Minimally Invasive Cardiac Surgery
Current Status and Trends

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INTRODUCTION
Cardiac surgery for acquired heart disease can involve significant surgical insult in order to effect the required structural repairs. The physiological and psychological stresses surrounding cardiac surgery are primarily related to how much invasion is necessary to enter and leave the chest, plus the trauma from ancillary support techniques such as cardiopulmonary bypass (CPB) and cardioplegia. The minimally invasive surgical strategies that have been developed over the past several years have focused on reducing or eliminating surgical trauma while making effective and lasting surgical repairs. Coronary revascularization has been the main beneficiary of these new techniques, although significant strides have also been made in cardiac valvular surgery, arrhythmia surgery, and congenital cardiac surgery (1).

There are several new directions being pursued in minimally invasive cardiac surgery, including using smaller or more directed "limited incisions" to access and repair only the area of interest on the heart. Coronary grafting is also now being done off-pump without the hemodynamic support of CPB or the "still heart" achieved by using cardioplegia. Conduits for bypass grafting are being harvested in a less invasive fashion, and robotic technology is now allowing some cardiac surgery to be done solely through intercostal trocar ports. An array of other enabling techniques are also being developed. This module will present examples of how these developments are impacting specific areas of cardiac surgical patient care.

PRIMARY CORONARY ARTERY BYPASS GRAFTING
Primary coronary artery revascularization is the most common cardiac surgical procedure in the world today. The typical patient presenting for this procedure requires multiple coronary grafts to various regions of the heart. Conventional coronary artery bypass grafting employs CPB for circulatory support, and cardioplegia to temporarily stop the heart during the grafting. The heart is accessed through a full median sternotomy incision, and additional longitudinal incisions are required to harvest the coronary bypass conduits. This results in a moderate amount of surgical trauma, a systemic inflammatory response, hemodilution from the CPB circuit, and the potential risk of achieving a suboptimal cardioplegic arrest.

The most important advance in coronary artery bypass grafting over the past decade has been the idea that coronary bypass grafting can be done safely and effectively without the use of cardioplegia or CPB circulatory support. The beating heart is repositioned within the mediastinum to expose the coronary targets using pericardial retraction sutures, and the area of interest is stabilized using various custom-made mechanical cardiac stabilization devices. The region involved in the bypass grafting is mechanically stabilized while the rest of the heart continues to beat. Coronary blood flow to that region is temporarily interrupted with snares while the artery is opened and the graft is sewn into place (Figure 1).
Centers that have focused on these new developments now perform the majority of their coronary artery bypass grafting procedures on a beating heart; but there will always be a small number of patients for whom this approach is not appropriate due to extremely poor ventricular function, concomitant valvular disease, cardiac arrhythmias, or unsuitable coronary anatomy.

Large comparative series of patients are just beginning to appear in the literature documenting the advantages of off-pump over conventional grafting (2,3). Most importantly, the results of off-pump coronary artery bypass grafting (OPCAB), both acutely and one year after surgery, are now paralleling that of conventional bypass grafting (4,5). The additional benefits noted include a shortened hospital stay, less blood loss and homologous blood product administration, decreased hospital costs, and a reduction in early (but not necessarily late) neurologic sequelae. The incidence of postoperative atrial fibrillation is reduced to roughly half of that seen with conventional bypass grafting, but is not completely eliminated (6).

Additional developments include minimally invasive saphenous vein harvesting from the leg and, most recently, minimally invasive radial artery harvesting from the forearm. These conduits can now be harvested through one-inch access incisions using scopes to visualize and remove the conduit from a subcutaneous tunnel (Figures 2 and 2). This has dramatically reduced surgical wound complications, particularly in obese and diabetic patients, and markedly improved early postoperative patient mobilization in the hospital (7). Minimally invasive direct coronary artery bypass (MIDCAB) grafting of a single coronary artery is an additional strategy reserved for situations where a sternotomy or catheter-based intervention are contraindicated, or a catheter-based intervention has previously failed. The most frequent use for single vessel MIDCAB grafting is in the reoperative setting discussed below.
Figure 2. Endovein leg incision: The required length of saphenous vein for bypass grafting can be harvested from both the upper and lower leg from a single small access incision.

Figure 3. Endoradial forearm incision: The entire length of radial artery within the forearm can be harvested from a single small access incision at the wrist.
REOPERATIVE CORONARY ARTERY BYPASS GRAFTING

Conventional reoperative surgical revascularization involves greater surgical risks than primary coronary artery bypass procedures because the patient population is older, has poorer ventricular function, and more systemic risk factors. Reoperative dissection carries the specific additional risk of direct cardiac injury from sternal re-entry and the dissection required to release pericardial adhesions, plus the risk of perioperative embolization from prior bypass graft manipulation and the dissection and clamping of a diseased ascending aorta. The net result is an increase in the morbidity and mortality associated with this procedure.

Minimally invasive reoperative coronary artery bypass grafting employs the same off-pump coronary bypass techniques that have been developed for primary off-pump grafting; but to prevent reoperative cardiac dissection, the grafting is done through a small directed MIDCAB incision instead of a re-sternotomy. This limited access approach exposes only the region of the heart containing the coronary artery that requires grafting, while the rest of the heart and the ascending aorta remain undisturbed. The risks outlined above are largely obviated with this strategy, and morbidity and mortality are decreased.

The greatest risks to this patient population often stem from their other compromised organ systems. Although their systemic problems make them candidates for this limited approach, these problems can also be the cause of complications or death. A number of centers are beginning to publish large series comparing their experiences with conventional reoperations to their more recent limited access experiences, and the overall results are much improved in the limited access procedures.

Reoperative coronary artery bypass grafting through limited access incisions can address any coronary artery location on the heart (8,9). The procedure is done through a spectrum of small incisions which include the left fourth anterior intercostal space for the left anterior descending coronary artery (Figure 4), the left third antero-lateral intercostal space for the diagonal or ramus branches (Figure 5), the posterior sixth intercostal space for the circumflex and obtuse marginal branches (Figure 6), and the epigastrium for the distal RCA and PDA branches (Figure 7). In the female, for both primary and reoperative grafting, more cosmetic results can be achieved by grafting the left anterior descending coronary artery through a left sub-mammary intercostal incision (Figure 8) or the mid right coronary artery through a lower partial sternotomy using a pedicled right internal thoracic artery (Figure 9). Arterial conduits are used almost exclusively, either as pedicled grafts (such as the left internal thoracic artery to the anterior circulation and right gastro-epiploic arteries to the inferior circulation) or as free grafts (such as the radial artery to the left subclavian or descending thoracic aorta). In all cases, the proximal anastomoses are done distal to the origin of the carotid arteries on the aorta to reduce the risk of cerebral embolization. Off-pump grafting done through a limited access incision without manipulating old bypass grafts or the ascending aorta has resulted in a dramatic improvement in reoperative coronary bypass grafting results over the past several years.
Figure 4. Primary anterior MIDCAB incision: The pedicled left internal thoracic artery is grafted to the left anterior descending coronary artery through a small transverse incision over the left fourth intercostal space.

Figure 5. Redo antero-lateral MIDCAB incisions: A free radial artery conduit is grafted from a ramus coronary artery branch to the left subclavian artery through a small transverse incision over the left third intercostal space along with a counter incision for the proximal anastomosis below the left clavicle.
Figure 6. Redo lateral MIDCAB incision: A free radial artery conduit is grafted through a limited posterior sixth intercostal space incision from the descending thoracic aorta to the obtuse marginal branch of the circumflex coronary artery.

Figure 7. Epigastric (inferior) MIDCAB incision: A pedicled right gastro-epiploic artery is grafted to the posterior descending branch of the right coronary artery through a limited vertical epigastric incision.
Figure 8. Sub-mammary anterior MIDCAB incision: A cosmetic alternative to the standard anterior MIDCAB incision is a sub-mammary incision in the skin crease below the left breast approaching the fourth intercostal space from below.
When more than one region of the heart requires revascularization, several other limited access options are available. These include treating one area with a catheter-based procedure and the other with single vessel MIDCAB grafting in a combined or “hybrid” fashion (10), two limited access incisions under the same anesthetic rather than a transsternal reoperation, and limited access MIDCAB grafting in one coronary distribution with surgical transmyocardial laser revascularization and/or angiogenic compound administration to a less optimal second ischemic site elsewhere on the heart.

**VALVULAR REPAIR AND REPLACEMENT**

Cardiac valvular disease, either congenital or acquired, presents a different set of issues for the minimally invasive cardiac surgeon. Currently cardiac valvular operations require opening the cardiac chambers, and therefore by definition need to be done with the support of CPB, usually with cardioplegic arrest. Operating off-pump is not possible, and access has to be sufficient to allow cannulation of the circulation to establish the CPB circuit.

How can limited or alternative access surgical incisions can improve results, given the constraints noted above? The benefits of minimal access cardiac valvular surgery will understandably be more modest, but are still important in this select population of patients (11).

Aortic valve disease is generally treated with prosthetic valve replacement. There are several choices
available for a new prosthetic valve, but the surgical approach to replace the valve is similar in all cases. Minimally invasive aortic valve replacement involves reducing the size or location of the incision by using either an upper partial sternotomy or some version of an upper right para-sternal intercostal approach. Although these approaches provide limited access, the clinical results in comparative series have not demonstrated significant advantages over a conventional transsternal approach (12,13,14). Cosmesis of a smaller incision is often the only tangible benefit, and this is not the primary goal of minimally invasive cardiac surgical development.

Mitral valve disease can be treated with either valvular repair or replacement. The minimally invasive approach to accomplish this is through a limited right fifth interspace thoracotomy that will access the left atrium and mitral valve in a more direct fashion than access through a median sternotomy. Cardiopulmonary bypass support is required, and cannulation can be done either directly though the thoracotomy incision or percutaneously through the groin. There are more advantages to limited access mitral valve surgery than using this approach for aortic valve replacement (15,16). The incision can be much smaller than a sternotomy and more cosmetic within the right infra-mammary fold, particularly in the female patient, but it may also be more painful in the early postoperative period. When the left atrium is small, this more direct right thoracotomy approach gives much better visibility of both the valve leaflets and the subvalvular apparatus which greatly facilitates mitral valve repair. In the reoperative setting, this approach eliminates the risks of sternal re-entry and avoids the manipulation of any previously placed bypass grafts (17,18).

OTHER MINIMALLY INVASIVE INITIATIVES

Congenital cardiac surgery has also developed minimally invasive approaches for a number of commonly seen problems in newborns and children. The largest experience has been the closure of patent ductus arteriosus using thoracoscopic techniques. This can usually be accomplished with only two thoracoscopic ports and a surgical stapling device for closure of the ductus (19). Another area of significant progress is intra-cardiac endoscopy at the time of the repair to help assess the location and size of congenital defects within the tiny chambers of pediatric hearts (20).

The surgical treatment of refractory atrial arrhythmias has traditionally involved a substantial operation called the Maze procedure. This involves the surgical division of re-entrant conduction pathways under direct vision while the patient is supported with CPB and the heart is arrested with cardioplegia. A minimally invasive Maze procedure through a sternal incision is now being developed to accomplish the same surgical result using a linear cryoprobe on the epicardial surface of the heart alone, obviating the need for cardioplegia and CPB support. Results on the efficacy of this less invasive Maze procedure are still preliminary and await further clinical experience.

The field of minimally invasive cardiac surgery continues to be very dynamic with several dramatically different technologies and approaches being developed. Surgical robots or more correctly "remote surgical telemanipulators" are now being employed for portions of both general and cardiac surgical procedures (21) (Figure 10). These efforts will be further advanced by a number of initiatives to develop stent-like devices that will facilitate the fashioning of the coronary and proximal aortic anastomoses eliminating the need for suture management or knot tying by instruments within small closed spaces. The result of all these advances over time will be the ultimate realization of totally endoscopic coronary artery bypass grafting through three one inch trocar ports on the left lateral chest wall (22) (Figure 11).
REFERENCES


Figure 10: Operating room configuration for robotic cardiac surgery: In the foreground is the patient with the sterile robotic arms in position connected to instruments entering the chest through three intercostal port incisions. In the background the surgeon sits at a separate console and directs the robotic arm movements through remote telemanipulation of his hand movements.

Figure 11: Totally endoscopic CABG port placement: Single vessel totally endoscopic coronary artery bypass grafting can be accomplished solely through three intercostal port access incisions on the left antero-lateral wall of the chest cavity.


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