# 2 Practical Approaches to the Current "On-Pump" Redo Coronary Artery Bypass Surgery

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## Introduction

The mortality (5–15%) [1] and morbidity are higher for redo coronary artery bypass grafting (CABG) operations than for primary CABG procedures. There are multiple causes for the higher mortality of patients in need of repeat CABG, including left ventricular dysfunction as coronary artery disease (CAD) has progressed and decreased function of multiple organs with advancing age. Several risk stratification models have evolved, over the years, to objectively assess the preoperative risk of patients undergoing cardiac surgery, and a patient can be well-informed about his or her surgical risk prior to the procedure. Whichever risk stratification method is used, risk stratification only gives a general guide to morbidity and mortality, and the individual's outcome depends on whether or not problems occur during the intraoperative course. Advanced age, chronic obstructive lung disease, low serum albumin levels, renal failure, and preoperative hemodialysis for management of renal failure are all predictors of higher morbidity and mortality after cardiac procedures. The timing of surgery (i.e., elective, urgent, and emergent procedures) is also a clear, independent predictor of higher mortality.

Starting in 1967, after the number of primary coronary artery bypass surgeries performed per year increased, the number of redo CABG procedures performed yearly also increased slowly from 2 to 3% to as high as 15% in high-volume centers at the peak period of CABG utilization. Redo CABG was needed in 2.5% of patients within the first 5 years of primary surgery and increased to 17% within 12 years after the first CABG revascularization procedure. Percutaneous catheter interventions and medical therapy have progressed simultaneously and decreased the need for isolated redo coronary bypass. Balloon angioplasty, atherectomy, and stent placement for the management of vein graft atherosclerosis have certainly changed the need for repeat CABG. While most centers performed at least 15% of their revascularization procedures in1990s for recurrent CAD, this volume has significantly decreased in most surgical centers, especially over the last 5 years. Additionally, our appreciation of the benefits of repairing a leaking mitral valve secondary to ischemic CAD or treating calcific aortic stenosis in the elderly has created combined procedures that are more common in the present era than redo CABG alone.

Younger age at the time of the primary revascularization is a good predictor of the need for a second operation during the patient's lifetime. The need for redo CABG also depends very heavily on the type of conduit used for the first operation,

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specifically whether an internal thoracic artery (ITA) graft was used or if only vein grafts were used. Using the ITA for bypass grafting was popularized by both Green and Loop [2]. However, before the left ITA became the standard conduit for bypass of the left anterior descending (LAD) coronary artery, several thousand patients had bypass surgery utilizing only saphenous vein grafts. The presence of a well-functioning ITA graft to the LAD has decreased the incidence of redo CABG by at least 50% in a 10-year period. The use of both ITAs as well as the use of other arterial grafts in CABG also diminished the need for repeat revascularization for conduit failures.

Cardiopulmonary bypass time per graft is longer, and incidence of perioperative myocardial infarction is higher for redo CABG than the primary procedure. However, the number of bypass grafts needed in a redo revascularization procedure is generally less than the number of bypass grafts needed during primary revascularization procedures, as some of the grafts from the first operation might be patent. However, there are instances when all the grafts are occluded because of multiple systemic predisposing factors. Single graft or target vessel revascularization procedures have been predominantly performed using off-pump techniques. Most multigraft revascularization procedures are performed on-pump, though some surgeons have initiated off-pump bypass surgery as their primary method of choice even for multiple grafts. If there is hemodynamic instability, cardiopulmonary bypass is still instituted and a beating heart bypass surgery is performed without arresting the heart. Left ITA bypass to the LAD, reverse saphenous vein bypass from descending thoracic aorta to a marginal branch of the circumflex coronary artery, and isolated gastroepiploic artery bypass to distal right coronary artery branches have all been performed off-pump in highly selected cases. The axillary artery is also used as inflow with a reverse saphenous vein to bypass coronary artery branches.

## Technical Demands

Successful reentry into the chest, management of patent ITA grafts, establishment of cardiopulmonary bypass, myocardial preservation, prevention of vein graft atheroembolism, and elimination of perioperative hemorrhage are key factors that are under the direct control of the surgeon and improve the final outcome. The occurrence of intraoperative stroke is partly under the control of the surgeon, and onset of renal and pulmonary failure is guided by several factors.

### Redo Sternotomy

Safe redo sternotomy is one of the major steps to a good outcome following redo cardiac surgery. Evidence of adhesion of a vein or arterial graft to the back of sternum, history of mediastinal irradiation, presence of an ascending aortic aneurysm, and long-standing mitral or tricuspid valvular disease that causes right heart enlargement are all predisposing factors for catastrophic hemorrhage during sternal reentry. Although in the majority of cases, redo sternotomy can be accomplished without major bleeding, once in a while, an unfortunate incident occurs because the right ventricle, a patent saphenous vein graft or a patent left ITA graft is inadvertently injured. In patients with aortic aneurysms, especially rare aneurysms that are eroding into the sternum, surgeons plan for a safe approach during sternal entry as the diagnosis is evident before the surgery begins. Complications generally occur when the surgeon is least suspicious of such problems and the patient is the most vulnerable at that time.

There are several techniques for safe sternal reentry that are described in the literature, and all of them stress the same singular point. Visualize the structures you are cutting. Lifting the sternal edges or performing mediastinoscopy to lyse the adhesions has been described as giving satisfactory entry into the chest cavity. I have consistently

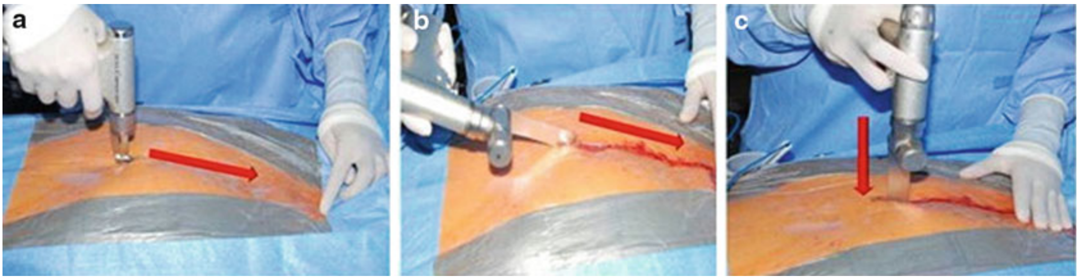


**Fig. 2.1** The difference between primary sternotomy (**a**), and safe (**b**) vs. standard (**c**) redo sternotomy techniques (from: Machiraju VR. How to avoid problems in redo coronary artery bypass surgery. J Card Surg. 2004 Jul-Aug;19(4):284–90; Used with permission)

approached the sternum being mindful of the following principles: (1) Safe sternal reentry is one of the key factors for successful outcome. (2) Presume that there may be vital structures adherent to the back of the sternum all the time. (3) The time spent performing a redo sternotomy is not critical but safe entry should be. (4) Visualization of the structures is important to avoid problems with catastrophic bleeding.

Our technique is based on the fact that the direction of the force in primary sternotomy is parallel to the body of the sternum (Fig. 2.1a), and there are no adhesions between the heart and back of the sternum as the intact pericardium shields the cardiac structures. Similarly, even in redo sternotomy, the saw blade is parallel (Fig. 2.1b) instead of perpendicular (Fig. 2.1c), and the sternum is incised up to the posterior table. Because it is the path of least resistance as half of the blade is inside the bone and half outside, in case the hand slips, the saw comes out rather than going into the chest cavity. This safe sternotomy technique is accomplished with a large oscillating saw or a microblade (Fig. 2.1b).

Then, using a spreader, the posterior table of the sternum is incised slowly under direct vision. We leave the sternal wires in place until this stage and then remove them one after another as we incise the posterior table of the sternum. With this technique, we have entered the mediastinal cavity safely without any catastrophic incidents in the last 15 years. We use peripheral cannulation through groin vessels in less than 2% of patients for fear of mediastinal bleeding during sternal reentry and always prefer central cannulation. However, peripheral cannulation techniques are resurging in cardiac surgery.

## Patent ITA Grafts

The presence of a well-functioning ITA-to-LAD graft is the most important contributing factor to the patient's long-term survival. Therefore, this graft should be preserved without any damage during redo cardiac surgical procedures. While this is an accepted philosophy among all cardiac surgeons, a patent ITA graft is injured in up to 4% of redo CABG procedures [1]. Though there is universal acceptance of using an ITA-to-LAD graft during the first procedure, there is great variability among surgeons as to how the conduit is attached to the coronary artery. Sometimes, it is too long and a redundant ITA is left inside the mediastinal cavity. Some surgeons bring the ITA in front of the intact pleura, while some surgeons bring it into pericardial cavity between the pleura and the lung parenchyma through a slit incision in the pericardium. Sometimes, a sequential ITA bypass is created to the coronary artery branches

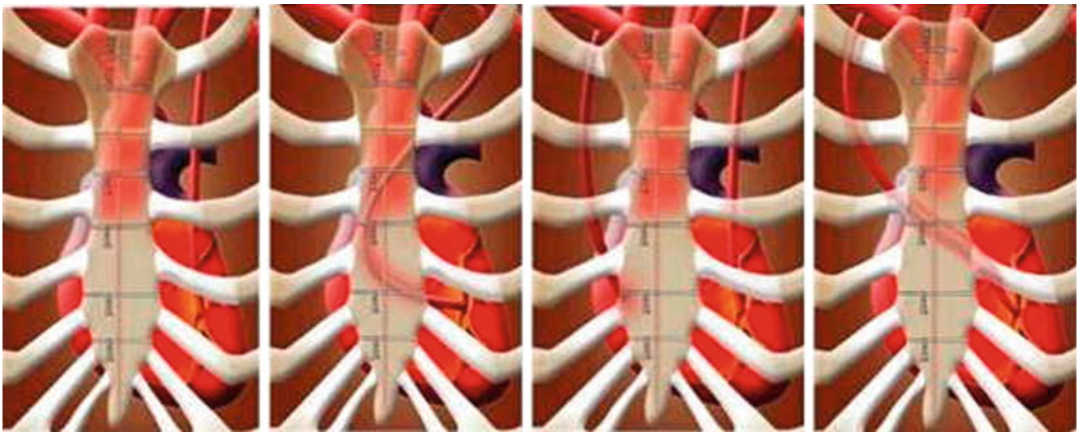

**Fig. 2.2** Some of the anatomic possibilities of ITA into coronary artery branches (from: Machiraju used with permission)

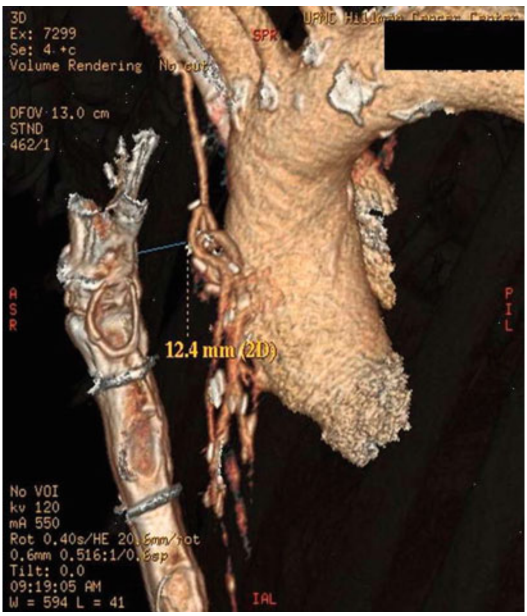


**Fig. 2.3** Showing the relationship of a patent right ITA across the midline to the body of the sternum

and, similarly, a skeletonized ITA to a pedicle graft is utilized. Furthermore, now that we have started using both ITAs for primary revascularization, the variations in the arrangement of the two arteries and coronary artery branches have increased (Fig. 2.2). Left ITA to LAD, diagonal and marginal branches, has been used as a pedicle graft. The right ITA has been brought down as a pedicle graft to the right coronary artery and also across the midline to the left-sided coronary artery branches. Even in cases where the right ITA is brought in front of the aorta across the midline, generally it tends to lie down on the aorta and stay much deeper than the back of the sternum (Fig. 2.3). This variability increases the risk for damage of the ITA graft. While the surgeon's prior experience with redo cardiac surgery helps, it is equally true that even the most experienced surgeons have damaged a patent ITA graft. Spending time when dissecting out the ITA is more important for avoiding injury to the structure than the experience of the surgeon.

If the ITA is injured during dissection, immediate hemostasis is important to prevent further blood loss. This is accomplished by ligating, clipping both ends, or successfully resuturing the bleeding site. Some surgeons have placed an intraluminal shunt into the injured ITA to prevent myocardial ischemia. This is more easily said than done because sometimes shunt insertion only causes the tear to get worse and the bleeding to become profuse. The ITA must be satisfactorily mobilized proximal and distal to the tear site before further maneuvers can be performed. If a well-functioning ITA has to be ligated after an injury, an early institution of cardiopulmonary bypass will help to prevent myocardial ischemia. It is prudent to dissect out the right side of the sternum and the heart first rather than the left side, whenever a patent ITA is present perfusing a large region of myocardium. In case, there is an injury to the ITA graft, cardiopulmonary bypass can be instituted quickly avoiding prolonged myocardial ischemia. The right ITA, when available, is the most suitable conduit during redo cardiac surgical procedures to replace an injured left ITA.

There are differing opinions as to whether a patent ITA should be left alone perfusing the myocardium during a redo cardiac surgery or if it should be dissected and clamped so that myocardial temperature can be maintained uniformly with the cardioplegic solution. Smith and associates [3] reviewed 206 patients who had redo cardiac surgery; 118 patients had the ITA dissected and occluded and 88 patients did not have the ITA occluded. In the dissected group, there were seven graft injuries which the authors believe could have been avoided if the ITA had not been dissected. There was no statistical difference in mortality between the groups. It has been my practice, over the years, to dissect out a small portion of the ITA and occlude it during the operation to maintain uniform distribution of cardioplegic solution. There are procedures that require mobilization of a patent ITA, such as revascularizing circumflex coronary artery branches. Also, whenever the chest needs to be opened widely for various procedures, it is necessary to mobilize at least a part of the ITA to avoid stretch injury by the scar tissue. When just replacing an aortic valve, a patent ITA graft can be left alone along with systemic cooling and administration of cold cardioplegic solution.

## Institution of Cardiopulmonary Bypass

When instituting cardiopulmonary bypass, the length of the ascending aorta, ascending aortic calcification, and the presence of atherosclerotic and patent vein grafts always create a challenge to finding a suitable place on the aorta for both cannulation and aortic cross-clamping. Carefully separating the superior vena cava and the pulmonary artery on both sides of the aorta is necessary for satisfactory clamping. We have used a Soft-Flow cannula (Edwards Co.) inserted high in the aorta and guided into the beginning of descending thoracic aorta to keep the perfusion site distal to the take of the aortic arch vessels. This, I believe, prevents the "Niagara Falls effect" in front of the arch vessels by avoiding all the turbulence. Direct palpation of the aorta and transesophageal echocardiogram (TEE) give a general idea of the condition of the aorta by which we make a judgment about the site of aortic cannulation. Epiaortic scanning gives further insight into the aorta in doubtful cases. Physical manipulation of the ascending aorta and institution of cardiopulmonary bypass alone can increase the incidence of neurological complications. However, the incidence of intraoperative stroke can be kept at a minimum by perfusing distal to the aortic arch, single aortic clamping, the use of the Soft-Flow aortic cannula, evacuation of all intracardiac air as guided by TEE, and thorough irrigation of the cardiac chambers after excision of the calcified valves. Similarly, fewer neurological complications are observed with axillary artery cannulation as it keeps the site of turbulence away from the take of the arch vessels. Arterial cannula can be inserted over a guide wire as well to minimize manipulation of the aorta.

## Myocardial Protection During Redo Cardiac Surgery

The goals of myocardial protection are as follows: (1) The myocardium should be electrically quiescent during the operation. (2) The myocardium should start contracting as soon as the aortic cross-clamp is removed. (3) Minimal inotropic support should be required during separation from cardiopulmonary bypass. (4) Myocardial reperfusion injury in the form of myocardial swelling and decreased contractility should be avoided. Myocardial preservation during cardiac surgery is a balancing act between myocardial ischemia and reperfusion injury. When the myocardium is not protected properly, myocardial stunning and cardiomyocyte necrosis occur depending on the length of ischemia and the time that is needed for the ischemic myocardium to recover during the reperfusion phase. Myocardial damage is attributed to either increase in intracellular calcium, the release of reactive oxygen species or both. These cause loss of the cell's phospholipid layer leading to swelling and loss of cell integrity. After the aortic cross-clamp is removed, cardiac myocyte function may become normal or dysfunctional depending on the level of ischemia, necrosis, or apoptosis.

Although potassium-supplemented ($K^+$) blood cardioplegia is the hallmark of intraoperative management, myocardial protection varies from surgeon to surgeon and from medical center to medical center. There is no standardized method of cardioplegia administration in the surgical community. There is great variability in the initial and maintenance doses of the plegic solution, solution composition, and route of administration (e.g., antegrade vs. retrograde). Administered cardioplegic solution must reach the myocardium to achieve the goals stated earlier. This may not happen during antegrade induction if there is some aortic insufficiency, severe CAD, or a paucity of collaterals between coronary artery branches. Similarly, cardioplegic solution may give inadequate myocardial protection during retrograde administration if the catheter is not positioned properly in the coronary sinus, if the catheter slips back into the atrium, or if the cardioplegic solution regurgitates back into the atrium due to a very large sinus. It is essential to monitor the coronary sinus pressure and, generally, we tend to keep it between 25 and 40 mmHg. Accidental perforation of coronary sinus and inability to place the retrograde catheter into a small sinus will preclude retrograde administration.

Since TEE is the standard method of monitoring every patient during cardiac surgery, TEE will certainly assist in locating the position of the retrograde catheter when the catheter is positioned at the beginning of the procedure; however, TEE will not help to localize the catheter during the cardiopulmonary bypass period when the heart is arrested and empty. Definitive ways of making sure that the retrograde catheter is properly positioned are by lifting the heart and palpating the balloon catheter in the coronary sinus and opening the right atrium, directly placing the catheter in the coronary sinus, and temporarily occluding the sinus opening with a pledgeted suture until the procedure is completed. Contrary to the popular belief that retrograde delivery of plegia solution does not protect the right ventricle, we have never seen inadequate protection of the right ventricle as long as the posterior descending coronary vein is filled with cardioplegic solution. Generally, we can see that the veins over the right ventricle are filled with bright red blood and that is sufficient for protection. We see right ventricular dysfunction when the left ventricle fails and during aortic surgery when a nondominant right coronary artery is not properly reattached to the main aorta or to the Dacron graft. We have also revascularized suitable right acute marginal branches and perfused them during the operation. Generally, these grafts flow 15–20 mL of plegia solution per minute, and this is certainly adequate to protect the right ventricle. While a single, ventricular dysfunction (right or left) can be managed relatively easily, biventricular failure certainly requires a ventricular assist device and this is followed by added complications related to the device.

We base our cardioplegia delivery methodology on the following principles: (1) Myocardial edema is bad for functional recovery and so there is no place for crystalloids in the cardioplegic solution. Initiation of cardiopulmonary bypass itself with resulting hemodilution and cytokine release causes some degree of myocardial edema, and adding crystalloid solution to the cardioplegia will further aggravate this process. Therefore, only blood is used as a cardioplegic delivery vehicle. (2) Because oxygen dissociation occurs only at higher temperatures, we keep the plegia temperature around 28°C constantly and have stopped using very cold (4–10°C) plegia. (3) Reperfusion injury occurs only when ischemic periods are created and, so, we deliver continuous retrograde blood cardioplegia through a coronary sinus catheter to avoid myocardial ischemia. Simultaneous antegrade plegia is given through the newly constructed bypass grafts. (4) Since there is significant reduction in the utilization of oxygen, by more than 80% in the quiet arrested heart compared with the normal beating heart, this oxygen demand can be met by giving 100–120 mL of blood continuously instead of larger quantities [4]. (5) Adding adenosine (12 mg) to the induction dose of high dose potassium and magnesium cardioplegic solution generally causes quick cardiac standstill by means of hyperpolarized arrest and limits us from giving larger quantities of cardioplegic solution. By adhering to these principles, even cross-clamping times of 3 h and longer have not resulted in higher rates of inotropic support or intraaortic balloon assistance. During surgical procedures that involve the aortic arch and require circulatory arrest, we administer much colder blood during the portion of the procedure involving the arch and then revert to our standard method once rewarming is started. Systemic temperature is kept at 34–35°C for all patients who do not require circulatory arrest. Blood glucose levels are closely monitored and regulated with insulin therapy. Although there have been several clinical trials of additives to the cardioplegic solution, at present, we only use potassium and magnesium for maintenance of cardiac silence.

Activated neutrophils cause endothelial damage, and the initial insult occurs when contact activation takes place upon initiation of cardiopulmonary bypass. Modalities to filter leukocytes or neutralize the effect of neutrophil-induced toxicity have become a routine part of the clinical practice. Leuko-reduced blood is administered routinely for all patients requiring blood transfusions. Heparin-bonded circuits also decrease the contact activation of neutrophils upon initiation of cardiopulmonary bypass. Several years ago, we adopted administration of 12 mg of adenosine intravenously just before going on cardiopulmonary bypass. Neutrophil activation is mediated by 11b/CD18 members of the integrin family of adhesion receptors, and both adenosine and acadesine inhibit 11b receptor upregulation in a dose-related fashion. Activation of the A1 and A2 adenosine receptors causes significant bradycardia and hypotension, and only activation of the A3 adenosine receptor is helpful to prevent myocardial ischemic injury. While the basis for adenosine treatment is only empirical, it is not cost prohibitive to give a small dose of adenosine after the patient is cannulated and ready to go on cardiopulmonary bypass. As there is no published date, we base our judgment solely on our clinical experience that with adenosine treatment prior to cardiopulmonary bypass, as well at the beginning of cardioplegic induction, even patients with a very low ejection fraction or prolonged cross-clamping come off cardiopulmonary bypass easily.

Clearly, the combined effects of every well-executed technical maneuver during the operation result in good outcomes. It is unlikely that any one step is solely responsible for good or bad functional recovery of the myocardium. While the type of myocardial protection used does not matter much in patients with good left ventricular function requiring a short cross-clamp time, it becomes of paramount importance in patients with poor left ventricular function and a decompensated heart who require a prolonged cross-clamping.

## Vein Graft Failure and Prevention of Vein Graft Atheroembolism

Saphenous vein graft failure is one of the main reasons for redo coronary artery bypass surgery. While some vein grafts remain free of disease, others show extensive atheroscelorosis and the underlying mechanisms are intriguing [15]. Injury to intimal layers during the preparation of the vein conduit increases neointimal thickening and smooth muscle proliferation. The most frequent operation in this country still uses the left ITA to bypass the LAD and reverse saphenous vein grafts to bypass the remaining coronary branches. Ten years after CABG surgery, 60–70% of vein grafts are either occluded or show severe stenosis. A diffuse fibromuscular hyperplasia decreases the lumen of vein grafts by 20–30% within the first 12 months. Vein conduits less than 3 mm diameter have a greater chance of failure. A vein with a thick wall at the time of implantation has higher propensity to develop atherosclerotic changes. Patients with hypercoagulable states have higher incidence of graft failure. These patients have either thrombocytosis or hyperfibrinogenemia.

The use of aspirin significantly increases the patency of both vein grafts and arterial grafts, though the patency is not increased by adding warfarin or dipyridamole. High serum lipoproteins are an independent risk factor for developing atheroscelorosis. Clopidogrel (Plavix) has a significant effect on platelet aggregation and decreases the incidence of vein graft closure. It is prescribed primarily by surgeons after off-pump CABG and by cardiologists after stenting a vein graft to treat stenosis.

Saphenous vein valves are a common site for atherosclerosis to occur. Occasionally, there is a congenital valve stenosis, which goes unnoticed at the time of surgery, and only manifests as a stenotic segment seen during angiography performed after surgery. Similarly, there can be vein valve stenosis secondary to phlebitis, which was already present but unsuspected. Although grafts stripped of the venous valves (via a valvulotome) and nonreversed vein grafts are used as in situ grafts for lower extremity revascularization procedures, this is not a common practice for CABG in most centers.

Initial cardioplegia can be given in an antegrade fashion in spite of vein graft stenosis, although retrograde administration for both induction and maintenance has also yielded satisfactory results. Prevention of vein graft atheroembolism using the "no-touch" technique was described by Savage and Cohn [6]. Vein graft atherosclerosis is intraluminal, and any manipulation can result in distal embolization of atherosclerotic material because the material, in general, is very friable and easily dislodged. However, we do not see such loose atherosclerotic material in patients who have received long-term statin therapy [7].

## Management of Perioperative Hemorrhage

Maintaining blood in the fluid state necessitates a balance between procoagulant and anticoagulant mechanisms, and shifting the balance can result in either thrombosis or bleeding. Reinfusion of shed blood aspirated from the surgical field by cardiotomy suction can enhance activation of coagulation and inflammation in the systemic circulation. During reinfusion, levels of factor VIIa, markers of thrombin generation, procoagulant microparticles, and activated complement proteins are all increased. Aspiration of shed blood through cardiotomy suction is related to the type of myocardial protection the surgeon uses. Giving intermittent cold cardioplegic solution does not release much blood into the pericardial cavity, so the volume of the cardiotomy suction will be low as well. However, there is chance for reperfusion injury because intermittent ischemia is created and more reactive oxygen species will be liberated when the cross-clamp is released. If continuous tepid cardioplegia is given through a retrograde catheter, there are larger quantities of blood in the pericardial cavity. If this volume is not returned to the pump, there will be significant blood volume loss and bank blood and blood products will need to be transfused, which again causes an inflammatory response.

It has been customary to use an antifibrinolytic agent during cardiopulmonary bypass. It is also clear that the extracorporeal circulation releases the proinflammatory cytokine interleukin (IL)-6 and the anti-inflammatory cytokine IL-10 as is evident in systemic inflammatory response syndrome. While aprotinin, a serine protease inhibitor, decreases the levels of IL-6, it is no longer available for clinical use because of suspected adverse effects on other organs. ε-Aminocaproic acid, a lysine analog that inhibits plasminogen cleavage by tissue plasminogen activator, is commonly used to inhibit fibrinolysis and prevent blood loss. Some surgeons prefer tranexamic acid as an antifibrinolytic agent.

There is an increased incidence of blood transfusions during redo cardiac surgical procedures because of surgical blood loss, prolonged cardiopulmonary bypass time, and low preoperative hemoglobin. Multiple blood transfusions are associated with increased perioperative complications, such as stroke, infection, renal failure, prolonged ventilation and surgical site infections, and increased mortality. However, hematocrit levels lower than 18 during cardiopulmonary bypass are also associated with increased morbidity and mortality because of tissue hypoxia. Postoperatively, patients tolerate hemoglobin levels around 8.0 g/100 mL, and increasing oxygen delivery by giving blood transfusions has not translated into increased oxygen uptake by the tissues in anemic patients. It is also understood that stored red blood cells become depleted of 2,3-diphosphoglycerate (2,3-DPG), which is important for oxygen transfer and several hours are needed for the transfused red blood cells to get replenished with 2,3-DPG. In the practice of most physicians, the threshold to transfuse elderly patients is very low and, as such, older patients tend to get more blood transfusions than younger patients. The need for transfusion of blood products also increases because of increased consumption of the fibrinogen and platelets during cardiopulmonary bypass.

## Conduits for Bypass Surgery

ITA, saphenous vein, and radial artery are the most commonly used bypass conduits. These may be available adequately, or the surgeon may have to scramble for alternate conduits like the gastroepiploic artery or the inferior epigastric arteries.

### Internal Thoracic Artery

The left ITA is the preferential conduit for redo CABG, provided it was not used during the initial revascularization procedure. Otherwise, the right ITA becomes the next most desirable conduit and should be used whenever possible. There is always some fibrous reaction in this area due to the primary cardiac surgery, and it certainly takes a longer time to dissect out the ITA graft. In my practice, right ITA is used more often as a free graft and is used as a pedicle graft in only 20% of cases. Recycling of previously grafted ITAs can be done in selective cases where there is stenosis at the anastomotic junction or there is an isolated area of narrowing. A patent ITA can be used as an inflow for a T graft with a right ITA or radial artery segment. Many surgeons prefer anastomosing a free ITA graft to the hood of a vein graft or as a T graft, instead of directly attaching it to the aorta. On occasion, when we anastomose to the aorta directly, we make a bigger punch hole in the aorta to avoid anastomotic stricture.

### Preparation of Venous Conduits

It is important to avoid conduit injury when preparing venous conduits. Overdistension of the vein and exposure of the vein to lower pH or lower oncotic pressure may cause biochemical or physical injury. Mechanical dilatation of the vein causes excessive distension and injury to the intimal layers and, as such, the pressure should be controlled. In a comparative study, low calcium Plasma-Lyte solution at 37°C resulted in the best venodilatation of all solutions tested to prepare venous grafts.

Vascular smooth muscle cells that proliferate during the first 2 weeks after implantation become the nidus for infiltration of macrophages, which later become foam cells. Intimal thickening itself may be the driving factor for some early graft closures or may promote late atherosclerosis. Vascular smooth muscle proliferation may be secondary to growth factors derived from either platelets or fibroblasts. Both wall stress and graft injury have been implicated in growth factor production. Additionally, Allen et al. [8] studied the effect of cysteinyl leukotrienes derived from activated leukocytes on saphenous vein grafts and ITA grafts and found that saphenous vein grafts were more sensitive to leukotrienes than the ITA grafts, and this may one of the factors underlying early graft failure in saphenous vein grafts as compared with ITA grafts. As opposed to vein grafts, ITA grafts also have a potent nitric oxide system that protects against vasospasm.

Injury to the saphenous vein endothelium affects the patency of the venous conduit. The endothelium acts as a barrier between blood components and subendothelial muscular layers. Any damage to the endothelium becomes the nidus for vein graft atherosclerosis and graft failure. Surgical manipulation also decreases the antithrombogenic nature of vein graft endothelium and increases vasospasm, thrombogenesis, and occlusive intimal hyperplasia. There is ongoing concern that saphenous vein conduits harvested by endoscopic techniques exhibit more structural and functional damage than those harvested with open surgical techniques. Irrespective of the method used to remove the saphenous vein, the venous endothelium gets damaged when it is subjected to the arterial pressure and a pseudointimal lining develops over time. This is why vein graft atherosclerosis is intraluminal and atheroemboli occur easily with the manipulation of vein grafts.

While the high incidence of vein graft closure after 10 years is clear, there is a debate over replacing angiographically nondiseased vein grafts at the time of redo cardiac surgery. Currently, we believe that this is not necessary and only increases the risk and morbidity [9]. There is no assurance that the newly created vein grafts will last any longer than the grafts they would replace because several factors determine the patency of a new graft. Our preference has been to leave a stenotic vein graft intact and reconstruct a new vein graft beyond the anastomosis of the old graft or to bypass only the diseased segment of the graft. Additionally, it is necessary to leave a stenotic vein graft to the LAD intact while reconstructing with a new ITA graft to avoid malperfusion in this important territory [10].

## Radial Artery

In the aged population, as well in diabetic and obese patients, the saphenous vein deteriorates and develops varicosities. The radial artery is the next arterial conduit available after both ITAs have been used. In 1973, Carpentier published the use of the radial artery as a coronary artery bypass conduit but this practice was abandoned in 1976 because of a higher incidence of graft closure. Use of the radial artery in CABG resurged in 1989 after Acar [11] used the radial artery along with vasodilator therapy. The radial artery is a thick-walled muscular artery, which has more elastic lamina than the ITA. Muscular layer response to endothelin I, angiotensin II, norepinephrine, serotonin, and thromboxane-2 results in radial artery spasm. Spasm of the radial artery is the main contributing factor for graft closure and using diltiazem as a vasodilating agent relieves the arterial spasm. Also, using the radial artery to bypass blood vessels that do not have critical stenoses causes competitive blood flow in the native coronary artery and results in graft closure. Currently, use of the radial artery is recommended for coronary artery branches that have >75% stenosis. The radial artery can also develop age-related calcification and is not suitable as a bypass conduit in some elderly patients.

Evidence of sufficient collateral flow in the hand is the most important consideration before radial artery can be taken as a bypass conduit. The modified Allen test is the simplest, most widely available test at bedside and, when inconclusive, digital pulse oximetry, digital plethysmography, and Doppler ultrasonography have been used to assess satisfactory collateral circulation in the hand. Originally, the radial artery was removed by a long forearm incision, which resulted in numbness of the fingers and did not appeal cosmetically to many young patients. Now, the radial artery is removed endoscopically with minimal surgical incisions and higher cosmetic appeal. This is a technically difficult procedure and needs to be performed by practitioners with sufficient training. The radial artery can be removed via pedicle harvesting or using a skeletonization technique. The skeletonized radial artery has higher patency rate as much of the connective tissue around it is removed. However, skeletonization results in leakage of blood from small arterial branches so all the small arterial branches have to be ligated after inflating the artery with vasodilating agents.

Papaverine has been used frequently to dilate the bypass conduits, but is very acidic and causes endothelial cell damage. The effects of papaverine are among the shortest of all available agents, so we use a phenoxybenzamine and verapamil combination in Plasma-Lyte solution and heparin. Because this combination dilates the artery very well, we have also used this solution to dilate

ITAs and have discontinued the use of papaverine. Milronone, another phosphodiesterase inhibitor, also dilates the radial arteries with the effects lasting longer than papaverine.

The radial artery can be used as a T graft from a pedicled ITA or directly from the aorta. The resurgence of use of the radial artery has allowed several surgeons perform primary revascularization procedures using arterial grafts exclusively, thereby limiting the need for redo revascularization procedures. Calcium channel blockers, like diltiazem, increase the patency of radial grafts and, as such, they should be prescribed for up to 1 year after revascularization.

### Alternative Conduits

There will always be specific cases where no routine conduits are available and surgeons have to scramble for alternate conduits. In such desperate cases, we have used 4-mm thin-walled polytetrafluoroethylene (Goretex) grafts as an aortocoronary bypass conduit without creating a distal right atrial or superior vena caval anastomosis. We believe that when Permaflow grafts [12] were created, the Goretex graft, which was very big and thick, compromised blood flow into a small coronary artery. Now that the thin-walled Goretex graft, which is used generally for hemodialysis purposes, is available, it can be anastomosed to a coronary artery without impinging on the lumen of the coronary artery.

## Indications for Redo Coronary Artery Bypass Surgery

Symptomatic or asymptomatic significant vein graft stenosis to the LAD requires therapeutic intervention. Atherosclerotic lesions in a vein graft to the LAD predict higher rate of death and cardiac events than native vessel disease with the same distribution [13]. Because vein graft atherosclerosis is not necessarily characterized by particular symptoms, vein graft stenosis to the LAD is an indication for reoperation, irrespective of symptoms. In the early 1970s and 1980s, coronary artery primary revascularization was performed with only saphenous vein grafts. Later, the left ITA became the standard conduit to revascularize the LAD. In a few cases, in which the left ITA either did not have sufficient flow or was traumatized during surgical dissection, either the left ITA was used as a free graft or the right ITA was used to revascularize the LAD. Patients who have a functioning left ITA to LAD graft do not gain any increased survival benefit from redo CABG, when the therapeutic intervention is made for non-LAD territory. However, the indication for repeat surgery is based on symptomatology and the presence of valvular disease.

On occasion, we have seen total graft failure following primary CABG requiring repeat surgical intervention. This is seen either very early, within a few months of the initial procedure or as a delayed graft closure. Metabolic conditions, such as uncontrolled diabetes mellitus; polycythemia; local factors, such as poor quality of the saphenous vein or small ITA; or technical conditions, such as poor choice of an anastomotic site in calcified coronary arteries have all contributed to such failure. While it is relatively easy to operate on patients with late graft failure more than 1 year after the procedure, early repeat revascularization, within a few months of the original procedure, is more challenging and difficult when the phlegmon is still present.

## Identifying Coronary Artery Branches

It is not easy to dissect out all the coronary artery branches all the time. The LAD may be deeply embedded in the interventricular septum. It is essential to dissect out the part of the LAD that has a larger caliber for graft anastomosis. Once the LAD is identified before it dips underneath the septum, the dissection should be carried out proximally by splitting small portions of the septal muscle until a larger caliber portion of the artery is reached. Secondly, sometimes even the ramus branch or the marginal branches are so deeply embedded in the lateral muscular wall that no trace of the artery is recognized on the surface.

In such cases, the dissection should start proximally near the left atrial appendage downward until the necessary branch is dissected out. Similarly, a suitable portion of the posterolateral branch of the right coronary artery may dip behind the coronary sinus making it difficult for anastomosis.

## Combined Surgical Procedures

Patient volumes for isolated redo CABG are decreasing, and the frequency of combined cardiac surgical procedures and repeat revascularization procedures is increasing. The two procedures most commonly combined with redo CABG are aortic valve replacement for age-related calcific aortic stenosis and mitral valve repair or replacement for ischemic mitral regurgitation. Aortotomy for aortic valve replacement may present some challenges if all the saphenous vein grafts that are attached to the ascending aorta are patent. Sometimes, the aortotomy has to be performed between the patent grafts. Percutaneous valve implantation techniques and transapical implantation techniques for aortic prostheses are rapidly advancing; some high-risk surgical patients may be offered alternative approaches for correction of their aortic stenosis.

Ischemic mitral regurgitation is a bigger problem, as it can present as an isolated eccentric jet secondary to posterior papillary muscle outward displacement, a retraction of the P3 segment of the mitral valve secondary to an inferior wall myocardial infarction, or a large central regurgitant jet from annular dilatation and ischemic cardiomyopathy. The cause for mitral regurgitation needs to be properly assessed. Although annuloplasty may correct the mitral regurgitation at the time of surgery, subvalvular surgical procedures, like excising the secondary chordae, approximating the papillary muscles, or posterior leaflet extension, are warranted for long-term satisfactory results.

## Conclusions

Redo CABG is a technically challenging operation. In the initial phase of its implementation, the mortality was higher than for primary revascularization procedures for lack of experience in handling the various issues that arise during redo cardiac surgery. As the surgeons performing the procedure have gained experience, the complexity of the patients' comorbid conditions has increased resulting in still higher morbidity and mortality. However, 85% of the patients who survive redo multivessel revascularization live symptom-free for at least 6 years. While isolated, repeat coronary revascularization procedures are on the decline, combined valve and redo CABG procedures are performed regularly in spite of higher morbidity and more perioperative complications. Proper preoperative assessment, skilled intraoperative care, and judicious postoperative management of these highly complex patients should lead to better outcomes.

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