotomy, CAGB with CPB and cardioplegic arrest through a ministernotomy or limited left anterior thoracotomy, and beating-heart CAGB through a limited left anterior thoracotomy combined with PTCA and/or stenting.

A common problem encountered during beating-heart CAGB through a sternotomy is the exposure of the posterior circumflex branches, as this is frequently accompanied by significant hemodynamic instability.10 To mitigate this response, the patient is placed in steep Trendelenburg position and rotated to the right. Fluid volume, pressor agents, or both are often required. Two deep pericardial stay sutures are placed just above the left superior pulmonary vein and another is placed midway between the left inferior pulmonary vein and the inferior vena cava. 12 By applying differential tension on the stay sutures, the cardiac apex is elevated and rotated right, exposing the posterior circumflex branches while preserving adequate hemodynamics. 13 A mechanical stabilizer is then positioned around the target vessel. Another approach uses a ministernotomy (8-10 cm) or limited left anterior thoracotomy (6-10 cm), CPB (ascending aorta or femoral artery, and femoral vein), and cardioplegic arrest.19,20 This technique allows for complete revascularization using the LITA or other arterial conduits and vein grafts on an arrested heart. 19,20 A third approach combines a limited left anterior thoracotomy (6-10 cm), anastomosis between the LITA and LAD on a beating heart, and PTCA and/or stenting of the left main, circumflex, or right coronary arteries. Anecdotical reports highlight the feasibility of this hybrid approach in selected high-risk patients with multivessel disease. 21 Currently, the minimally invasive approach of choice that best achieves the objective of complete revascularization while preserving ideal anastomatic conditions (a still and bloodless field) entails CAGB through a ministernotomy or limited left anterior thoracotomy with CPB on the arrested heart.

Avoiding the Use of CPB

Based on the major complications and cost surrounding the use of CPB, significant interest has focused on approaches to perform CAGB on the beating heart. The primary complications of CPB—adverse neurological events, the systemic inflammatory response, postoperative bleeding, and pulmonary dysfunction—were described earlier. Although CAGB on the beating heart to avert cerebral microemboli in patients with severe proximal aortic atherosclerosis is an accepted indication, well-designed studies that demonstrate a significant decrease in adverse neurological events in patients without severe aortic disease currently are not available. The systemic inflammatory response was studied by Gu et al22 in 31 patients who underwent beating-heart CAGB, and was compared with the response of 31 patients who underwent conventional operation. Serum levels of leukocyte elastase, platelet β-thromboglobulin, and complement C3a were unchanged from baseline in the beating-heart group, whereas all 3 inflammatory markers were significantly increased after conventional CAGB. Importantly, these findings correlated with less pulmonary dysfunction and postoperative bleeding in the beating-heart group. 21 Indeed, beating-heart CAGB has been shown to reduce the need for blood transfusions. 12,17 Finally, the effect of avoiding CPB on relative hospital costs was examined by Fonger et al, 23 who compared 25 patients who underwent beating-heart LITA to LAD anastomosis with 25 patients who underwent conventional CAGB. In contrast to the conventional approach, the cost of supplies (predominantly operating room expenditures) and total cost for beating-heart CAGB were decreased by 65% and 45%, respectively. Magovern et al27 also documented savings in overall cost (28%), primarily in higher-risk patients. Thus, although the avoidance of CPB seems to reduce the elaboration of inflammatory mediators and may reduce the incidence of adverse neurological events, clinical correlates of reduced postoperative bleeding, pulmonary dysfunction, and stroke await the outcome of appropriately designed randomized controlled trials.

Avoiding the Morbidity of Sternotomy

Because conventional CAGB involves significant operative trauma and morbidty, particular attention has been directed toward developing approaches to avoid sternotomy. One method, called port-access, avoids the sternal splitting incision by combining femoral venoarterial CPB and a proprietary intra-aortic catheter that serves as an aortic cross-clamp by means of an expandable balloon at its distal end. Cardioplegia is delivered either through the proximal port of the balloon catheter or through a separate percutaneously placed coronary sinus catheter. With the heart arrested, CAGB is performed through a limited left anterior thoracotomy incision with dissection of the LITA and anastomosis to the target coronary artery under direct vision. Thus, the term port-access is somewhat inappropriate. Bypass grafts to other coronary arteries are accomplished using radial artery or saphenous vein sewn from the LITA or ascending aorta. To reduce operative trauma and mor-
bidity, the port-access approach therefore relies on avoiding the sternal splitting incision while preserving CPB and cardiopulmonary arrest. In a report by members of the Port Access International Registry, a voluntary, industry-sponsored database, the results of 583 patients who underwent port-access CAGB were reviewed. The mean age was 60.6 years, 87% had elective operations, and 48% had single-vessel revascularization. The operative mortality was 1%, and the stroke rate was 2.2%. Early concerns regarding a high incidence of retrograde aortic dissection associated with femoral arterial cannulation have been addressed by improved catheter design with more flexible guidewires, strict adherence to the Seldinger technique, early conversion to a sternotomy if guidewire passage is difficult, and excluding patients with severe atherosclerosis, kinking, or ectasia of the aorta or peripheral vessels. Based on this report, port-access CAGB can be accomplished safely in appropriately selected patients with morbidity and mortality rates similar to conventional surgery.

Few clinical reports have compared limited anterior thoracotomy with sternotomy in terms of pain and quality of life. Glower et al prospectively studied 41 consecutive patients undergoing mitral valve operations; 20 patients through a limited right anterolateral thoracotomy using port-access techniques (mean ± SD incision length, 8 ± 2 cm), and 21 through a conventional sternotomy (mean ± SD incision length, 26 ± 2 cm). Patients who underwent limited thoracotomy resumed work or normal activity sooner than those undergoing sternotomy (4 ± 2 vs 9 ± 1 weeks, P = .01). In contrast, Mohr et al studied 51 patients who underwent similar port-access mitral valve operations (mean incision length, 5 ± 2 cm), and found no difference in pain perception compared with 20 patients who had had sternotomy. Hence, additional studies are needed to fully elucidate functional outcome (less pain, faster recovery) and clinical effectiveness (long-term graft patency rates, freedom from angina, and cost containment) after port-access CAGB.

To facilitate true port-access operations, advances in endosurgical instrumention must overcome issues of poor optical quality and the technical challenges posed by attempting precise surgical movements through transthoracic ports. Significant progress has been achieved in these areas. Advances in optics include a 3-dimensional endoscope composed of two 3-chip cameras mounted on a custom endoscope with 2 separate optical channels. These images provide more realistic depth perception and enhance surgical dexterity. Image magnification is up to 10 times the actual size. To reproduce precise surgical movements, electronic instrument controllers are manipulated by the surgeon seated at a master console. The surgeon’s hand movements are translated directly to robot-assisted instruments placed within the patient’s chest through ports. These instruments have mechanical wrists that permit a full range of motion at the tips (ie, vertical, horizontal, and out, rotational, and grasping). In addition, the instrument tips are electronically aligned with the instrument controllers on a high-resolution video display to reproduce the hand-eye coordination found in open surgery. The surgeon’s hand movements are electronically scaled, and natural tremor is filtered and completely eliminated. In May 1998, the first robotic-assisted intracardiac operation in a human was performed by Carpenter et al. In June 1998, the same group performed the first 2 totally endoscopic CAGB operations, where LITA harvest and anastomosis to the LAD were accomplished on the arrested heart using robotic-assisted instruments. This preliminary experience clearly demonstrates that true port-access CAGB operations are possible, but also highlights several inherent problems with the current robot-assisted technology: unwieldy devices, interference between the instrument arms, heavy reliance on sophisticated technology, and lack of tactile feedback. Finally, before truly endoscopic coronary bypass procedures can be promoted, patient safety, quicker recovery, long-term graft patency, and cost containment must become firmly established.

In summary, minimally invasive CAGB is a work in progress. Its clinical goals, however, are well-defined: (1) to achieve graft patency rates equal or superior to conventional CAGB (avoid repeated revascularization); (2) to reduce incisional pain and discomfort (reduce invasivity); (3) to facilitate a more rapid return to work or normal activity levels (reduce invasivity); (4) to shorten the length of hospital stay (decrease complications); and (5) to decrease cost. To achieve these goals, 4 technical objectives must be considered: (1) effective coronary anastomosis, (2) complete revascularization, (3) avoidance of CPB, and (4) avoiding the morbidity of sternotomy. Currently, a myriad of minimally invasive approaches to achieve surgical myocardial revascularization currently exist. The extent to which each approach fulfills the technical objectives and achieves the clinical goals will determine its ultimate role in the cardiac surgeon’s armamentarium.

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