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Coronary Artery Bypass Grafting: Surgical Anastomosis: Tips and Tricks

Mohd. Shahbaaz Khan

Abstract

The definite feature of coronary artery disease is the focal narrowing in the vascular endothelium, and this leads to the decrease in the flow of blood to the myocardium. Atherosclerotic plaque is the main lesion. These patients can present with chest pain (angina or myocardial infarction) and need further workup noninvasively and invasively for the management. The main reasons for myocardial revascularization can be: (1) relief from symptoms of myocardial ischemia; (2) reduce the risks of future mortality; (3) to treat or prevent morbidities such as myocardial infarction, arrhythmias, or heart failure. Coronary artery bypass grafting (CABG) is the surgical technique of cardiac revascularization. In 1910, Dr. Alexis Carrel described a series of canine experiments in which he devised means to treat CAD by creating a “complementary circulation” for the diseased native coronary arteries. No clinical translation occurred at the time, but he was awarded the Nobel Prize in Medicine. Experimental refinements of coronary arterial revascularization, including the use of internal thoracic artery (ITA) grafts, were later reported by Murray and colleagues, Demikhov, and Goetz and colleagues in the 1950s and early 1960s. Dr. Rene Favaloro performed his first coronary bypass operation in May 1967 with an interposed saphenous vein graft (SVG) and shortly thereafter used aortocoronary bypasses sutured proximally to the ascending aorta. The stenosed segment is bypassed using an arterial or venous graft. Left internal thoracic artery is the most commonly used artery, and long saphenous vein is the most commonly used vein for the coronary artery grafting to reestablish the blood flow to the compromised myocardium. This can be performed with or without the help of cardiopulmonary bypass machine and also with or without arresting the heart. These techniques are called as on-pump beating or on-pump arrested and off-pump beating coronary artery bypass grafting surgery. Distal and proximal anastomoses are usually performed in an end-to-side manner, but in the case of doing sequential grafting, side-to-side anastomosis is also performed proximal to the end-to-side anastomosis. In this chapter we are going to discuss the coronary artery bypass grafting tips and tricks in details.

Keywords: coronary artery bypass grafting, off-pump CABG, on-pump CABG, LIMA, RIMA, radial, RSVG, sequential grafting

1. Introduction

Coronary artery disease is a major cause of mortality and morbidity not only in the developed countries but also in developing countries. Over the last decade,

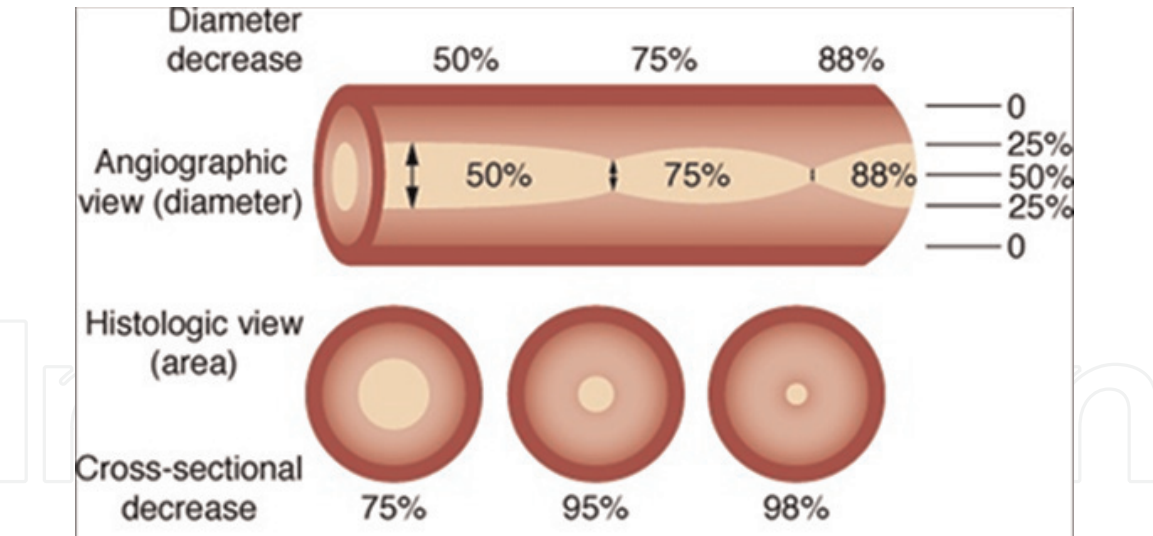


Figure 1.
Relationship between loss of cross-sectional area and diameter of the vessel.

mortality with this disease has decreased, but still it accounts for approximately one-third of all the deaths in people over the age of 35 years. The American Heart Association reported that nearly 16.5 million people (20 years or more age) had coronary artery disease in 2017, with male predominance of 55% [1].

Coronary artery disease is the narrowing or occlusion of the vessel lumen due to arterial wall thickening caused by subintimal deposition of atheroma and loss of elasticity of the arterial wall. Atherosclerosis involves the proximal portions of the coronary arteries, specifically at the branching sites. In the beginning it only affects the flow reserve of the coronary artery, but as it advances, it affects the blood flow even at rest and leads to myocardial ischemia or infarction depending on the severity of the disease. This can be divided as supply ischemia (myocardial infarction and unstable angina) and demand ischemia (stable angina as during exercise, fever, emotional stress, etc.) [2]. The subendocardium is most vulnerable to myocardial ischemia due to the limited collateral blood flow. Therefore myocardial necrosis progresses from the subendocardium to the epicardium with continuing ischemia.

A 75% cross-sectional area loss (50% diameter) is considered an important but moderate stenosis, while a 90% cross-sectional area loss (67% diameter) is considered severe stenosis (**Figure 1**) [3].

There are three methods of treating coronary artery disease—medical management, percutaneous intervention, and coronary artery bypass graft surgery [4, 5].

2. Medical management of coronary artery disease

1. Aspirin—it should be used daily in the case of stable angina. Daily use of aspirin in stable angina decreases myocardial infarction and sudden death. Its role is very important in unstable angina and myocardial infarction. Aspirin should also be continued after PCI or CABG.
2. Platelet inhibitors—it inhibits the binding of the ADP to platelet P2Y₁₂ receptors and consequently inhibits activation of GPIIb/IIIa complex. Therefore it inhibits platelet aggregation. Clopidogrel is recommended if patient is intolerant to aspirin or there are adverse or side effects of aspirin such as GI bleeding or allergic reaction [6]. Both aspirin and clopidogrel are

recommended for at least 1 year after PCI and CABG. Aspirin and clopidogrel combination is not recommended for stable angina as it is not superior to aspirin alone and increases the risk of bleeding [7].

3. Beta blockers—these medicines decrease the myocardial oxygen demand and improve exercise capacity. These are effective for stable angina, and dose should be adjusted to keep heart rate about 60/min at rest and less than 100/min with exercise.
4. Calcium channel blocker—as beta blockers, these agents are also effective to treat stable angina. They act mainly by causing vasodilatation and reducing peripheral vascular resistance. The dihydropyridines (nifedipine, amlodipine, etc.) do not affect the SA or AV node conduction. Their mechanism of action is by dilating the coronary arteries and reducing the peripheral resistance, thereby leading to the decrease in myocardial oxygen demand. On the other hand, non-dihydropyridines (verapamil, diltiazem, etc.) also affect the SA and AV nodes and decrease the oxygen demand.
5. Nitrates—these are the coronary vasodilator agents. In the lower doses, they are venodilator and reduce the preload, while in higher doses they are also arterial dilators and thereby decrease the afterload too.
6. Ranolazine—this is the selective inhibitor of the late influx of sodium, thus decreasing the myocardial contractility. It is usually used in combination with beta blockers to treat angina.
7. Statins—these are hypolipidemic drugs that inhibit the HMG-CoA reductase enzyme and decrease atherosclerotic effect.
8. ACE inhibitors—they inhibit the angiotensin-converting enzyme. These are the class I recommendation for patients with chronic coronary artery disease with low LVEF (<40%) or diabetic and a class II recommendation for patients without these mentioned features [8].

3. Percutaneous coronary intervention (PCI)

Although the term percutaneous coronary intervention refers to any therapeutic coronary artery intervention, it has become synonymous with the percutaneous coronary stent implantation. In the earlier days, bare metal stents were used, but over the last decades, drug-eluting stents are the most commonly used stents for PCI. PCI is performed in patients with stable coronary artery disease and also in settings of acute coronary syndrome.

3.1 Indications for PCI

1. Moderate to severe stable angina with evidence of reversible ischemia.
2. High-risk unstable angina or ST elevation myocardial infarction (STEMI).
3. Acute STEMI.
4. Rescue PCI after failed thrombolysis.

5. Cardiogenic shock after myocardial infarction (MI).
6. Revascularization after successful resuscitation.

3.2 Absolute contraindication

1. Lack of vascular access.
2. Active untreatable severe bleeding.

3.3 Relative contraindications

1. Bleeding disorder.
2. Severe renal insufficiency unless patient is on hemodialysis or has severe electrolyte abnormality.
3. Sepsis.
4. Poor compliance with medicines.
5. Terminal illness (advanced or metastatic malignancy).
6. Short life expectancy.
7. Difficult coronary anatomy.
8. Failed previous PCI or not amenable to PCI.
9. Severe cognitive dysfunction or advanced physical limitation.
10. Other indication for open heart surgery.

3.4 In view of the following conditions, patients should not go for PCI

1. Small area of myocardium is at risk.
2. No objective evidence of ischemia with either noninvasive or invasive testing (e.g., fractional flow reserve).
3. Less likelihood of technical success.
4. Left main coronary artery (LM) or multivessel coronary artery disease with a high SYNTAX score (better for CABG).
5. Insignificant stenosis (<50% stenosis).
6. End-stage cirrhosis with portal hypertension resulting in encephalopathy or visceral bleeding.

4. Coronary artery bypass grafting (CABG)

Coronary artery bypass grafting is a coronary revascularization by surgery. Dr Rene Favaloro performed his first coronary bypass operation in May 1967 with an interposed saphenous vein graft (SVG) and shortly thereafter used aortocoronary bypasses sutured proximally to the ascending aorta. In the words of Dr Denton Cooley, “Although he [Favaloro] was always hesitant to carry the moniker of ‘father’ of coronary artery bypass surgery, he is the surgeon we should credit with introducing coronary bypass surgery into the clinical arena” [9]. It has been shown to be highly effective in the relief of severe angina and under some circumstances has the capability for considerably prolonging useful life. The stenosed segment of the coronary artery is bypassed using an arterial or venous conduit, and by this it reestablishes the blood flow to the distal ischemic myocardial area. Many studies have shown that surgical revascularization is superior to medical and percutaneous interventional management for multivessel CAD. Full workup should be done before taking patient for surgery.

4.1 The anatomical factors which favor the CABG are as follows

1. Significant LM disease.
2. Significant proximal left anterior descending (LAD) disease.
3. Lesions not amenable to PCI.
4. Diabetes mellitus.
5. Depressed left ventricular (LV) ejection fraction.

Indications for CABG can be classified as per **Table 1**.

4.2 Indications for CABG

1. High-grade LM stenosis.
2. Significant stenosis (>75%) of proximal LAD with double- or triple-vessel disease.

Treatment Class	Description
I	Conditions for which the operation is indicated on the basis of a demonstrated advantage over medical treatment in terms of longevity or relief of symptoms or both
II	Conditions for which the operation is acceptable treatment but for which its advantages over medical treatment have not yet been fully defined
III	Conditions for which the operation is not generally considered to be indicated, because of lack of demonstrated advantage over medical treatment.

Table 1.
Classification of indications for CABG surgery.

3. Symptomatic double- or triple-vessel disease.
4. Disabling angina despite maximal medical therapy.
5. Poor LV functions.
6. Post MI angina.
7. Post NSTEMI with ongoing ischemia that is unresponsive to medical therapy or PCI.
8. STEMI with inadequate response to all nonsurgical management.
9. Emergency CABG.
10. Failed PCI.

4.3 Contraindications

4.3.1 Absolute contraindication

There is no absolute contraindication.

4.3.2 Relative contraindications

1. Asymptomatic patient with low risk of MI or death.
2. Advanced age.
3. Co-morbidities (COPD, pulmonary hypertension, etc.)

4.4 Factors increasing mortality after CABG

1. Preoperative renal insufficiency.
2. Peripheral vascular disease.
3. Recent MI.
4. Recent brain stroke.
5. Emergency surgery.
6. Cardiogenic shock.

5. Types of grafts

5.1 Arterial grafts

- Internal thoracic artery (internal mammary artery)
- Radial artery

- Right gastroepiploic artery
- Inferior epigastric artery
- Ulnar artery
- Splenic artery

5.2 Venous grafts

- Greater saphenous vein
- Short saphenous vein
- Cephalic vein

5.3 Arterial grafts

5.3.1 Left internal mammary artery (LIMA)/left internal thoracic artery (LITA)

Drs. Vineberg and Miller were the first to recognize the properties of internal mammary artery (IMA) and used it for myocardial revascularization in 1945 [10]. They found that it is usually spared from atherosclerosis and reasoned that its branches could form collaterals with myocardial arterioles. They injected contrast medium in postmortem specimens demonstrating connections between the implant and the coronary arteries, but few surgeons took their work seriously [11].

LIMA originates from subclavian artery just above and behind the sternal end of the clavicle (**Figure 2**). The artery descends vertically 1 cm lateral to the sternal border, behind the first six costal cartilages. **Figure 3** shows the LIMA position regarding pectoralis muscle, sternum, and pleura with endothoracic fascia. LIMA is widely used these days, especially for the anastomosis with LAD. After dividing the sternum, retractor is placed to lift the left sterna edge. The operating table can be elevated and rotated to expose LIMA properly and harvest it. LIMA can be harvested as pedicle graft (along with internal thoracic veins, fat, muscles, and pleura) or skeletonized vessel. Skeletonized LIMA is supposed to preserve the venous drainage of the sternum, and it is often preferred when there is suspicion of sternal healing and wound infection. All small branches of LIMA are clipped. The proximal end of the LIMA kept attached to the subclavian artery, and then after giving heparin, the distal end is ligated and divided. In the same way as LIMA is harvested, RIMA can also be harvested if it is needed for grafting.

5.3.2 Radial artery

The second most commonly used artery is the radial artery (RA). It is usually harvested from nondominant hand (**Figure 4**). The RA arises from the bifurcation of the brachial artery in the cubital fossa and terminates by forming the deep palmar arch in the hand. The main concern using RA is blood supply to the wrist and hand. Before using the radial artery, we should assess the patency and collateral blood circulation from the ulnar artery. It can be assessed clinically by Allen's and modified Allen's tests. This can also be assessed by preoperative arterial ultrasound.

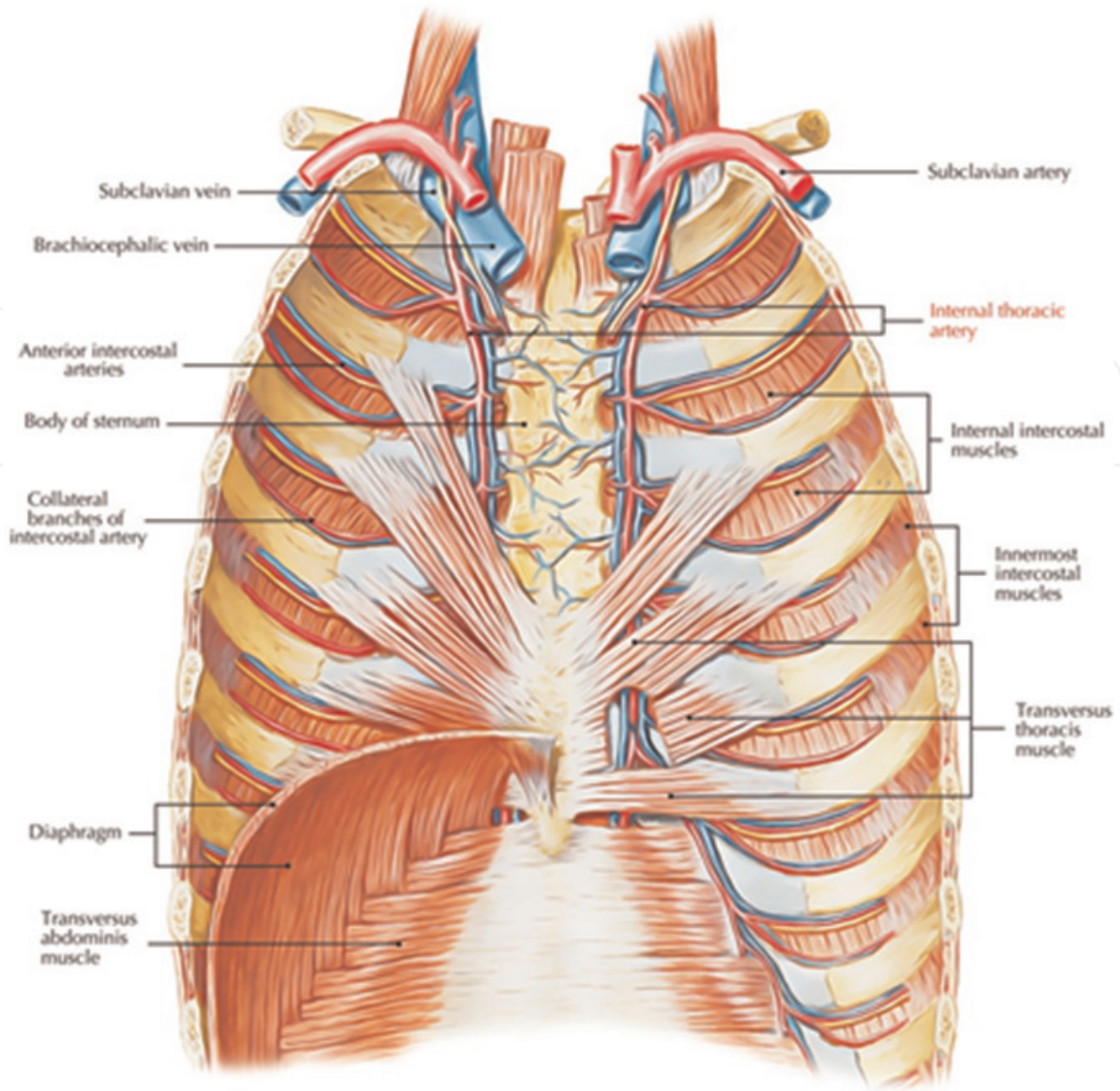


Figure 2.
Internal mammary artery course.

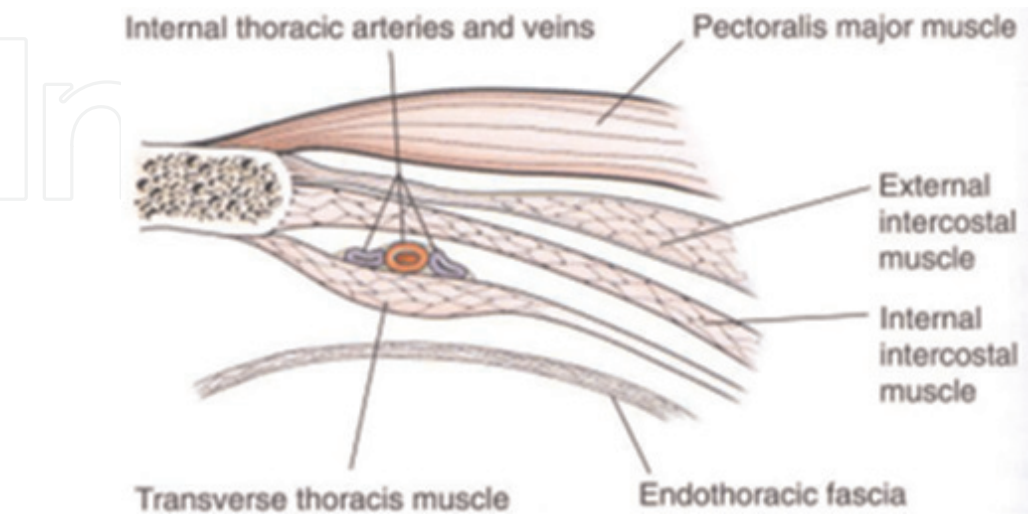


Figure 3.
Relationship of LIMA with sternum, thoracic muscles, pleura, and endothoracic fascia.

The radial artery can be harvested by open conventional method or endoscopically. The radial artery should be flushed and kept in a solution prepared with Ringer lactate (500 ml), sodium nitroprusside (50 mg), and heparinized blood (30 ml).

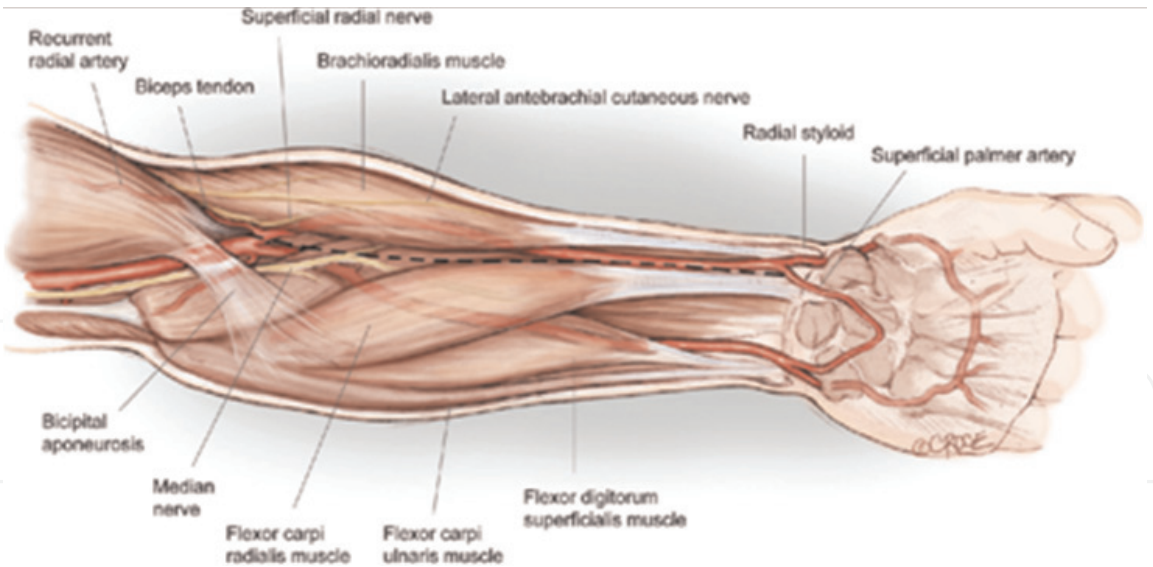


Figure 4.
Radial artery and palmer arch.

5.3.3 Right gastroepiploic artery

It is very rarely used as an arterial graft when other conduits are not available. To harvest this artery, the midline incision over the sternum is extended to the upper abdomen, and the abdominal cavity is opened. There are two gastroepiploic arteries (**Figure 5**): left and right. Both arteries participate in the stomach vascularization and are collateral blood circulation with other blood vessels of the stomach. Harvesting right gastroepiploic artery as conduit does not compromise stomach blood supply. Branches of this artery to the stomach and omentum are ligated and divided. This artery is positioned either anteriorly or posteriorly to the duodenum

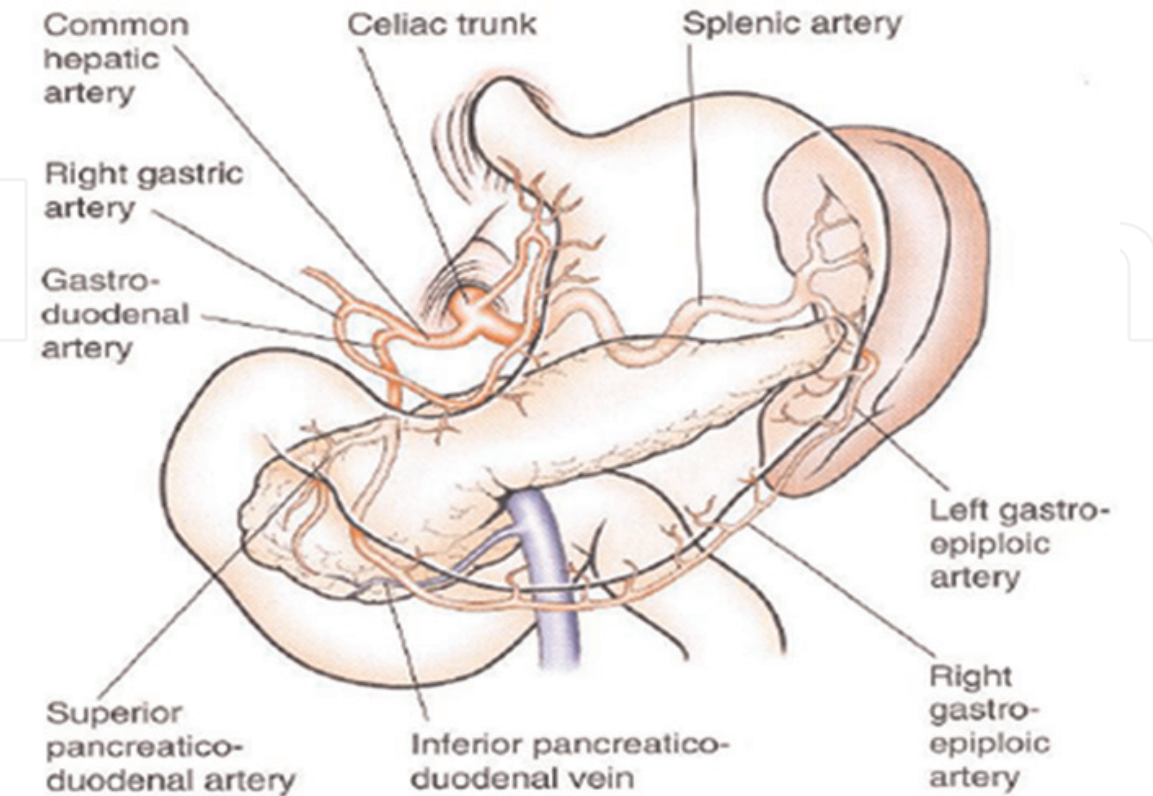


Figure 5.
Gastroepiploic artery.

and stomach, depending on the tension on graft. A circular opening is made in the diaphragm, medial to the inferior vena cava, and the gastroepiploic artery is passed through this opening to anastomose it with RCA or PDA coronary arteries. The anatomy of gastroepiploic arteries is presented in **Figure 6**.

5.3.4 Inferior epigastric artery

The inferior epigastric artery (**Figure 6**) arises from the medial aspect of the external iliac artery and gives branches to the spermatic cord, pubis, abdominal muscles, and skin. Its harvesting requires additional either low midline, or paramedian, or oblique inguinal approach. The anterior sheath of the rectus muscle is divided, and then the muscle is pushed medially. The artery is harvested along with the accompanying veins as a pedicle graft and kept in the solution as mentioned for radial artery preservation.

When the length of this artery is not sufficient for an independent graft, it is used as a composite graft with the LIMA as extension graft.

5.3.5 Ulnar artery

Occasionally, when surgeons do not have other choice, they use the ulnar artery as arterial conduit.

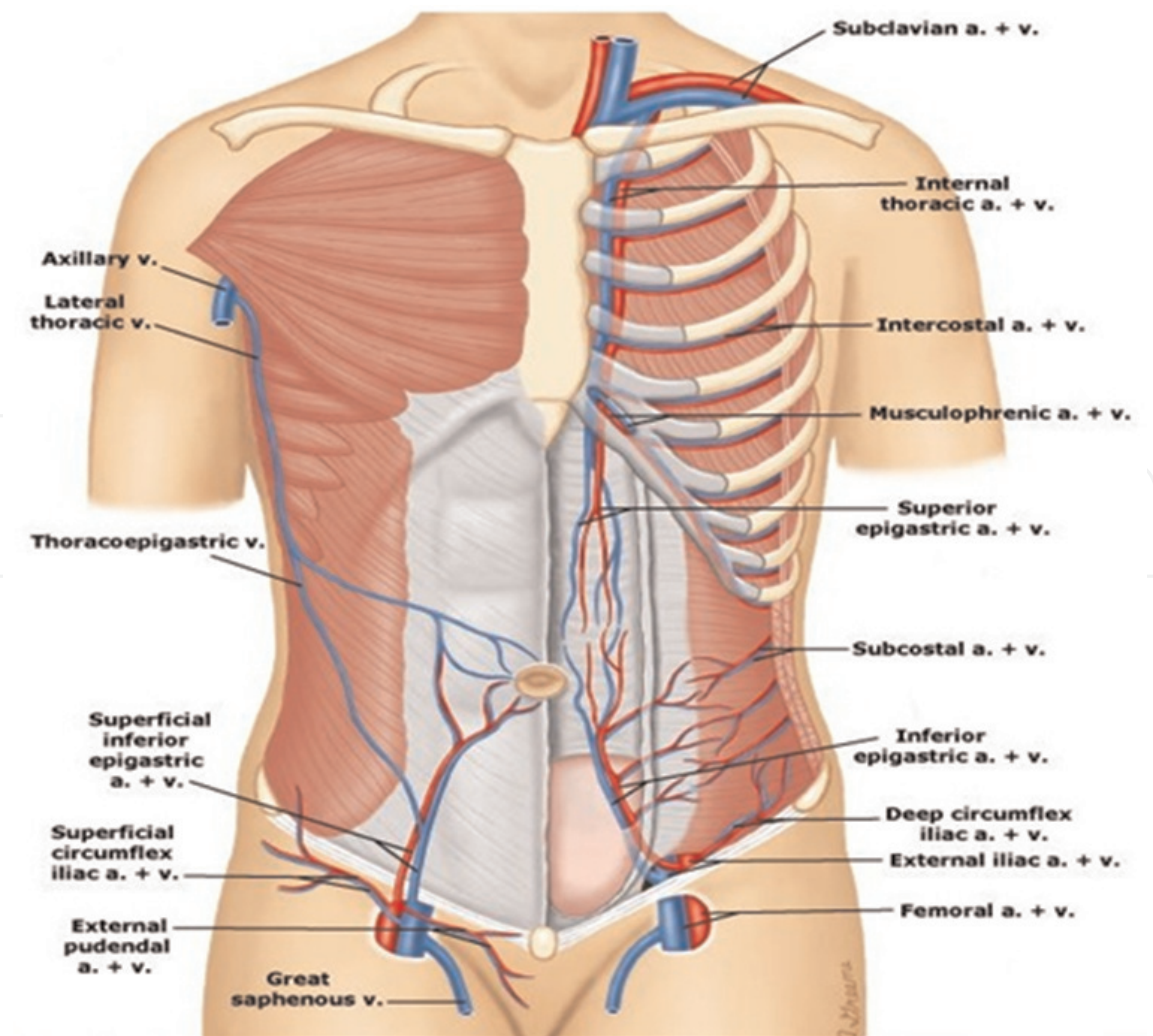


Figure 6.
Inferior epigastric artery.

5.3.6 Splenic artery

When there is lack of other conduit, the splenic artery can be used for grafting. The same as harvesting gastroepiploic artery, midline sternal incision can be extended over the abdomen, and the abdomen is opened. Then lesser peritoneal sac is opened. The splenic artery (**Figure 7**) runs along the superior margin of the pancreas. Branches to the pancreas are ligated and divided. Then the splenic artery is ligated and divided at the splenic hilum and passed through an opening made in the diaphragm medial to the inferior vena cava.

5.4 Venous grafts

5.4.1 Greater saphenous vein

The greater saphenous vein (**Figure 8**) is the most commonly used conduit for CABG. The greater saphenous vein (GSV) of the lower extremity is the best choice of this type of graft based on:

- There are two independent types of low extremity vein system, and removal of superficial one (GSV) does not jeopardize the venous flow from the leg.
- Position, diameter, and length of the GSV are in constant pattern which simplifies its harvest.

Usually a single long segment is harvested. About 12–15 cm segment may be needed for diagonal branch, about 20–24 cm length for OM branches, and 18–22 cm

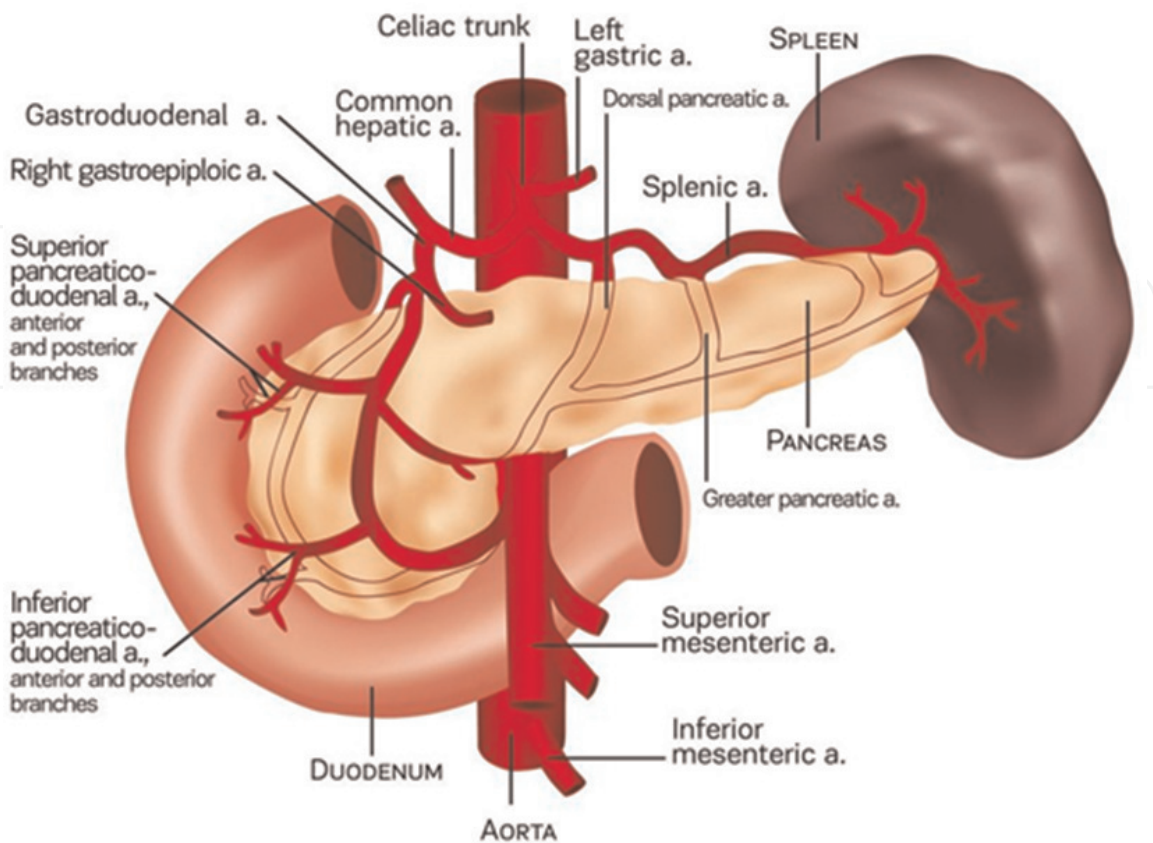


Figure 7.
Splenic artery.

length for RCA and PDA coronary arteries. Poor quality and veins with varicosities should be avoided. Branches can either be ligated or clipped. These should be ligated or clipped; just flush with GSV to avoid the narrowing or diverticulum. Creation of skin flaps should also be avoided.

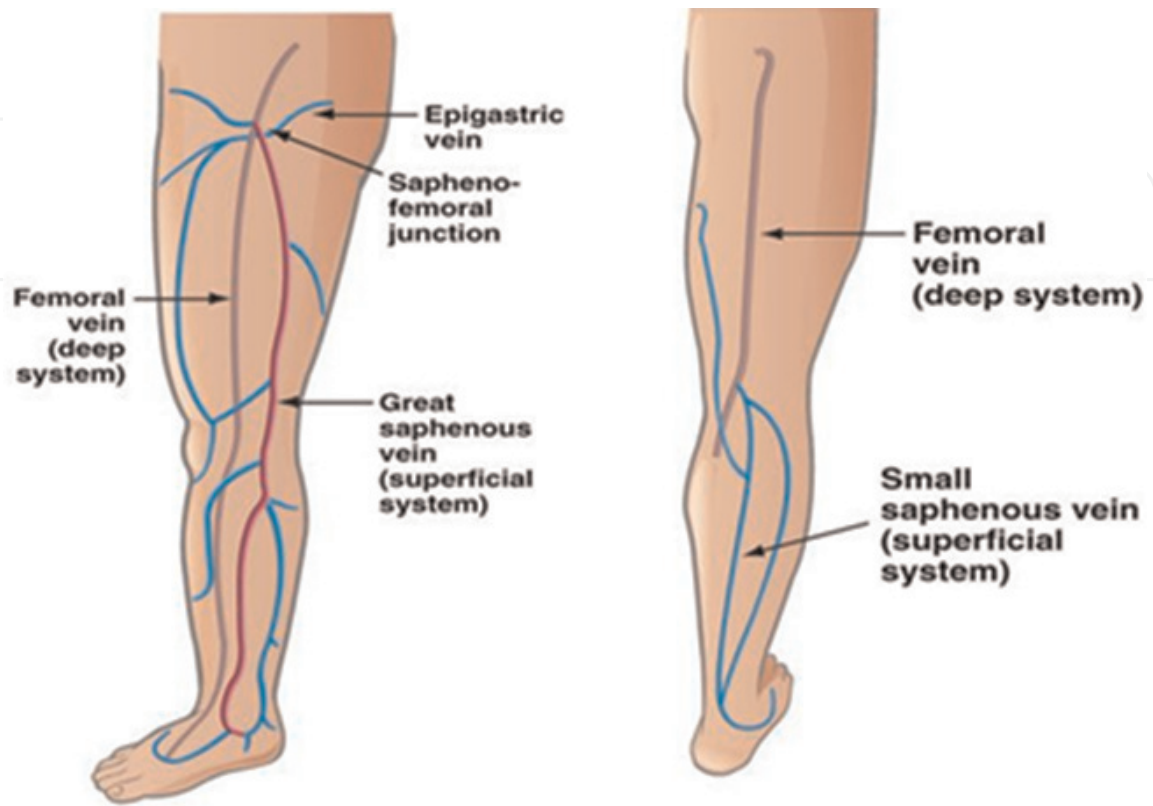


Figure 8.
Greater and short saphenous veins.

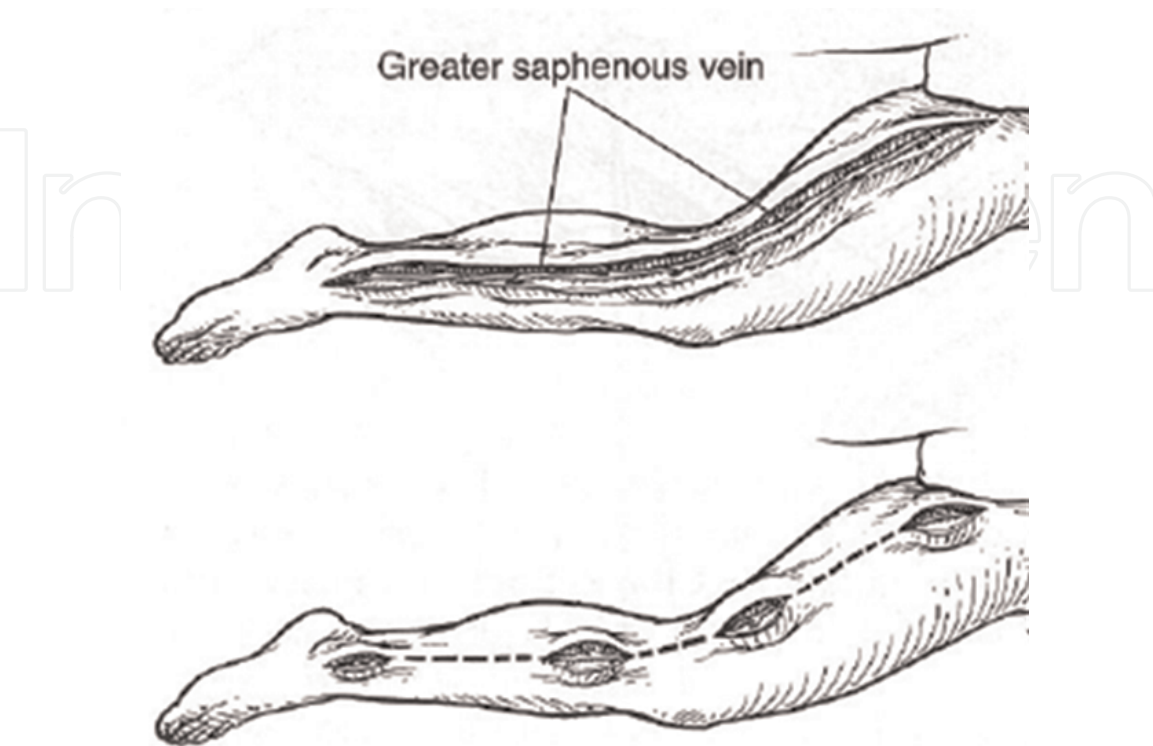


Figure 9.
Direct continuous and interrupted harvesting method of SVG.

GSV is harvested in two different ways:

- Directly by single full incision or through multiple incisions (**Figure 9**)
- Endoscopic vein harvest

5.4.2 Short saphenous vein

In rare cases when not enough conduits are available, some surgeons have to use short saphenous vein (**Figure 8**). It can be harvested by positioning the patient in prone or supine position.

5.4.3 Cephalic vein

Even though we have not used the vein as alternative graft, this can be used in the case other grafts need it. The cephalic vein can be harvested from the wrist up to the shoulder. The walls of the vein are thinner than the saphenous veins, and long-term patency is also lesser than saphenous veins [12].

6. Types of CABG

1. Traditional on-pump CABG.
2. Off-pump CABG.
3. Minimally invasive direct.
4. Totally endoscopic CABG.

6.1 On-pump CABG technique

- A median sternotomy is done (**Figure 10**).
- The same time arterial or venous conduit is harvested.
- LIMA is harvested.
- Full-dose heparin is given.
- LIMA is divided distally and a bulldog clamp is placed on the artery.
- Distal segment of LIMA on the chest wall is ligated or clipped.
- The pericardium is opened and pericardial stay sutures placed.
- Purse string sutures are placed on the ascending aorta and right atrial appendage for cannulation.
- A purse string suture is placed on the ascending aorta for cardioplegia cannulation.
- Aortic and right atrial cannulae are inserted.

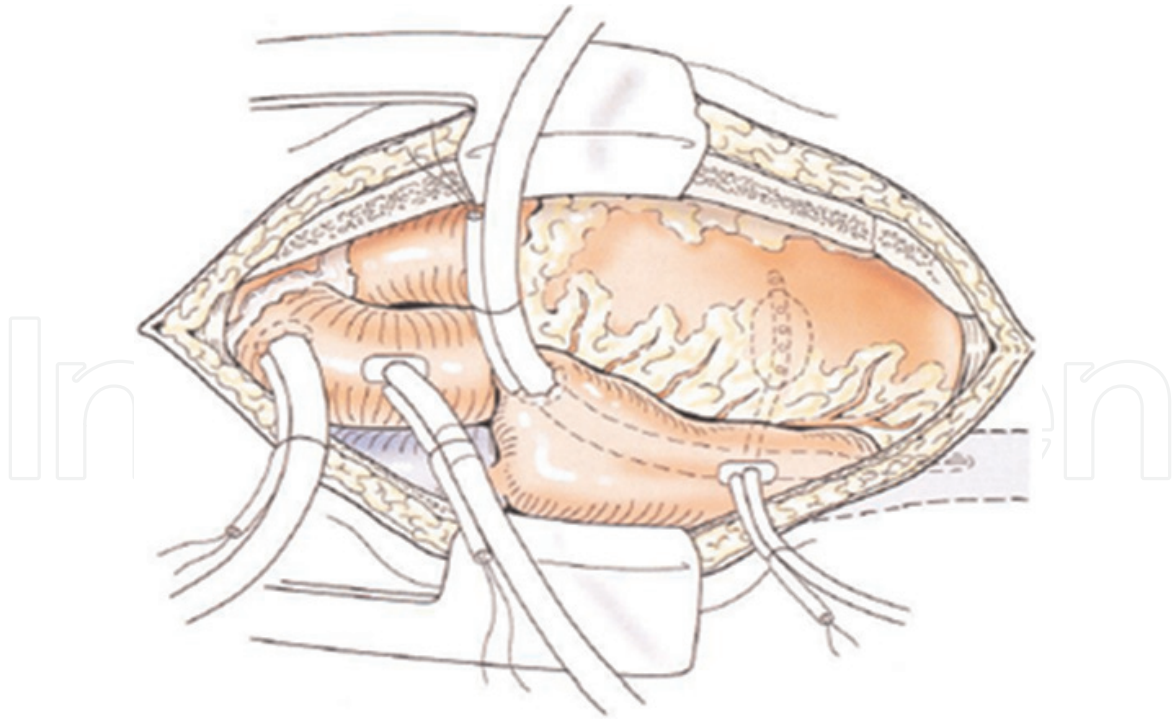


Figure 10.
Cannulation for on-pump CABG.

- Epiaortic ultrasound can be used to find the site devoid of calcification or atherosclerotic plaques, for cannulation [13].
- Aorta is cross clamped and antegrade cardioplegia given.
- Cold saline or ice slush can be used for topical cooling.
- The heart is retracted out of the pericardial cavity, toward the head of the patient.
- Usually first distal graft is done to RCA or PDA (**Figure 11**).

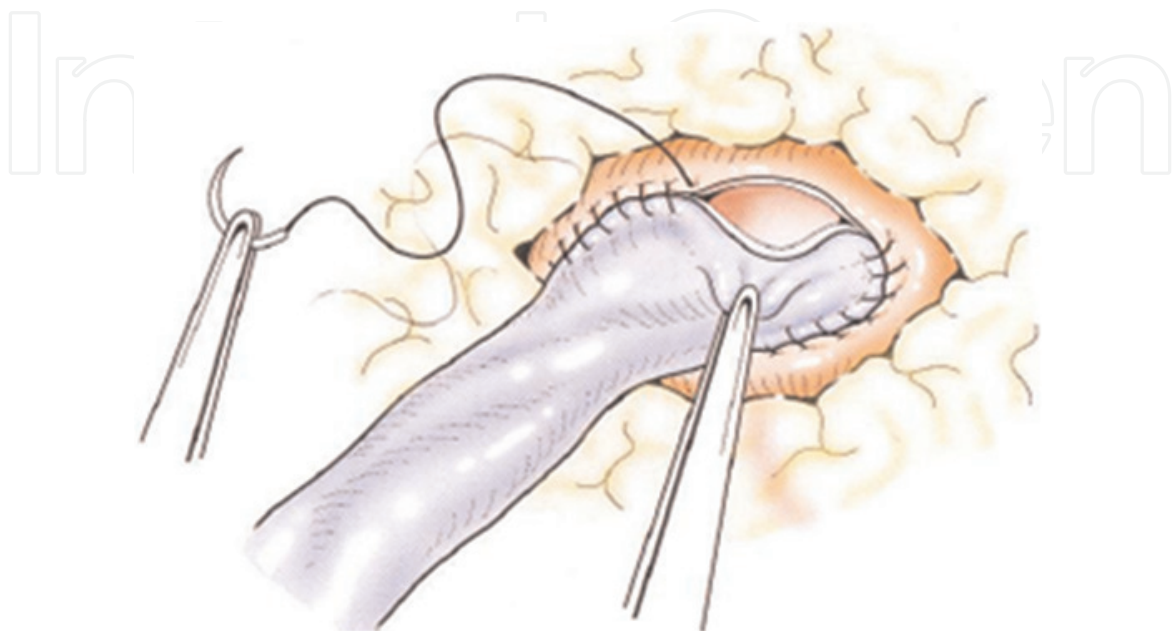


Figure 11.
SVG-coronary artery anastomosis.

- Graft is distended with blood cardioplegic solution, graft lie is checked, and appropriate length is divided.
- The heart is then retracted to the right and then OM is selected for grafting.
- Distal anastomosis is done to selected OM vessel.
- Graft is distended with solution and appropriate length divided.
- The same technique is used for diagonal anastomosis.
- Then focus is changed to LIMA-LAD anastomosis.
- LIMA is cut to appropriate length.
- LIMA-LAD anastomosis is created with Polypropylene 7-0 or 8-0 sutures (**Figure 12**).
- Rewarming is started while doing anastomosis.
- A pericardial window is made to pass LIMA without tension.
- Phrenic nerve should not be injured.
- Aortic cross clamp is removed.
- Partially occluding clamp is applied on the ascending aorta (**Figure 13**).
- Two to three openings are made in the aorta using aortic punch.
- Proximal anastomosis is done between the aorta and grafts with Prolene 6-0 sutures.
- Partially occluding clamp is removed.
- De-airing of the grafts is done.

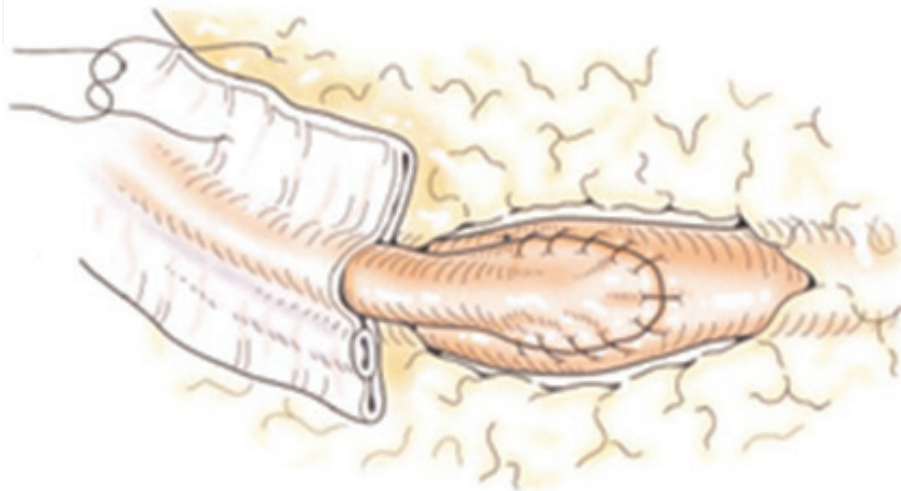


Figure 12.
LIMA-LAD anastomosis.

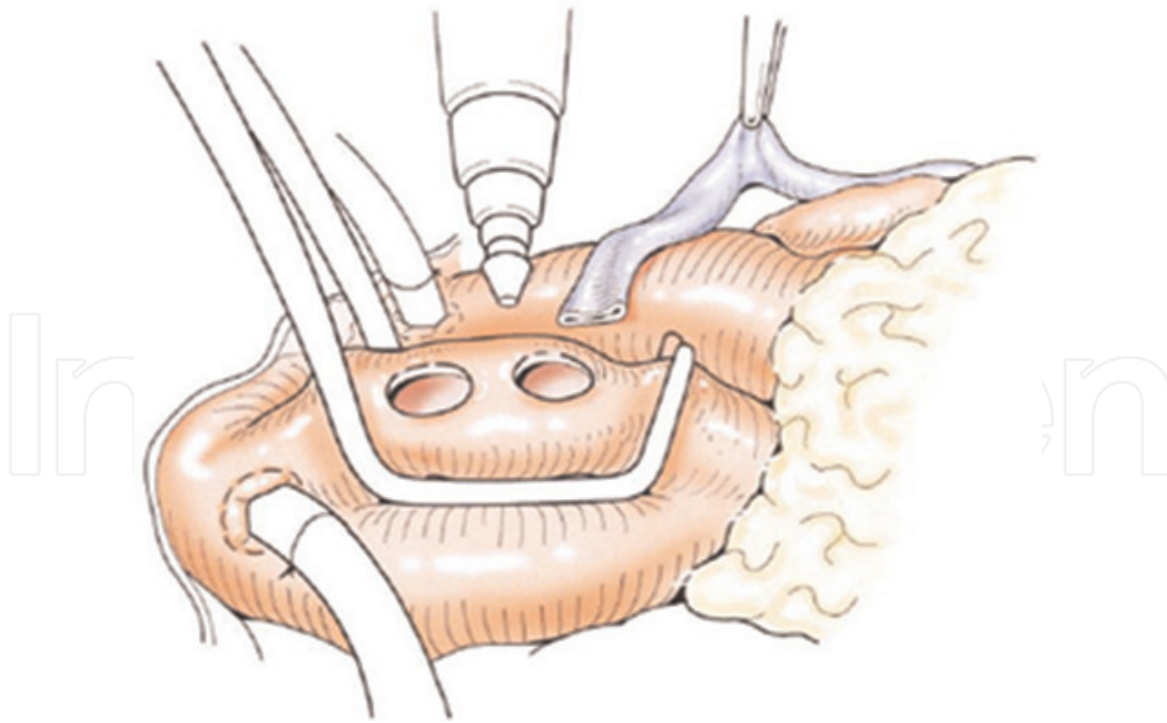


Figure 13.
Side-biting clamp on the ascending aorta for proximal anastomosis.

- Proximal anastomosis can also be done on the arrested heart with single aortic cross clamp [14],
- If the heart is in sinus rhythm, then start weaning off CPB.
- Graft flow could be checked with flow meter device.
- Protamine is given to reverse the effect of heparin.
- Decannulation is done and bleeding secured.
- Temporary pacing wire is placed on RV.
- One mediastinal and one left pleural drains are inserted.
- Sternum is closed with wires.
- The skin and subcutaneous tissue are closed in layers with vicryl sutures.

6.2 Off-pump CABG (OPCABG) technique

6.2.1 Patient selection

6.2.1.1 Beginner beating heart surgeon

They should avoid patients with unfavorable characteristics:

- Cardiomegaly-making exposure of lateral and inferior walls difficult
- Small (<1.5 mm diameter), intramyocardial, and diffusely diseased vessels

- Hemodynamically unstable patients
- Critical left main disease
- Recent acute MI
- LV EF <35%

6.2.1.2 Experienced beating heart surgeons

Majority of the cases can be performed without complication after getting a good experience in off-pump CABG, but it is better to avoid if multiple unfavorable factors are present in the same patient (cardiomegaly with EF <25% and small vessels).

OPCAB is particularly beneficial for:

- High-risk patients
- Left ventricle dysfunction
- High calcific load
- Age older than 75 years
- Diabetes mellitus
- Renal failure
- Left main stem disease
- Reoperations
- Chronic pulmonary disease
- An overall EuroSCORE >5 [15, 16]

6.3 Contraindications

6.3.1 Absolute contraindications

- Preoperative hemodynamic instability
- Deep myocardial LAD
- Moderate to severe mitral regurgitation

6.3.2 Relative contraindications

- Pulmonary hypertension
- Diffuse coronary artery disease
- Dense myocardial adhesions during reoperative surgery

- Enlarged ascending aorta
- LM disease with a non-reconstructable RCA system

6.4 Operative steps

- Preserve normothermia by keeping the operating room warm.
- CPB machine and perfusionist should be available in OR.
- No need to prime the CPB machine.
- Off-pump setup (octopus, starfish, CO₂ blower, intracoronary shunts) should also be available (**Figure 14**).
- Maintaining the systolic BP is important during positioning of the heart for grafting.
- Inotropic supports and IV fluid is usually required.
- Midline sternotomy.
- LIMA and other conduits are harvested.
- Heparin is given (1–1.5 mg/Kg) to keep ACT of about 300 s.
- ACT should be checked every 20 min and added as required.
- Coronary arteries should be grafted in the order of increasing cardiac displacement (anterior wall vessels, then inferior wall, and finally lateral wall vessels).

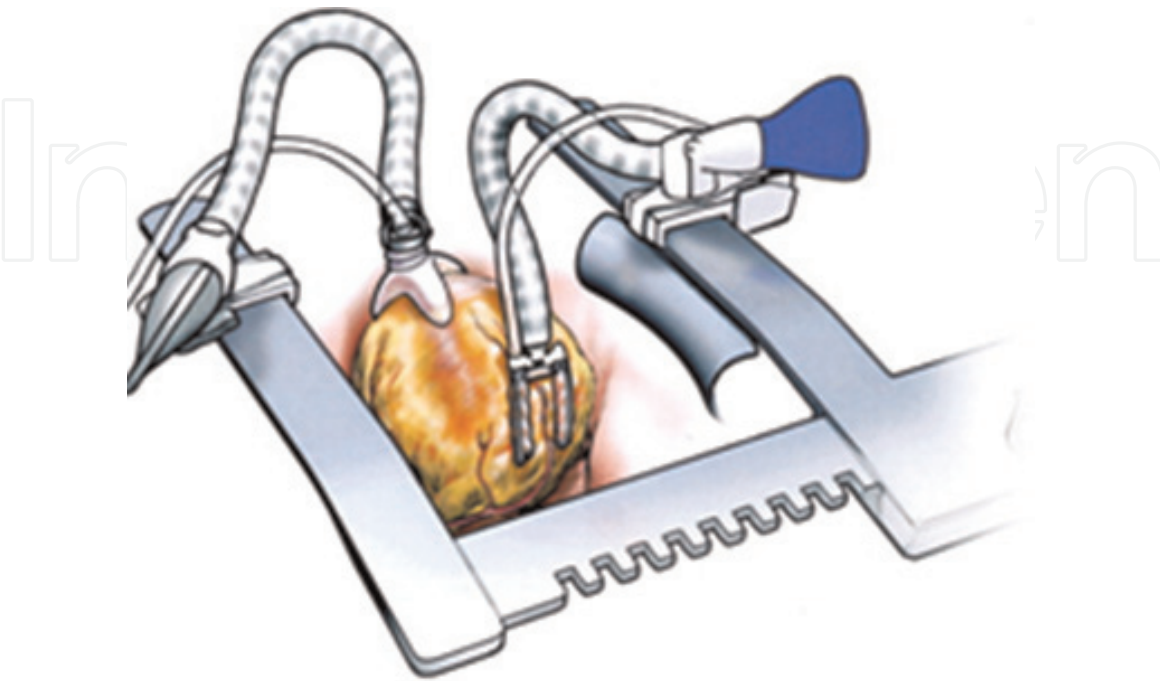


Figure 14.
OPCABG setup: octopus and starfish.

- Most of the surgeons usually do distal anastomoses first, but proximal anastomoses can be done before distal anastomoses.
- Performing proximal aortic anastomoses last allows precise estimation of graft length, whereas performing them first allows immediate myocardial reperfusion once each distal anastomosis is completed.
- Positioning the heart is very important and needs mechanical stabilizers as octopus and starfish.
- **Anterior wall vessel anastomosis**—anterior wall vessels (LAD, diagonal, ramus) need to be brought near midline for better visualization and anastomosis. Deep pericardial retraction sutures of silk, vicryl, or ethibond (1-0) should be taken fast near the left superior pulmonary vein in order to prevent hemodynamic instability.
- **Inferior wall vessel anastomosis**—for distal right coronary artery and posterior descending artery, the table is in steep Trendelenburg position. Manipulation of the deep pericardial retraction sutures is done to better expose the grafting vessel. For grafting the right coronary artery, the table is made flat, and retraction sutures are relaxed with the heart failing to the left side. Maneuvering the heart for RCA and PDA grafting can cause bradycardia and hypotension, so anesthetists should be more vigilant and need to give fluid and inotropes to keep hemodynamic stability during grafting.
- **Lateral wall vessel anastomosis**—for obtuse marginals, posterolateral branches of the right coronary artery, the OR table is placed in steep Trendelenburg position, raised and rotated toward the right [17]. This will allow gravity to displace the heart to the right and apex anteriorly. The right pleura is opened, and the right pericardial incision is extended toward the inferior vena cava, so that the heart can be displaced toward the right side without hemodynamic compromise. Some extra deep pericardial retraction sutures may need to be taken between the inferior vena cava and pulmonary vein. The first suture is anchored just above the left superior pulmonary vein, the second below the left inferior pulmonary vein, the third one called “the intermediate” is located between the inferior pulmonary vein and the inferior vena cava, and the fourth one close to the inferior vena cava. These stitches are quite comparable to the “Lima Stitches” introduced in North America in 1997 by Tom Salerno [18].
- Do not compromise the exposure, and if it is not possible, then convert to conventional on-pump CABG.
- A silastic tape or vascular sling is passed around the selected coronary artery proximal to the site chosen for anastomosis.
- Intracoronary shunts are inserted in coronary arteriotomy.
- A CO₂ blower is used to disperse the blood to create the anastomosis.
- Blower is used selectively when needed and at a rate not >5 L/min to prevent endothelial damage.

- A temporary pacing wire can be placed for anastomosis to RCA to combat the bradycardia.
- Anastomosis is performed in a routine manner with Polypropylene 7-0 or 8-0 sutures for LIMA grafting or venous grafting.
- The intima of both the graft and the recipient vessels must be visualized each time the needle is placed through the anastomosis.
- Bilateral IMA grafting (typically to the left heart) has been shown to improve survival and intervention-free survival and should be performed whenever contraindications do not exist.
- After completion of anastomoses, heparin could be reversed with protamine.
- Protamine is given (0.75–1.0 mg/kg) to incompletely reverse the heparin, leaving each patient with an ACT less than 150 s at the conclusion of the case.
- The avoidance of CPB should not come at the price of any compromise in anastomotic precision.

6.5 Hemodynamic instability and conversion to cardiopulmonary bypass

In some of the situations, CABG should be performed on CPB. These are as follows:

- a. Ischemic arrhythmias unresponsive to heparin and antiarrhythmic medications.
- b. Cardiogenic shock due to acute infarction or severe global ischemia.
- c. Physical conditions that limit rightward displacement of the heart (deep pectus excavatum, previous left pneumonectomy)

Although avoidance of CPB is generally a worthwhile goal, it does not supersede the goals of hemodynamic stability and complete, precise revascularization.

6.6 Causes of hemodynamic instability

- Imperfect technique in cardiac displacement (compressing the right atrium or right ventricle or kinking of the right ventricular outflow tract during rightward displacement of the heart).
- Application of compression with the coronary stabilizer—achieve and maintain tissue capture with a minimum of downward pressure on the heart. This will optimize both coronary stabilization and hemodynamic stability.
- Less commonly, regional myocardial ischemia is a cause of hemodynamic instability.

The risk of myocardial ischemia during off-pump CABG can be reduced by keeping the following points in consideration:

- The most stenotic vessel is always revascularized first because this vessel is normally well collateralized.
- The proximal anastomosis of the graft is performed just after the distal anastomosis of the same graft is completed before proceeding to the next distal anastomosis.
- Intracoronary shunts are used to prevent ischemia.
- The ascending aorta is side clamp only once during the procedure to minimize the aortic trauma.
- The systemic pressure is always reduced around 90–100 mmHg before and during the entire side clamping of the ascending aorta.
- The anterior and the inferior territories are always grafted before the posterior territory.

6.7 Sequential bypass grafting

The sequential bypass graft is an effective multiple-bypass technique when graft availability is limited [19] and has been reported to allow improved rates of patency in bypass procedures on narrow coronary arteries [20, 21]. Compared with regular end-to-side anastomosis, however, side-to-side anastomosis is a relatively complex procedure.

Methods of side-to-side anastomosis include the following:

1. A diamond configuration, in which the graft axis lies perpendicular to the axis of the target coronary vessel (crossed side-to-side anastomosis) (**Figure 15**)

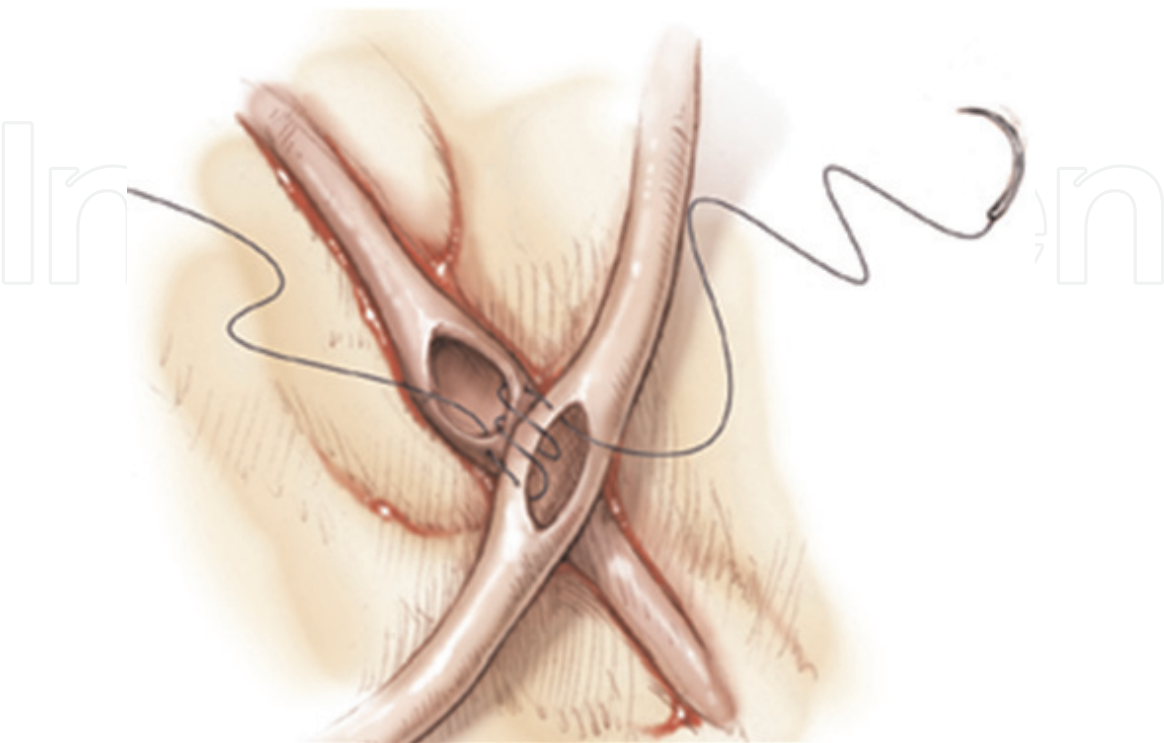


Figure 15.
Crossed side-to-side anastomosis.

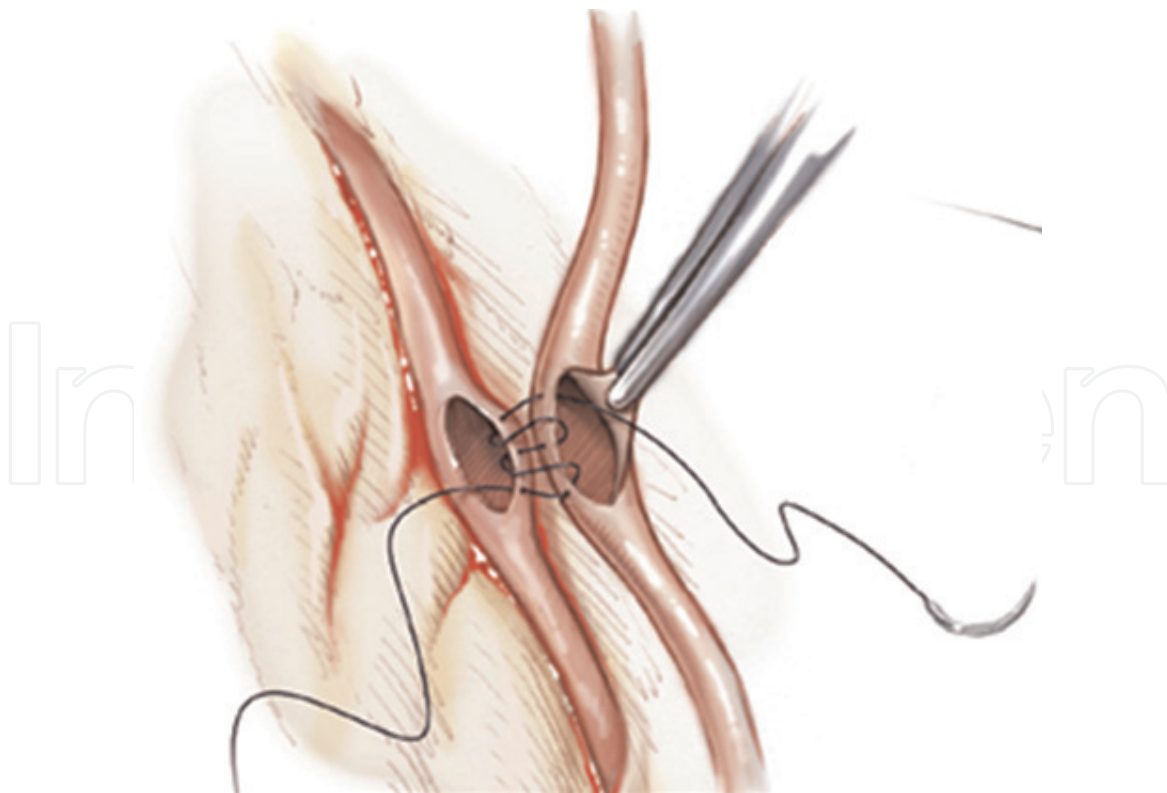


Figure 16.
Parallel side-to-side anastomosis.

2. A parallel configuration in which the graft and target coronary axes are aligned (parallel side-to-side anastomosis) (**Figure 16**)

- Continuous or interrupted sutures can be used.
- The side-to-side anastomoses used in SB are technically difficult compared with regular end-to-side anastomoses.
- Interrupted crossed side-to-side anastomosis greatly simplifies this procedure.

In an experimental study with animals, Shioi [22] compared various techniques for performing anastomoses, reporting that crossed side-to-side anastomosis enabled a larger opening than did parallel side-to-side anastomosis and that interrupted sutures enabled a larger anastomotic opening than did a continuous suture.

6.8 Complications

- **Early death**—in general, after isolated CABG, approximately 98% of patients survive at least 1 month, and 97, 92, 81, and 66% survive 1, 5, 10, and 15 years or more, respectively. In an analysis of seven large datasets representing more than 172,000 patients, Jones and colleagues identified seven variables most predictive of early mortality [23]:
 - Older age
 - Female gender
 - Previous CABG

- Urgency of operation
 - Severe LV dysfunction
 - Left main disease
 - Increased extent of coronary artery disease
- **Adverse neurological outcomes**—a multicenter study by Roach and colleagues of 2108 patients undergoing CABG with CPB documented adverse cerebral outcomes in 129 patients (6.1%) [24]. Type 1 deficits (major focal deficits, stupor, and coma) occurred in 3.1%, and type 2 deficits (deterioration in intellectual function or memory) in 3.0% of the patients. Predictors of type 1 deficits included the presence of proximal aortic arteriosclerosis, history of prior neurologic disease, intra-aortic balloon pump, diabetes, hypertension, unstable angina, and older age.
 - **Mediastinitis**—deep sternal wound infection occurs in 1–4% of patients after CABG with CPB and is associated with increased mortality [25]. Obesity is a risk factor for mediastinitis [26]. Other factors associated with an increased prevalence of deep wound infection include diabetes, previous CABG, the use of both IMAs, and duration of operation [26, 27]. Randomized trials have shown that off-pump CABG is not associated with a lower prevalence of sternal wound infection [25, 28].
 - **Renal dysfunction**—in a multicenter study of renal dysfunction after CABG with CPB in 2222 patients, “dysfunction” was defined as a postoperative serum creatinine level of 2.0 mg dL^{-1} or greater, or an increase of 0.7 mg dL^{-1} or more from preoperative level [29]. Renal dysfunction occurred in 171 (7.7%) patients, and 30 (1.4%) required dialysis. Early mortality was 0.9% among patients who did not develop renal dysfunction, 19% in those with renal dysfunction who did not require dialysis, and 63% among those who required dialysis. Preoperative risk factors for renal dysfunction included advanced age, moderate to severe cardiac failure, previous CABG, diabetes, and preexisting renal disease [29]. In two randomized trials, prevalence of postoperative renal failure was similar in on-pump and off-pump groups [28, 30].
 - **Myocardial infarction**—perioperative MI, usually defined by the appearance of new Q waves in the ECG or non-Q wave MI can also occur which are detected by elevation of serum myocardial biomarkers, is most often related to inappropriate myocardial management, technical problems, or incomplete revascularization. Prevalence of MI is approximately 2.5–5% [31]. Perioperative infarction, when quantitatively more than trivial, is a risk factor for later death [32]. Including perioperative cases, MI is relatively uncommon after CABG, with 94% of patients in the Katholieke Universiteit, Leuven, Belgium (KU Leuven) experience free of infarction for at least 5 years and 73% for at least 15 years [33].

7. Results

- **Unsatisfactory quality of life**—even though unsatisfactory quality of life after CABG is one of the most important unfavorable outcome events, quantifying it is very difficult because it depends on the following three factors:

1. Freedom from angina or heart failure;
2. Freedom from the need for medication, rehospitalization, and reintervention.
3. Preservation of exercise capacity.

Most of the patients have a satisfactory quality of life early after CABG, but this gradually begins to decline after about 5 years [34].

- **Neurobehavioral outcomes**—damaging effects of CPB machine are usually blamed for neurobehavioral disturbances and decline in cognitive function in some patients. These are mild most of the times and might not be apparent unless patients are tested specifically for them. As many as 75% of patients may exhibit these subtle defects when tested 8 days after CABG, but by 3–6 months postoperatively, proportion drops to only about 10–30% [35]. Gross defects most likely result from embolization of arteriosclerotic debris from the ascending aorta or from air and intracardiac thrombus rather than from damaging effects of CPB [36]. Prevalence is about 0.5% in relatively young patients but rises to about 5% in patients older than age 70 and about 8% in those older than 75 [37]. Randomized trials comparing on- and off-pump procedures showed similar prevalence of adverse neurologic outcomes [28].
- **Functional capacity**—maximal exercise capacity of patients is improved by CABG. The degree of exercise capacity depends on preoperative LV function, graft patency, and completeness of revascularization. Maximal exercise capacity generally is improved more by CABG than by medical treatment, at least for 3–10 years [38].
- **Left ventricular function**—resting regional perfusion defects are improved after CABG in at least 65% of patients [39]. Left ventricular wall segments that are hypokinetic, akinetic, or even dyskinetic at rest preoperatively often have improved systolic function after CABG [40]. This is associated with increased regional myocardial perfusion. Improvement in segmental wall motion 12 months after CABG has been observed even in areas of scarring from previous MI [41]. This finding supports the concept that viable muscle cells, which may be hibernating, are scattered through hypokinetic and, at times, even akinetic and dyskinetic segments and that wall motion in such segments can be improved by CABG [42]. When segmental wall contraction does not occur after CABG, incomplete revascularization is the cause in some patients. LV diastolic function, more specifically LV “relaxation,” is also improved by successful CABG, and improvement may be immediate [43].
- **Exercise**—the decrease in EF with exercise that is a characteristic of ischemic heart disease is absent 2 weeks after operation in most patients. This favorable response to stress can be brought about only by CABG or PCI and does not result from collateral circulation alone, even when extensive [44]. When global and segmental function during exercise is not improved early (3 months) after operation, one or more bypass grafts are usually occluded or stenosed.
- **Patency of grafts: internal mammary artery**—the highest patency rates for coronary bypass grafts are associated with the use of the left internal mammary (thoracic) artery to bypass the left anterior descending coronary artery. These

patency rates are approximately 95% at 10 years after operation, and closure of the mammary artery after that time is uncommon. This favorable performance of the internal mammary artery when anastomosed to the left anterior descending coronary artery is probably due to its particular wall structure and function and the potentially large runoff through the left anterior descending artery system. Internal mammary artery grafts to other vessels appear to have lower patency rates late postoperatively than do those to the left anterior descending artery, and these may be no greater than those of vein grafts [45]. IMA as a free graft from the aorta to LAD provides patency almost as high as with an in situ graft.

- **Other arterial grafts**—early (<13 months) patency of radial artery grafts exceeds 90% and does not differ from ITA patency [46]. A native coronary stenosis of less than 70% is associated with lower patency of a radial artery graft than if the stenosis is 70% or greater. Tatoulis and colleagues [47], in a study of long-term patency of 1108 radial artery grafts, reported patency of 89% at a mean follow-up interval of 48 months. Of 318 grafts in place for more than 5 years, 294 (92%) were patent. Of 107 in place for more than 7 years, 99 (92%) were patent. Patency was highest for grafts placed to the LAD (96%) and lowest for grafts to the RCA (83%).

In a study by Suma and colleagues [48] of gastroepiploic artery grafts in 685 patients who underwent postoperative angiographic evaluation, patency was 94% within 1 year in all 685 patients, 88% between 1 and 5 years in 102 patients and 83% between 5 and 10 years in 102 patients. Time-related patency at 1 month, 1 year, 5 years, and 10 years was 96, 91, 80, and 62%, respectively. The principal causes of late occlusion were anastomotic stenoses and anastomoses to less critically stenosed coronary arteries.

For the inferior epigastric artery, Gurne and colleagues [49] performed postoperative angiography in 122 patients early (11 ± 5 days) and in 72 patients late (11 ± 6 months) after operation. Early patency was 98%, and late patency was 93%. Of 14 grafts that were occluded or threadlike at the late study, 8 were anastomosed to arteries with a stenosis of 60% or less.

- **Saphenous vein grafts**—diffuse intimal hyperplasia is a universal finding in vein grafts that have been in place for more than 1 month [50]. Thickness of the intimal hyperplasia seems to be inversely related to flow in the graft, and the process appears to result in a matching of vein lumen size to that of the coronary arteries supplied by the graft. About 10% of vein grafts get closed within the first few postoperative weeks. By 10 years after insertion, half of vein grafts still patent have undergone at least some arteriosclerotic changes [51]. About 20% of vein grafts have proximal suture line stenosis within 1 year; about one fourth of these are found to be occluded 5 years later. Almost 50% of patients have some narrowing of the distal anastomosis within 1 year, but most have not progressed by 5 years after CABG. The 10-year patency rate of vein grafts appears to be highly variable, and in some reports [52] only 50–60% overall are still patent. Arm veins have a still lower prevalence of patency [53] as do synthetic conduits. The patency rates are lower when the anastomosis is to small coronary arteries and to arteries supplying areas with considerable scar. Thrombosis, another process that can reduce graft patency, may develop early postoperatively. Endothelial cell loss and exposure of the basement membrane and collagen to blood tend to appear early after inserting the vein graft, predisposing it to early accumulation of platelets, fibrin, and thrombus on its luminal surface.

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