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# Coronary Artery Bypass Surgery

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## Abstract

Surgical treatment of coronary artery disease should increase regional coronary flow reserve and not increase any early or late morbidity and mortality more than the other treatment modalities. In the past 50 years, surgical treatment of coronary artery disease has been adapted rapidly worldwide and several techniques have been developed to decrease total surgical risks and to improve early and late results with the highest level of quality of life. In spite of the last guidelines that offer stents for single or multiple vessels disease, the fact is that surgical revascularization has better outcomes in all groups of coronary artery patients. In the past two decades, the main target has been to limit or eliminate side effects of extracorporeal circulation and cardioplegia (off-pump), and general anesthesia (awake coronary bypass). The prime goal of surgical revascularization is to obtain complete revascularization by bypassing all severe stenotic coronary arteries having a diameter larger than 1 mm. Surgical revascularization with cardiopulmonary bypass through a full sternotomy remains the most widely used surgical technique. With the development of stabilization devices, off-pump procedures can be safely performed in most patients with single or multivessel disease. Minimal invasive and/or robotic surgery is an attractive procedure to catch invasive cardiology. The gold standard strategy involves single graft to single target vessel bypass, especially the left internal mammary artery to the left anterior descending artery. The early cumulative mortality rate is below 3%, but lower than 1% in lower-risk patients. There are some variables most predictive of early mortality: older age, female, reoperation, non-elective surgery, left ventricular dysfunction, accelerated atherosclerosis. The survival rate is higher than 65% for 15 years. Late mortality is dependent not only on non-use of internal mammary artery, closure of grafts, progression of native arterial disease but also on comorbidities. Satisfactory quality of life after surgery depends on the long-term duration of the freedom from angina, heart failure, rehospitalization and reintervention, and improvement of the exercise capacity. Return of angina during the first 6 months depends on incomplete revascularization or graft failure, whereas progression of native-vessel disease and grafts are serious risk factors for the late recurrence of angina. Venous graft occlusion is the most common reason for reintervention, and native vessel disease is the second.

**Keywords:** Coronary artery bypass, arterial graft, revascularization, off-pump, awake

## 1. Introduction

Coronary artery disease (CAD) is the most common pathology which prepossesses cardiologists and cardiac surgeons in the past century. It was the most common (38.8%) cause of death in Turkey in 2013 [1]. Ischemic heart disease was also the most common reason of mortality in the world as reported by the World Health Organization in 2012 [2]. Coronary artery disease is caused by an atherosclerotic plaque which narrows the internal lumen of the coronary artery. This lesion decreases coronary arterial blood flow and oxygen supply to the myocardium, and causes several symptoms such as chest pain, dyspnea, syncope, sometimes pulmonary edema. The low blood flow through the coronary artery territory cannot increase and support the increasing daily-life effort capacity, and the increased demand of oxygenated blood supply starts angina pectoris. There are several examinations such as exercise test, myocardial perfusion scintigraphy and computed tomography, but biplane coronary angiography is the gold standard for diagnosis. An improved understanding of the pathophysiology of CAD has forwarded efforts to increase myocardial blood supply. According to the result of angiography, patients should be treated either medically or with invasive treatment modalities. Because myocardial revascularization prolongs survival, relieves angina, and improves quality of life, percutaneous coronary intervention and coronary artery bypass surgery (CABG) can be the only treatment strategies to perform this revascularization. The general condition of patients is the decisive factor to select the best acceptable revascularization strategy. The most adequate surgical technique will be selected according to the degree and number of the affected coronary artery lesions, lesion type, and lesion location. The potential aim of the minimally invasive techniques is to reduce postoperative patient discomfort, to decrease bleeding and wound infection, and to shorten recovery times.

## 2. History

The first method to establish blood supply to the ischemic myocardium is to place the pedicled pectoralis muscle flap on the pericardium performed by Beck in 1935 [3]. The following 10 years passed with the developments such as chemical pericarditis and revascularization through the coronary sinus. Beck I operation (abrasion of the pericardium and epicardium + application of an inflammatory agent + partial occlusion of the coronary sinus) was described in 1945 and Beck II operation (total or partial ligation of the coronary sinus + brachial artery bypass between the descending aorta and the coronary sinus) was introduced in 1947. Vineberg described the direct implantation of internal mammarian artery (IMA) into the myocardium in 1950 [4]. A modification of the Vineberg procedure (anastomosis of a long saphenous vein between the aorta and the apex of the heart) was performed by Smith in 1955. The first successful coronary endarterectomy was performed by Bailey in 1956 [5]. Goetz performed the first successful planned CABG operation in 1960 [6]. The first patch graft technique to enlarge the obstructed left main coronary artery was performed by Effler in 1962 [7]. The first usage of a saphenous vein as an aorta–coronary artery bypass conduit was described by Sabiston in 1962 [8]. Favalaro placed a saphenous vein between the ascending

aorta (side-to-end) and the right coronary artery (RCA) (end-to-end) in 1960s. [9] The official start of CABG surgery happened at the end of 1960s and saphenous vein grafts were used in all major branches with the same technique as we use nowadays [10]. Kolessov performed the first successful left internal mammary artery (LIMA) to the left anterior descending (LAD) coronary artery anastomosis on the beating heart through a left thoracotomy in 1964 [11]. Internal mammary artery grafts have been the first choice and gold standard for LAD revascularization after their superior long-term patency became known [12].

After all of the developments in cardiac surgery, the cornerstone is the development of the cardiopulmonary bypass machine. This staged development has brought CABG surgery as a standard treatment modality after 1960s. The first stage was the discovery of heparin in 1915, which opened the door for open heart surgery. The second stage was the development of a heart–lung machine. The first successful open heart procedures on a human utilizing the heart–lung machine were total left-sided heart bypass procedures, where the patient's own lungs were used to oxygenate the blood. The right-sided heart bypass procedure was performed by Dordill and colleagues in 1952 [13]. The first successful total cardiopulmonary bypass (CPB) procedure using a heart–lung machine was performed by Gibbon to close an atrial septal defect in 1953 [14]. The third stage was the development of membrane oxygenators in the 1960s. The first successful usage of a membrane oxygenator for extracorporeal circulation was performed by Hill and colleagues in 1972 [15]. The fourth stage was using a potassium-based cardioplegia solution to protect myocardium during open heart surgery. Melrose and colleagues presented the first experimental study with blood cardioplegia in 1955, but toxicity of this solution prevented usage of this cardioplegia for several years [16]. Several types of crystalloid cardioplegia solution with different elements were tried to protect myocardium after a significant protection of myocardium during potassium-induced cardiac arrest was demonstrated in 1973 [17]. Follette and colleagues reintroduced the technique of blood cardioplegia in 1978 [18].

After all of the developments in the conventional CABG surgery, the next step has been to minimize the standard surgical revascularization procedure using different techniques. Coronary bypass surgery is performed without opening a cardiac chamber and it is not necessary to use extracorporeal circulation. Continuing ventilation of the lungs eliminates the use of any oxygenator and keeping a beating heart eliminates any pump. Even though the first CABG procedures were performed with off-pump technique, cardiac arrest during on-pump technique has pressurized beating heart surgery. Ankeney tried to increase the interest of the off-pump revascularization in 1972, but it took only 10 years to be able to perform off-pump CABG routinely [19]. Benetti [20] and Buffolo [21] popularized this strategy in 1980s. The first cases were revascularization of anteriorly located coronary arteries. Three limiting factors have inhibited ideal myocardial revascularization: adequate exposure, blood flow, and motion. The technical advances regarding exposure and stabilization have facilitated complete revascularization. Several new strategies have been developed for off-pump CABG. First strategy was to stabilize the beating heart with different devices [22]. Second strategy was to position the beating heart for the adequate exposure of all epicardial coronary arteries [23]. Third strategy was to minimize surgical intervention with different minimal invasive approaches [24]. Last

step was to avoid general anesthesia to minimize respiratory side effects [25], whereas Kirali and colleagues [26] performed off-pump complete arterial revascularization with using bilateral IMAs for in awake patients. Harvesting IMAs was the other issue for off-pump surgery. Endoscopic IMA harvesting was used, but it did not widespread [27]. Today, we are facing fully endoscopic off-pump myocardial revascularization-assisted robotic surgery. Loulmet [28] was the first to report a successfully completed robotic CABG, but conversion was very common in early series. Stepwise progression of robotic technology and development of specific procedures will result in simpler robotic CABG in the near future [29].

### 3. General information

Coronary artery disease varies enormously from patient to patient; therefore, recommendations to patients on the basis of predictions and comparisons of outcomes between CABG and the other treatment options are of little value. Surgical treatment of CAD should increase the regional coronary flow reserve and not increase any early or late morbidity and mortality more than the other treatment modalities. Patient-specific features, risks, and predictions are required to offer patients the surgical treatment. Because anginal symptoms are very subjective for both patients and surgeons and there is a weak correlation between the severity of symptoms and the involvement of coronary arteries, the gold standard biplane coronary angiography is the only option to decide which surgical revascularization strategy to use. Perfusion imaging and echocardiography examinations can diagnose associated cardiac pathologies, which require surgical intervention at the same time. Computed tomographic angiography is a new option, but not a suitable alternative, and gives more detailed information about distal vascular bed or ostial lesions. Intravascular ultrasound and fractional flow reserve can clarify the severity of intermediate lesions.

Myocardial revascularization represents an effective treatment strategy shown to prolong survival. In the past 50 years, surgical treatment of CAD has been adapted rapidly worldwide because CABG provides excellent short- and mid-term results in the management of ischemic heart disease with the highest level of quality of life. But long-term results of surgical revascularization are affected by failure of conduits, and late patency of conduits is affected by graft-type, coronary runoff, and severity of distal native vessel atherosclerosis. Several techniques have been developed to decrease total surgical risks and to improve early and late outcomes, but CABG surgery with or without CPB through median sternotomy remains the standard surgical intervention despite an increasing risk profile and diffusing coronary artery involvement. The aim of CABG is to increase the blood supply in coronary arteries by obtaining complete revascularization of all severe stenotic epicardial coronary arteries with a diameter larger than 1 mm. However, optimal patency rates can be obtained in saphenous vein grafts with a distal lumen of  $\geq 2$  mm. Most patients undergoing CABG have extensive three-system disease, often with important stenoses in more than three coronary branches. The standard strategy involves usage of LIMA to the LAD and saphenous veins to the remaining coronary arteries, whereas full arterial revascularization is preferred in young population. "Single graft to single target vessel bypass" is the gold standard for myocardial revascularization, but in



some situations sequential bypass or complex configuration of conduits can be used for complete revascularization in the presence of inadequate venous grafts. The condition of the distal coronary vasculature is important for the outcome of bypass conduits, and the rate of CAD progression appears to be three to six times higher in grafted native coronary arteries than that in no grafted native vessels. If coronary arteries are diffusely diseased ( $> 10$  mm) or occluded, several surgical techniques can be chosen to complete surgical revascularization as explained in the next chapter.

Indication for surgical revascularization depends on the need of improvement in the quality and/or duration of life. Despite the increase of CAD, nowadays, the indications for CABG have changed a little, but became more limited. Aggressive percutaneous coronary interventions (PCI) suppress surgery and minimal invasive surgical procedures force surgery. The last guidelines offer stents for single or multiple vessels disease, but the fact that surgical revascularization has better outcomes in all groups of CAD patients and stents is best used if there are no anatomic indications for CABG. The decision to perform myocardial revascularization with stent or CABG depends mainly on coronary anatomy, left ventricular function, and other medical or non-medical comorbidities that may affect the patient's risk. Patients with more extensive and severe coronary atherosclerosis could have more increasing benefit from surgery over stent therapy.

#### 4. Indications

The only base for the indication of surgical myocardial revascularization is the positive benefits of CABG against no treatment, medical treatment, or treatment by PCI. Regardless of symptoms, indication for CABG is determined by the clinical status of the patient and patient-specific predictors. The main purpose is to improve the quality of life and to prolong the life expectancy. The number of the affected vessels, the degree and the localization of lesions are important to make this decision. 2011 ACCF/AHA Guideline for CABG supports surgical revascularization for patients with extensive and severe multivessel CAD, especially associated with left ventricular dysfunction (LVD), renal insufficiency, and/or diabetes mellitus (Table 1) [30]. In the real world, patients with proximal LAD lesion must be sent to surgical revascularization regardless of the number of affected coronary arteries, but cardiologists like to revascularize these patients with stent regardless of the superiority of LIMA-LAD anastomosis (Figure 1). Although patients with LVD would benefit from CABG more, the real data suggest that poor left ventricular function increases early mortality after surgery. Patients with good left ventricular function can have better prognosis than patients with LVD. Risks and benefits of CABG become more uncertain when resting left ventricular ejection fraction (LVEF) is less than 30%, particularly when it is less than 20%. The only exception is myocardial hibernation which causes severe reduction in resting LVEF. Stable angina requires elective myocardial revascularization, but unstable angina or non-ST-segment elevation acute coronary syndrome or non-Q-wave myocardial infarction requires priority CABG to prevent patients from transmural myocardial infarction. In the early period ( $< 4$  h) after acute transmural myocardial infarction, emergency CABG can be a lifesaving procedure, but some

patients cannot be salvaged. Myocardial re-revascularization can be necessary when myocardial ischemia returns after CABG, and stent implantation is the first choice for restenosis of grafted coronary arteries or vein grafts.

Revascularization	CABG			DES		
	No-risk	DM	LVD	No-risk	DM	LVD
1-vessel	N	N	N	Y	Y	Y
Proximal LAD	Y	Y	Y	N	N	N
2-vessel without LAD	N	N	N	Y	Y	Y
2-vessel with LAD	Y	Y	Y	Y	Y	Y
2-vessel + proximal LAD	Y	Y	Y	N	N	N
3-vessel	Y	Y	Y	C	C	C
3-vessel + proximal LAD	Y	Y	Y	N	N	N
LMC ± other lesions	Y	Y	Y	N	N	N

CABG = coronary artery bypass grafting; DES = drug eluting stent; DM = diabetes mellitus; LAD = left anterior descending artery; LMC = left main coronary artery disease; LVD = left ventricular dysfunction.

\*Y = yes; N = no; C = controversial

**Figure 1.** The reality of myocardial revascularization strategies in patients with isolated coronary artery disease.

#### Asymptomatic CAD

##### Class I

1. LMC stenosis
2. LMCE disease
3. Three-vessel disease

##### Class IIa

1. Proximal LAD (one- or two-vessel)

##### Class IIb

1. One- or two-vessel disease not involving proximal LAD  
(if a large territory at risk on noninvasive studies or LVEF < 50%, IIa and IIb become class I indications)

#### Stable Angina

##### Class I

1. LMC stenosis

	2. LMCE disease
	3. Three-vessel disease
	4. Two-vessel disease with proximal LAD stenosis and LVEF < 50% or demonstrable ischemia
	5. One- or two-vessel disease without proximal LAD stenosis but with a large territory at risk and high-risk criteria on noninvasive testing
	6. Disabling angina refractory to medical therapy
<b>Class IIa</b>	
	1. Proximal LAD stenosis with one-vessel disease
	2. One- or two-vessel disease without proximal LAD stenosis, but with a moderate territory at risk and demonstrable ischemia
<b>Unstable Angina / Non-ST-Segment Elevation MI (NSTEMI)</b>	
<b>Class I</b>	
	1. LMC stenosis
	2. LMCE disease
	3. Ongoing ischemia not responsive to maximal nonsurgical therapy
<b>Class IIa</b>	
	1. Proximal LAD stenosis with one- or two-vessel disease
<b>Class IIb</b>	
	1. One- or two-vessel disease without proximal LAD stenosis when PCI not possible (becomes class I if high-risk criteria on noninvasive testing)
<b>ST-Segment Elevation (Q wave) MI</b>	
<b>Class I</b>	
	1. Failed PCI with persistent pain or shock and anatomically feasible
	2. Persistent or recurrent ischemia refractory to medical treatment with acceptable anatomy who have a significant territory at risk and not a candidate for PCI
	3. Requires surgical repair of post-infarct VSD or MR
	4. Cardiogenic shock in patients < 75 years of age who have ST elevation, LBBB, or a posterior MI within 18 hours onset
	5. Life-threatening ventricular arrhythmias in the presence of ≥ 50% LMC stenosis or three-vessel disease
<b>Class IIa</b>	
	1. Primary reperfusion in patients who have failed fibrinolytics or PCI and are in the early stages (6-12 h) of an evolving STEMI
	2. Mortality with CABG is elevated the first 3-7 days after STEMI/NSTEMI. After 7 days, criteria for CABG in previous section apply.
<b>Poor LV Function</b>	



**Class I**

1. LMC
2. LMCE
3. Proximal LAD stenosis and two- to three-vessel disease

**Class IIa**

1. Significant viable territory and noncontractile myocardium

**Life-Threatening ventricular Arrhythmias****Class I**

1. LMC
2. Three-vessel disease

**Class IIa**

1. Bypassable one- or two-vessel disease
  2. Proximal LAD disease and one- or two-vessel disease
- These become class I indications if arrhythmia is resuscitated cardiac death or sustained ventricular tachycardia

**Failed PCI****Class I**

1. Ongoing ischemia with significant territory at risk
2. Shock

**Class IIa**

1. Foreign body in critical position
2. Shock with coagulopathy and no previous sternotomy

**Class IIb**

1. Shock with coagulopathy and previous sternotomy

**Previous CABG****Class I**

1. Disabling angina refractory to medical therapy
2. Nonpatent previous bypass grafts, but with class I indications for native CAD

**Class IIa**

1. Large territory at risk
2. Vein grafts supplying LAD or large territory are  $> 50\%$  stenosed

Class I: Conditions for which there is evidence and/or general agreement that a given procedure or treatment is useful and effective

Class II: Conditions for which there is conflicting evidence and/or a divergence of opinion about the usefulness or efficacy of a procedure
Class IIa: Weight of evidence/opinion is in favor of usefulness/efficacy
Class IIb: Usefulness/efficacy is less well established by evidence/opinion
Class III: Conditions for which there is evidence and/or general agreement that the procedure/treatment is not useful/ effective and in some cases may be harmful

ACC = American College of Cardiology; AHA = American Heart Association; CABG = coronary artery bypass grafting; CAD = coronary artery disease; LAD = left anterior descending artery; LBBB = left bundle branch block, LMC = left main coronary artery; LMCE = left main coronary equivalent; LVEF = left ventricular ejection fraction; MI = myocardial infarction; MR = mitral regurgitation; NSTEMI = non-ST elevation myocardial infarction; PCI = percutaneous transluminal coronary angioplasty; STEMI = ST elevation myocardial infarction; VSD = ventricular septal defect

**Table 1.** AHA/ACC guidelines for CABG

Myocardial revascularization in special circumstances is another important issue (Table 2). The common denominator of these distressed conditions is the accelerated risk of surgery. Intraoperative mortality and morbidity increase after CABG due to the multi-organ dysfunction. Prolonged intubation, requiring ultrafiltration or hemodialysis, mechanical hemodynamic support, and/or infection risk can be very harmful despite full multisystem treatment. Nowadays, an aggressive strategy is favored to early myocardial revascularization in acute coronary syndrome, and surgical indication can be extended for these patients, but stent implantation is the first choice in the majority of this population. Surgical treatment has the advantage to bypass all occluded and/or stenotic coronary arteries at the same time, which suppresses early adverse outcomes. Left main or left main equivalent disease should be treated surgically, and this pathology is not a contraindication to use arterial grafts in any situation, especially for LIMA to LAD anastomosis. Severe LVD is not considered as an indication for surgery, but patients with hibernating or stunned myocardium can benefit from CABG. The only surgical indication for patients with severe LVD is the possibility of full revascularization during CABG. Otherwise, stent implantation should be the preferred approach. Total occlusion is not a contraindication for stent; but if it cannot be applied, surgery will be the alternative treatment. The important point is the diffuse involvement of atherosclerosis, which needs endarterectomy or long-segment anastomosis, and the choice of the acceptable revascularization procedure, which will be particularly influenced by the presence of comorbidities, especially in the elderly patients; but they cannot prevent usual surgery. In general, women have a higher risk for perioperative complications, but this adverse outcome can be explained by the presentation of female population at older ages with more extensive CAD, associated risk factors, LVD, and smaller body size. Diabetes is characterized by an inflammatory, proliferative, and prothrombotic state with more diffuse atherosclerosis, which may have a role in the increased risk of restenosis and occlusion. The first option is the complete revascularization, which is more often performed surgically than percutaneously. Coronary artery disease is a common reason of mortality among patients with end-stage renal failure and CABG is the option for myocardial revascularization. The main problem is the excessive atherosclerosis with severe calcification on the aortic wall and in the coronary arteries, which make surgery difficult. Recurrent ischemia after CABG or stent implantation is an indication of re-

revascularization. Severe stenosis must be treated with stent after previous CABG, but CABG is the first option for re-revascularization after previous PCIs.

1. Acute coronary syndrome
2. Left main or left main equivalent (proximal LAD and Cx) disease
3. Severe left ventricular dysfunction
4. Total occlusions
5. The elderly population
6. The female population
7. Diabetes mellitus
8. End-stage renal disease
9. Previous myocardial revascularization (CABG or stent)

Table 2. Special circumstances for myocardial revascularization

5. Bypass conduits

Conduits for CABG are the base of surgical myocardial revascularization, because they are critical to the success of the procedure. Easy harvesting, simple implantation, long-term patency, and possible side effects must be taken into consideration during the preference of usable conduits for each patient to avoid an uneventful postoperative outcome and to achieve better long-term survival. Arterial grafts are favorable because of their long-term patency and resistance against atherosclerosis, which is related to the differences in biological characteristics between veins and arteries. Early vein graft failure (stenosis or occlusion) is the most important drawback of venous conduits; nevertheless, using venous grafts is still an integral part of coronary surgery. There are some differences between venous and arterial conduits, which may affect the long-term patency rate (Table 3).

1. Veins are more susceptible to vasoactive substances than arteries.
2. The venous wall is supplied by the vaso vasorum whereas the arterial wall may be supplied through the lumen in addition to the vaso vasorum.
3. The arterial endothelium may secrete more endothelium-derived relaxing factor and nitric oxide.
4. The structure of veins is more suited to low pressure whereas the artery to high pressure.

Table 3. Differences between venous and arterial grafts

5.1. Arterial grafts

Arterial grafts are not similar in anatomy or function, and there are differences regarding to contractility and endothelial function. Commonly harvested arterial conduits relate to different groups of arteries in the body (Table 4). The most important variation is the structural histology of arteries, whereas some arteries (Type II and III) contain more smooth muscle cells

in their wall, thus are less elastic, or some arteries (Type I) contain more elastic laminae, thus are more elastic. Arterial grafts can develop spasm during surgical harvesting and handling, but the IMA shows the lowest vasospasm rate. Internal mammary artery releases more nitric oxide and endothelium-derived relaxing factor than the other arterial conduits. The reactivity of the arterial conduits changes along the length of arteries and the main mid-portion of them is less reactive than distal or proximal portions. This is the reason why the small and highly vasospastic distal part of the arterial grafts is trimmed before anastomosis. This part of conduits contains relatively smoother muscle cells and has a smaller diameter. The incidence of atherosclerotic changes in arterial conduits is rare and lower than in coronary arteries. Based on the superior long-term patency of the IMA, orientation to the other arteries has been popularized. The radial artery (RA) and the gastroepiploic artery (GEA) have been used for complete revascularization. Their usage has decreased in the past decade due to their lower patency rate, where the early occlusion of both grafts depends on higher response to vasoconstrictive situations like the inotropic support, the low cardiac output syndrome (LCOS), and usage of different spasmogens.

<b>A. Type I (somatic arteries; less spastic)</b>
1. Internal mammary artery
2. Inferior epigastric artery
3. Subscapular artery
<b>B. Type II (splanchnic = visceral arteries; spastic)</b>
1. Gastroepiploic artery
2. Splenic artery
3. Inferior mesenteric artery
<b>C. Type III (limb arteries; spastic)</b>
1. Radial artery
2. Ulnar artery
3. Lateral femoral circumflex artery

Table 4. Arterial grafts

5.1.1. Internal mammary artery

The IMAs lie vertically and slightly laterally at a short distance from both margins of the sternum. The length of in situ left IMA is slightly longer than the right and ranges from 15 to 25 cm (mean 20 ± 2 cm). The IMA bifurcates into its terminal branches (musculophrenic and superior epigastric arteries) at the level of the sixth rib, and the in situ IMA should be cut before this distal bifurcation to get the acceptable intraluminal diameter for IMA–coronary artery anastomosis. Excessive traction, stretching, clamping, or misplaced metal clips during harvesting should be avoided to get a nontraumatized IMA without any injury (hematoma,

dissection, rupture). We prefer to harvest the IMA using semi-skeletonized technique, which allows an increasing luminal diameter, providing a longer graft, allowing more distal anastomosis and sequential grafting. The full length of this IMA prevents any tension on the conduit, but some associated maneuvers can be needed to avoid stress on the IMA [31]. Making a window on the pericardium at the left side of the pulmonary artery, where the LIMA is lied down into the pericardium, prevents also the stretch of the LIMA [32]. The full length of the right IMA (RIMA) allows anterior (on the front of the heart) or lateral (through the transverse sinus) wall revascularization with optimal long-term patency, but the RCA revascularization is more difficult due to the distance of the distal segments [33].

#### 5.1.2. Radial artery

The radial artery with higher patency rate according to saphenous vein can be a second alternative bypass conduit instead of vein grafts. The RA can have more atherosclerotic changes at the time of harvest than the IMA. The RA is very vasoreactive, and therefore is very sensitive to competitive flow. In the past two decades, using the RA as a pedicled arterial graft has been the preferred conduit as the second bypass graft, but the mid- and long-term patency rates are controversial. The failure of the RA grafts depends on three general ways: complete occlusion, string sign, or focal stenosis. The graft failure rate is the highest at the right system and equal to the saphenous vein graft [34]. The mid-term patency on the left coronary system is higher if the proximal anastomosis is performed on the ascending aorta [35]. Because the IMAs have higher long-term patency rates than the RA and the acceptable approach is using both IMAs for the left coronary system, usage of the RA has not increased and the saphenous vein is a more practicable conduit with a comparable patency rate than the RA for the right system [36]. The patient's nondominant arm is chosen for harvest, but the extremity must have adequate ulnar collateral circulation and the recurrent radial branch should be left intact [37]. The harvest of the left RA can be performed easily and simultaneously with the LIMA. Transient paresthesia, numbness, and thumb weakness could be seen, but the symptoms resolve with time [38].

#### 5.1.3. Gastroepiploic artery

The gastroepiploic artery has been used as an alternative conduit or as part of an all-arterial revascularization strategy. The widespread use of the GEA has not been adopted due to the increased harvesting time, the potential abdominal complications, and inadequate early- and long-term patency rates. Opening the abdomen is a serious intervention and the GEA may be used only in patients who require any abdominal aortic surgery [39]. This arterial conduit has been used usually for the RCA revascularization because the in situ right GEA can reach only to the distal branches of the RCA.

#### 5.1.4. Other arteries

Bilateral IMAs and the RA are often adequate to get full arterial complete myocardial revascularization. These grafts can be used in situ or in combined fashion, and distal anastomoses can be made single or sequential. Revascularization with the other arterial conduits has been

left as an anecdotal use in the literature. Maybe, they can be used during redo or tredo CABG operations if there is no another conduits left. The studies on these arterial grafts have been left as academic researches [40].

## 5.2. Venous grafts

### 5.2.1. Greater saphenous vein

The saphenous vein is one of the most commonly used conduits in CABG. The early- and long-term patency of vein grafts is worse than that of arterial grafts, and one third of the vein grafts shows an important reduction in flow compared with the early postoperative period. Second disadvantage is easy kinking or torsion after anastomosis, which can cause fatal myocardial ischemia. However, its easiness to harvest, availability, usability, resistance to spasm, and acceptable long-term patency rate make vein grafts the second choice for revascularization conduits. There are no detrimental effects of harvest technique on vein morphology, endothelial structure or function, or graft patency. Saphenous vein can be harvested with an open (conventional = standard) or endoscopic technique. Endoscopic or minimal invasive harvest techniques could be more harmless. Open harvesting can be achieved with a complete or bridged approach. In reality, no-touch technique during open-vein harvest, in which the vein is removed with a pedicle of surrounding tissue, prevents vein injury and prolongs long-term durability. Specifically, vein grafts must not be grasped with forceps, stretched, or overdistended to avoid any endothelial damage. All venous tributaries should be ligated or clipped away from the vein itself and the lumen of the graft should not be injured, narrowed, or left with a blind sac on the side branches.

### 5.2.2. Other veins

Alternative venous grafts such as the lesser saphenous and cephalic veins are seldom secondary choice for vein graft. The lesser saphenous vein could be harvested with the same technique performed during standard vein harvest. Arm veins have significantly lower patency rate than saphenous veins, and for that reason, they are not used as a venous conduit.

## 6. Surgical procedures

Coronary bypass surgery can be performed with different techniques. The most common approach for CABG is on-pump revascularization via median sternotomy and under general anesthesia. Patients' characteristics and risk factors forward surgeons to prefer the appropriate approach for each individual case. Different techniques, variant approaches, new technologies, surgeon experience, and associated cardiovascular or organ pathologies restrict or direct cardiac surgeons to specific CABG procedures (Table 5). The benefits of off-pump techniques can be more evident for patients with high risk, especially for complications associated with cardiopulmonary bypass (CPB) and aortic manipulation. Myocardial protection prevents perioperative infarction and/or postischemic ventricular dysfunction (Table 6). Although



considerable progress has been made in this field, the ideal technique has not yet to be discovered due to complex nature of ischemia–reperfusion cascade during surgical revascularization.

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**A. Arrested heart surgery with CPB**


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**B. Fibrillating heart surgery with CPB**


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**C. Beating heart surgery with circulatory support (central or peripheral)**


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1. Veno-arterial support (CPB, ECMO)

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2. Atrio-arterial support (LHB devices)

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3. Veno-venous support (RHB devices)

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4. IABP support

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**D. Beating heart surgery without CPB**


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1. Standard off-pump through the median sternotomy (OPCAB)

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2. Minimal invasive off-pump (MIDCAB)

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3. Endoscopic off-pump (OP-TECAB)

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4. Robotically assisted off pump (BHTECAB)

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5. Awake off-pump (ACAB)

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**Table 5.** Surgical revascularization techniques

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**A. Arrested heart (cardioplegic) surgery**


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1. Crystalloid cardioplegia (hypothermic)

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2. Blood cardioplegia (cold – warm – tepid)

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- a) Antegrade (intermittent, continuous)

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- b) Retrograde (continuous)

---

- c) Combined

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- i. Antegrade (arrest) – retrograde (continuous)

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- ii. antegrade (arrest and intermittent) – conduits (intermittent)

---

- iii. antegrade (arrest) – retrograde (continuous) – conduits (intermittent)

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**B. Beating heart surgery**


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1. off-pump CABG

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2. on-pump CABG

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**C. Fibrillating heart surgery**


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1. Intermittent aortic cross-clamping with fibrillation

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2. Systemic hypothermia and elective fibrillatory arrest

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**Table 6.** Myocardial protection

6.1. On-Pump CABG

On-pump CABG surgery is the standard conventional technique for myocardial revascularization which is performed via CPB. Despite the fact that off-pump CABG was the first performed technique, on-pump CABG has been used widespread around the world and became the first choice for surgery. An empty, nonbeating heart, a bloodless surgical field, and an easy exposure are essential reasons to prefer on-pump CABG for success of the revascularization procedure. Cardiopulmonary bypass technique includes several stages: cannulation, extracorporeal circulation, myocardial protection, distal with/without proximal anastomoses, and weaning from CPB.

Arterial cannulation for inflow and venous cannulation for outflow are necessary to establish extracorporeal circulation. Arterial cannulation is performed mostly on the ascending aorta, but in case of a contraindication, alternative arteries (femoral or axillary artery) can be preferred. The right atrium is the first choice for venous cannulation; but if there is a contraindication, femoral vein can be used. After inserting the cannulas and finishing harvest of grafts, cardiopulmonary bypass machine starts to work. Blood comes out from the right atrium to the venous blood reservoir, then passes through the oxygenator and is sent to the aorta with a pump. A roller or centrifugal pump is used to continue body perfusion with an acceptable arterial pressure.

Extracorporeal circulation for support during cardiac surgery is uniform, because blood contacting to foreign, nonendothelial surfaces is collected in the reservoir and continuously recirculated throughout the body after oxygenated in the oxygenator. The heart and lung machine has some side effects on the body, which increases early and late morbidity and mortality. There are several adverse effects which cause organ dysfunctions (Table 7). The inflammatory reaction to CPB starts a powerful thrombotic stimulus and the production, release, and circulation of vasoactive and cytotoxic substances that influence the whole body. The inflammatory response produces the cytotoxic compounds and activates neutrophils and monocytes that will destroy organ and tissue cells. On the other hand, the body is able to resist and repair the most part of the cellular damage, although some abnormalities may appear later. The body temperature is lowered according to surgical procedures, but usually mild hypothermic (32–34°C) body perfusion is preferred for isolated CABG procedures to avoid cold or warm body temperature.

A systemic inflammatory response
Releasing cytokines
Metabolic changes
Ischemia-reperfusion injury
Activation of the clotting cascade
Micro-embolization

Table 7. Adverse effects of cardiopulmonary bypass

After cross-clamping the ascending aorta, cardiac arrest is achieved with a cardioplegic solution. Cardioplegic solutions containing a variety of chemical agents are used to arrest the heart rapidly in diastole, create a bloodless anastomotic field, and prevent myocardium against ischemia-reperfusion injury. Blood cardioplegia is chosen for myocardial protection of the arrested heart. Both cold (4–10°C) and warm (37°C) blood cardioplegic solutions have temperature-related advantages and disadvantages. But, tepid (29–32°C) blood cardioplegic solution is the other effective alternative to reduce anaerobic lactic acid released during the arrest period. The best and easiest way to prepare blood cardioplegic solution is to get isothermic (= body perfusion temperature; 32–34°C) blood directly from the pump. The most common cause of postoperative LCOS is inadequate myocardial preservation. There are many different ways of administering the cardioplegic solution: intermittent antegrade ± antegrade via grafts, continuous retrograde, or combined. Continuous retrograde cardioplegia is preferred for severe LMC lesions or diffuse multivessel disease; intermittent antegrade cardioplegia can preserve the myocardium in the other cases effectively. Noncardioplegic surgery is used very seldom, and elective fibrillatory arrest with systemic hypothermia is particularly applicable in case of severely calcified “porcelain aorta”, where clamping the ascending aorta may be associated with increased risk of stroke and aortic dissection.

On-pump coronary artery bypass gives an advantage to the surgeon to make the distal anastomoses safely and confidently. Arteriotomy sites should be chosen as accurate as possible to reach the largest-sized coronary target, but distal enough to keep away from obstruction or significant atherosclerotic stenosis. If any target coronary artery has an intramyocardial course, this coronary artery must be opened at the epicardial indentation (for the LAD) or the myocardium on the reflection of the coronary artery can be divided with tight sharp dissection until the coronary artery is reached (for the Cx). The coronary arteriotomy must be performed at least 1.5 times the luminal diameter of the distal coronary artery to get acceptable blood flow, and the distal end of the conduit should be cut vertically at least the luminal diameter of the coronary artery to avoid any anastomotic kinking. Longer incision is not necessary and cannot increase blood supply; but if the graft has a wide diameter, the coronary arteriotomy should be kept open as long as to perform a successful anastomosis. The aim of the anastomosis is to connect the graft and the target coronary artery with fully endothelial approximation affording minimal resistance to flow. Sequential grafting permits efficient use of grafts and the distal anastomosis must be performed on the largest target vessel. The most important drawback of sequential grafting is the source of two or more distal targets on a single graft, where the flow could not be enough for this large myocardial area. For that reason, sequential anastomoses must be performed only on the branches of the same coronary artery. The LAD artery should be revascularized alone or sequential on itself. With the same reason, the IMA should be anastomosed on the LAD alone. Any composite grafting on the IMA (T- or Y-grafting) can increase the risk of inadequate perfusion of the LAD. Coronary arteriotomy and anastomotic technique in diffuse diseased coronary arteries are discussed in the next chapter. Proximal anastomoses are performed after the distal anastomoses under the same cross-clamp or after releasing the cross-clamp under the side-clamp during the rewarming. If the ascending aorta is severely calcific, proximal anastomoses can be performed on the in situ IMAs or

brachiocephalic artery, or on the prosthetic tubular graft after the replacement of the ascending aorta.

On completion of all distal with/without proximal anastomoses, the aortic cross-clamp is removed and the heart begins to beat. The patient is prepared for conversion from mechanic circulation to native circulation, and during this period the bypass grafts are checked for kinks, twists, or tension and for presence of hemostasis. Persistency or regional wall motion abnormalities may require bypass graft revision or replacement of additional bypass graft.

## **6.2. Off-Pump CABG**

The conventional on-pump CABG can be harmful for patients because of the side effects of the heart-lung machine causing fatal complications like stroke, renal, or respiratory failure. Although off-pump revascularization procedures have gained popularity because of the avoidance of the heart-lung machine during surgery in the past two decades, off-pump CABG appears to have reached a plateau, and currently approximately 20% of all CABG procedures are performed on the beating heart without CPB. The main refuse is to success uncomplicated distal anastomoses on the beating heart, which needs bloodless and immobile anastomotic area. Coronary collateral circulation is not necessary until 15 min; but if the anastomotic duration will be longer, an intracoronary shunt may be used to prevent intraoperative ischemia [41].

## **6.3. OPCAB**

Ideal candidates for off-pump coronary artery bypass (OPCAB) include those undergoing primary CABG with good target anatomy and preserved ventricular function. The benefit may be small in low-risk patients, but it is also not so much in high-risk patients. High-risk patients with diffuse multivessel disease and/or LVD cannot tolerate longer ischemia during distal anastomosis, cardiac manipulation, and/or displacement, which cause ventricular arrhythmia or hemodynamic deterioration. Standard OPCAB is performed through the median sternotomy, and cardiac positioners and stabilizers increase the ability of the manipulation of heart with minimal hemodynamic compromise during lateral and/or inferior wall revascularization. A suction-based positioner is placed at the apex to pull the heart in the appropriate direction. The heart is not compressed, anatomo-functional geometry is kept, and cardiac positioning is usually well tolerated. Then, a stabilizer is established with minimal tension on the epicardium to get a motionless anastomotic area. Some maneuvers may be used to get better exposure such as Trendelenburg position, turning the table toward any side, deep traction stitches; but usually they are not necessary. Medical support can be necessary to stabilize the arterial blood pressure and pulse rate. Anesthesia management is important not to make a per-operative myocardial infarction and life-threatening arrhythmia during distal anastomoses. Heparinization dose is lower than that in the standard on-pump CABG surgery. A soft silastic retractor tape is placed around the proximal segment of the lesion for transient occlusion of coronary blood flow, whereas a second tape could be placed around the distal segment in the presence of strong coronary backflow. The field is kept free of blood with a humidified CO<sub>2</sub> or O<sub>2</sub> blower.

Careful attention must be paid to the sequence of grafting because regional myocardial perfusion is temporarily interrupted in the beating heart (Table 8). As a general rule, the collateralized vessel is grafted first and the collateralizing vessel grafted last. Additional option is a “proximal first” approach. But in our experience, the priority for grafting belongs to the in situ LIMA conduit and LIMA-LAD anastomosis is performed first. There is no doubt to manipulate the heart after this anastomosis, which is the main safety valve of the off-pump revascularization.

<b>First</b> , to revascularize the LAD with in situ LIMA to get fully LAD perfusion immediately after finishing the anastomosis.
<b>Second</b> , to anastomose the other in situ conduits to the target vessels (first IMA-LAD, then IMA-Cx, then RGEA-RCPD)
<b>Third</b> , to perform distal anastomoses of completely occluded or collateralized coronary arteries first, and then to perform proximal anastomoses.
to perform proximal anastomoses first, and then to perform distal anastomoses.
<b>Fourth</b> , to use an intracoronary shunt when beware of a large, dominant RCA with moderated proximal stenosis.
<b>Fifth</b> , to pass small or intramyocardial vessels on the lateral wall with an appropriate lesion for stent.
<b>Sixth</b> , to avoid any sequential grafting and to apply one-to-one bypass grafting.
<b>Seventh</b> , to keep away from endarterectomy if not total occluded coronary artery is present.
<b>Eight</b> , to convert on-pump beating heart surgery if moderate MR is present in patients with Cx and/or distal RCA lesions.

Table 8. Sequence of grafting in OPCAB

6.4. MIDCAB

Minimally invasive direct coronary artery bypass (MIDCAB) procedures have evolved to minimize surgical trauma caused by CPB and aortic manipulation, to avoid wound complications developed by full median sternotomy and open harvesting techniques for bypass conduits, and to prevent respiratory troubles caused by prolonged mechanical ventilation. Only contraindication is emergent revascularization, and severe chronic obstructive pulmonary disease may also not be ideally suited to minithoracotomies. This surgical strategy is a very attractive procedure for coronary patients due to excellent cosmetic and an early and quick recovery. This approach has begun with the single LAD revascularization, but then it has been generalized to multivessel CABG. Another situation for MIDCAB is hybrid procedures, where all coronary arteries that required revascularization (except the LAD) are stented. There are several procedures to perform MIDCAB for single or multiple coronary artery revascularization (Table 9). The main difference of some MIDCAB techniques is the selective right lung ventilation and fast-track approach for extubation.

A. Incisional (avoid from sternotomy)
1. Mini-thoracotomy (MIDCAB)
2. Mini-sternotomy
a) Reversed-J-inferior partial sternotomy
b) T-sternotomy
3. Rib cage lifting technique
4. Subxiphoidal approach
B. Instrumental
1. Conventional
2. Endoscopic
3. Robotic assisted fully endoscopic (TECAB)
C. Respiratuar (avoid from extended mechanical ventilation)
1. Limited mechanic ventilation (fast track anesthesia = intraoperative extubation)
2. Spontaneous ventilation with high thoracic epidural anesthesia (ACAB)
D. Circulatuar (avoid from cardiopulmonary bypass)
1. Off-pump
2. Partial support
a) ECMO
b) IABP
E. Myocardial (avoid from cardioplegia)
1. Off-pump
2. On-pump on the beating heart
3. Ventricular fibrillation
F. Proximal anastomotic (avoid from aortic manipulation)
1. Special devices for proximal anastomoses on the ascending aorta
2. Proximal anastomoses on the LIMA (T- or Y-graft)
3. All in situ arterial grafts

**Table 9.** Minimal invasive surgical techniques

6.4.1. Minithoracotomy

Standard MIDCAB is usually performed through a left anterior minithoracotomy. The skin incision is made 5–6 cm long in the fourth intercostal space, but removal of a rib is not necessary in any case. This approach is used for single vessel bypass (LIMA-LAD), and the anastomosis is performed with/without any stabilizator. Rib dislocation or fracture is very seldom. After the completion of the anastomosis, the rest of the operation is standard and the patient can be



extubated in the operating room or in a couple of hours in the intensive care unit. The patient can be discharged on the 3rd or 4th postoperative day. Because this approach is a highly demanding technical procedure and must be performed by experienced surgeons, this single-vessel CABG procedure will remain an alternative revascularization strategy to stent for patients with complex proximal LAD lesion, chronic occlusions, and in-stent restenosis.

#### 6.4.2. *Ministernotomy*

This approach is preferred mostly by unexperienced surgeons because of similar technical manipulations of the full median sternotomy procedure. The sternotomy is performed partially and divided from xiphoid to the second intercostal space in a down to up direction. Then, the sternum is transected obliquely to the left side (reverse-J-inferior ministernotomy) for single-vessel CABG or the sternum is cut bilaterally (T-sternotomy) for multivessel CABG. These both partial lower median sternotomy techniques leave the manubrium intact to preserve the continuity and stability of the superior thoracic aperture for early and late postoperative recovery. Furthermore, conversion to full sternotomy is more practical than the other small thoracotomy techniques. Only reverse-J-inferior ministernotomy can obstruct proximal anastomosis on the ascending aorta if any free graft is used for bypass surgery [42]. The rest of the surgical revascularization is similar to the conventional CABG procedures. Reverse-J-inferior sternotomy approach preserves respiratory function postoperatively and accelerates the early postoperative recovery, especially in ACAB [43]. T-ministernotomy causes less chest tube drainage, and shorter recovery with early discharge [44].

#### 6.5. **TECAB**

Robotically assisted totally endoscopic coronary bypass surgery (TECAB) is the most advanced form of less invasive surgical coronary revascularization, which can be an elegant surgical component to hybrid revascularization. However, procedural complexity and a steep learning curve have limited its penetrance in the surgical community. The procedure can be applied on on-pump or off-pump. There are several instruments for anastomoses, but on-pump is more acceptable. Peripheral cannulation is the main disadvantage in some patients, who are not candidates for TECAB.

#### 6.6. **ACAB**

Awake coronary artery bypass (ACAB) surgery has been offered as a new and unique technique to decrease the adverse effects of general anesthesia. This new modality of CABG combines the minimal invasive nature of MIDCAB with the avoidance of endotracheal intubation and mechanical ventilation. Due to its nature, ACAB offers several advantages over general anesthesia, including better analgesia, decreased myocardial ischemia, improved pulmonary function, reduced stress response, and discharge in couple days of surgery. Cardiac sympathectomy achieves bradycardia, coronary and arterial grafts' vasodilatation and prevents arrhythmia. The aim of this technique is to provide somatosensory and motor block at the T1 and T8 levels and motor block of the intercostal muscles while preserving diaphragmatic respiration. Thoracic sympathectomy allows complete arterial revascularization with bilateral

IMAs with/without RA [45]. A perfect understanding and cooperation between patient and anesthesiologist is necessary for ACAB, while an excellent collaboration between cardiac surgeon and anesthesiologist provides a flawless procedure. Combining advanced anesthetic and high-level surgical merit, this alternative CABG procedure makes surgical treatment feasible and suitable for patients who are not candidates for conventional general anesthesia with endotracheal intubation.

## 7. Special circumstances

Coronary artery surgery is not unique because of other tissue and/or organ pathologies (Table 10). Coronary revascularization can be performed isolated in patients with single- or multi-vessel disease or combined with other coronary artery interventions and/or cardiac procedures. Associated non-coronary arterial pathologies can make CABG procedures more complex. Surgical strategies for diffuse CAD are discussed in the next chapter.

A. Associated cardiac pathologies
1. Ascending aorta diseases
2. Left ventricular dysfunction
3. Ischemic mitral insufficiency
4. Valvular lesions
5. Congenital pathologies
6. Coronary anomalies
B. Acute coronary syndrome
C. Associated acute mechanical complications of myocardial infarction
1. Mitral regurgitation
2. Ventricular septal defect
3. Free wall rupture
4. Congestive heart failure
D. Associated non-coronary arterial pathologies
1. Carotid artery disease
2. Abdominal aorta pathologies
3. Peripheral arterial diseases
4. Venous diseases
E. Combined diseases
1. Renal disease
2. Diabetes mellitus
3. Malignancy
4. Chronic obstructive pulmonary disease

Table 10. Special situations

### *Ascending Aorta Pathologies*

Ascending aortic pathologies can be treated with different methods. Ascending aortic atherosclerosis can be a very important risk factor for distal embolization, especially for stroke. Epiaortic ultrasound is the only method to identify the extent of atherosclerosis of the ascending aorta. Severe atherosclerosis of the ascending aorta forwards surgeons to the right axillary or femoral artery cannulation. Coronary bypass is performed with “no-touch technique” using only pedicled arterial conduits or composite grafts (T- or Y-graft). If aortic valve replacement is required, the ascending aorta replacement will be performed. Ascending aortic aneurysm and/or dissection required a composite graft replacement during CABG; proximal anastomoses can be performed easily on the tubular graft or composite conduits can be used.

### *Left Ventricular Dysfunction*

Nowadays, most patients with multivessel disease are candidates for surgical revascularization, but the depressed left ventricular function could be a serious contraindication for surgery or risk factor for early adverse outcomes. Resting regional perfusion defects and LV systolic function are improved after CABG in at least 65% of patients with LVD. However, preoperatively depressed resting global left ventricular systolic function cannot change less than 2 weeks after surgery. If this improvement fails to occur, incomplete revascularization or early graft failure is usually found. When preoperative global LVD is severe (LVEF < 30%), myocardial scarring is usually greater and limits recovery of left ventricular function. Complete revascularization is more effective than CABG strategy for myocardial recovery, and there is no reason to prefer OPCAB with incomplete revascularization [46].

### *Ischemic Mitral Regurgitation*

Ischemic LVD represents the first leading cause for mitral regurgitation (MR), which can alter the spatial relationship between the papillary muscles and chordae tendineae and thereby results in functional MR. Some degree of functional MR is found approximately 30% of patients undergoing CABG. In most cases, MR develops from tethering of the posterior leaflet because of regional LVD. The incidence and severity of MR vary inversely with the LVEF and directly with the left ventricular end-diastolic pressure. Correction of reversible ischemia changes the left ventricular geometry and functional MR can decrease or it can be corrected intraoperatively using a ring. The new designed 3D mitral rings are useful, but MR can worsen with time if the left ventricular remodeling continues.

### *Valvular Pathologies*

Nonischemic mitral valve diseases are not common with CAD, but they are not contraindications for coronary surgery. Mitral stenosis is rare, but mitral valve resection with subvalvular apparatus does not decrease left ventricular function. Degenerative mitral valve regurgitation can be associated with LVD; in this situation, subvalvular apparatus should be preserved to prevent the limited left ventricular function. Tricuspid regurgitation is a rare pathology and seen mostly secondary to the left-side valvular diseases, and can be a sign of pulmonary hypertension.

Degenerative aortic stenosis is the most common associated cardiac pathology because of advanced age of CAD patients. Aortic stenosis can be moderate or severe, but asymptomatic. The decision for aortic stenosis may be mixed. If CABG is the decisive indication, the indication for moderate aortic stenosis is more flexible and aortic valve replacement should be performed to prevent patients from reoperation. Aortic valve stenosis with moderate signs (mean gradient  $> 30$  mmHg; aortic valve area  $1\text{--}1.5\text{ cm}^2$ ), pathologic bicuspid aortic valve, or severe annulo-valvular calcification can indicate for associated aortic valve replacement. Stentless biological valves must be the first choice if the aorticoventricular continuity is not disturbed [47].

#### *Acute Coronary Syndrome*

Acute coronary syndromes cover a wide spectrum of CAD, while non-ST-segment elevation is the best and risk-free indication for early CABG, if stent implantation is ineffective. Isolated and limited elevation of troponin is not a contraindication for early surgical treatment. Surgical revascularization can be postponed in patients with transmural myocardial infarction without life-threatening complications. But, acute hemodynamic deterioration is a serious and often fatal complication of ongoing myocardial infarction, and delay of CABG can be disadvantageous.

#### *Carotid Artery Disease*

Carotid artery disease is an important risk factor of stroke after CABG, especially in the older age group, and the prevalence is higher than 30%. Routine carotid sonographic evaluation is the most widely used preoperative screening test to detect important asymptomatic carotid artery stenosis. If the preoperative carotid Doppler study demonstrates significant stenosis ( $>80\%$ ), it must be verified by arteriography. Combined surgical revascularization has been used in most centers with two different approaches: concomitant or staged. In both approaches, carotid endarterectomy is performed primarily to prevent stroke. When a concomitant procedure is performed, carotid endarterectomy can be performed during hypothermic CPB before CABG, which provides additional brain protection [48]. Neither strategy has not been proved to be superior to another, and an individualized approach is most appropriate. Preoperative stenting is a more suitable alternative approach to combine carotid endarterectomy and CABG.

#### *Abdominal Aortic Disease*

When an abdominal aortic pathology is elective, it should be postponed after CABG. The combination of an abdominal aortic aneurysm and CAD can be seen more common in elderly patients. A combined procedure can be necessary in patients with unstable CAD and abdominal aortic aneurysm. Combined surgical treatment using CBP is a safe and effective strategy. Because conventional surgery can increase complications postoperatively, any minimal invasive combined approach can improve early postoperative outcomes.

#### *Peripheral Vascular Disease*

Patients with CAD and peripheral atherosclerosis are older and have more widespread vascular disease with/without end-organ damage. Coronary atherosclerosis is usually diffuse and requires more complicated surgical revascularization. Left subclavian artery stenosis is a

major contraindication for harvesting LIMA, but left subclavian artery bypass or stent implantation can increase LIMA flow. In this situation, RIMA can be used as a pedicled graft to LAD, or LIMA can be used as a free graft. Iliac artery stenosis with LIMA collateral circulation is another contraindication for LIMA-LAD anastomosis, but peripheral artery revascularization can solve this problem. Except severe peripheral stenosis, staged surgical approach should be preferred (CABG first).

#### *Chronic Renal Failure*

One of the main reasons of death in 40 to 50% of patients on hemodialysis is coronary atherosclerosis. It is well known that cardiac pathologies have more serious outcomes if the established renal failure is concomitant, especially the progression of the CAD is more accelerated in hemodialysis patients. Calcification of the coronary territory is a serious complication of long-term hemodialysis and complicates surgical revascularization. Cerebral and/or visceral vascular complications related to accelerated atherosclerosis and particle embolization after CABG are seen more often in patients with end-stage renal failure than in other patients. Hemodialysis-dependent patients are at high risk of CPB-related complications such as bleeding, volume overload, and cerebrovascular events during conventional CABG, whereas OPCAB surgery can be the optimum revascularization strategy to prevent these complications [49].

#### *Malignancy*

Recently, cardiac disease and malignancy are seen together more frequently in patients undergoing surgical revascularization. Cancer therapy should be applied as soon as possible after diagnosis; however, patients with high risk of a major cardiac event should take cardiac surgery as a priority. Conventional open cardiac surgery causes a transient immunosuppression due to increasing immunoregulatory factors. Although these biochemical changes are short term and not likely to induce carcinogenesis, they may lead to cancer surveillance with the spread and growth potential of coexisting cancer cells. Overall mortality increases after open heart surgery, and a shorter time interval (especially < 2 years) between the cancer diagnosis and subsequent cardiac surgical intervention can aggravate cancer-specific deaths. Results of a multicenter research show that on-pump CABG surgery with CPB increases significantly the relative risk of skin melanoma, cancer of the lung and bronchus, and overall cancer incidence when compared with those patients who underwent OPCAB [50]. Off-pump myocardial revascularization must be preferred over the use of CPB in combined surgery to prevent the adverse effects of the extracorporeal circulation, especially during lung surgery [51]. Further researches may obtain optimal strategies for management of cancer patients with cardiovascular comorbidities.

#### *Chronic Obstructive Pulmonary Disease*

Chronic obstructive pulmonary disease (COPD) is often considered as a risk factor for postoperative outcomes after CABG, but the presence and worsening of COPD do not show any increase in mortality following surgical revascularization in patients with COPD compared with normal patients. However, severe COPD patients have more frequent pulmonary infections, atrial fibrillation, and a longer hospital stay when they are compared with mild to



moderate COPD patients and patients with normal spirometry. Cardiopulmonary bypass has adverse effects on the alveolar stability by activation of the complement cascade, sequestration of the neutrophil in the pulmonary vascular territory, release of the oxygen-derived free radicals, and change of the composition of alveolar surfactant. Atelectasis is the most observed complication after CPB and mechanical ventilation, especially in the first two days after the operation. Because patients with COPD are affected negatively from adverse effects of both CPB and full median sternotomy in the mean of postoperative pulmonary complications, it seems more advantageous that this patient group will be operated on using OPCAB, especially with minimal invasive techniques [52].

## 8. Outcomes

Because CABG is probably the most performed procedure in cardiac surgery, an enormous amount of information is available about morbidity and mortality, and also long-term survival. Comparison with stent can never give us the real world results, because every patient has his/her specific risk analysis. The early mortality and morbidity rates for isolated CABG are stabilized (Table 11) [53].

Preoperative Characteristics	
Age (years)	65 (58 – 73)
Male	74.8%
Body Mass Index	29 (26 – 33)
Hypertension	88.3%
Dyslipidemia	87.5%
Diabetes Mellitus	46%
Peripheral vascular disease	14.4%
Stroke	7.3%
Dialysis	4.8%
Cardiac Characteristics	
Previous myocardial infarction	47%
Previous stent	25.3%
Previous CABG	1.32%
Presentation of NSTEMI	23.7%
Three-vessel disease	79.4%
Left main disease	33.8%
Proximal LAD disease	56.9%



Operative Characteristics	
Elective	42.2%
OPCAB	16.6%
Full median sternotomy	98.5%
IMA harvesting technique (standard direct vision)	98.9%
IMA use	100%
LIMA	94%
BIMA	5.1%
Operation durations (minutes)	
Cardiopulmonary bypass	91 (71 – 115)
Skin-to-skin	225 (183 – 275)
Operating room	301 (253 – 359)
Any blood products used	31.4%
RBC	2 units
Early Outcomes	
Operative mortality	1.5%
Mortality or morbidity	11.8%
Permanent stroke	1.2%
Re-exploration	2.2%
Renal failure required dialysis	1.8%
Prolonged ventilation	8.2%
Mediastinitis	0.3%
Surgical site infection	1.2%
Sepsis	0.7%

**Table 11.** STS-database for isolated CABG (July 2011 – March 2013; N = 197,672)

### *Operative Mortality*

The risk profile of patients with isolated CAD has changed in the past decade and they have more complicated comorbidities: older age, LVD, accelerated coronary atherosclerosis, a higher burden of non-coronary atherosclerotic disease, re-operation, emergency operation, multi-stent application, multi-organ pathologies. However, early outcomes after CABG continue to improve and the early cumulative mortality rate is below 2%, lower than 1% in lower-risk patients. The most common reasons for death are heart failure (65%), neurologic events (7.5%), hemorrhage (7%), respiratory failure (5.5%), and dysrhythmia (5.5%).

### *Long-Term Survival*

The survival rate after isolated CABG is higher than 98% for the first month and 97% for first year, 92% for 5 years, 80% for 10 years, 65% for 15 years, and 51% for 20 years. Late mortality depends on non-use of ITA, closure of grafts, progression of native coronary atherosclerosis, and also comorbidities. Procedure-related factors that influence long-term survival include complete revascularization, selection of bypass grafts, and intraoperative myocardial protection. Mortality rate is the highest in the first month, but it is parallel to that of general population after the first postoperative year. Time-related prevalence of sudden death is low after CABG (at least, 95% for the first 10 years) and the most significant risk factor for sudden death is LVD.

### *Quality of Life*

Satisfactory quality of life after CABG is the most important and favorable outcome for all patients who quantify that according to freedom from angina, heart failure, re-hospitalization or re-intervention, and to improvement of a reasonable exercise capacity. Maximal exercise capacity is generally improved at least for 3 to 10 years after CABG, whereas degree of recovery and ultimate exercise capacity reached depend on preoperative LV function, completeness of revascularization, and long-term graft patency. When preoperative global LV dysfunction is severe ( $EF < 30\%$ ), myocardial scarring usually affects a wide area and limits improvement of LV function. But, incomplete revascularization of viable myocardium is the primary cause of the failure of postoperative recovery. Global LV function during exercise begins to increase noticeably 2 weeks after CABG in most patients; however, when it still does not improve in 3 months after CABG, one or more bypass grafts are usually occluded or stenosed.

### *Recurring Myocardial Ischemia*

Return of angina is the most common post-CABG ischemic event. Freedom from angina is approximately 95% at 1 year, 80% at 5 years, 60% at 10 years, 40% at 15 years, and 20% at 20 years. Return of angina during the first 6 months depends on incomplete revascularization or graft failure, whereas progression of native-vessel disease and grafts are serious risk factors for the late recurrence of angina. Including perioperative myocardial infarction, the overall freedom from new myocardial infarction after first surgical complete revascularization is 95% at least 5 years, 85% at 10 years, 75% at 15 years, 55% at 20 years. The overall freedom from any re-intervention (stent or re-CABG) is about 97% at 5 years, 90% at 10 years, 70% at 15 years, and 50% at 20 years. Venous graft occlusion (incidence: 15% at the first year, and 60% at 10 years) is the most common reason for re-intervention, and progression of atherosclerosis in the native coronary arteries (incidence: 50% at 10 years) is the second. Using IMA(s) reduces the frequency of reoperation, but not the frequency of stent implantation. Requirement of reoperation begins to rise noticeably after 5 years and it is usually preferred when the left main or LAD disease is life threatening. Because the operative risk is double in the second CABG than those in the primary, stent implantation with the assistance of embolic protection devices for stenotic vein grafts or native vessels is used more often in symptomatic patients with patent IMA-LAD anastomosis.

### *Early Postoperative Complications*

1. Perioperative myocardial infarction is defined by appearance of new Q waves or significant elevation of myocardial biomarkers. It relates with early or late death and also with

postoperative ischemic cardiomyopathy. It depends on inadequate myocardial preservation, incomplete revascularization or graft failure. Prevalence of perioperative myocardial infarction is between 2.5 and 5%. Early renewing or completing revascularization of the target vessels can be lifesaving.

2. Low cardiac output syndrome varies between 4 and 9% and develops during or after the operation and increases operative mortality 10- to 15-fold. Inotropic supports with/without intra-aortic balloon pump support or mechanical circulation support must be used to maintain a systolic blood pressure > 90 mmHg or a cardiac index > 2.2 L/min/m<sup>2</sup>.
3. Adverse neurologic events after surgery can be major or minor. Type 1 deficits (stupor, coma) are more fatal, but the incidence is lower than 1.5%. Severe atherosclerosis of the ascending aorta and/or severe stenosis with/without any calcification in the carotid arteries are the most common risk factors for the type 1 neurologic events. Type 2 deficits are characterized by deterioration of intellectual function and memory, but it is more difficult to characterize. The risk factors are CPB, aortic manipulation, or air embolization. Off-pump is not superior to on-pump, but avoidance of proximal anastomoses on the ascending aorta can prevent type 2 neurologic deficits.
4. Renal failure can develop after cardiac surgery and the incidence of renal dysfunction not requiring dialysis rises to 6.5%, but requiring hemodialysis is below 1.5%. Operative mortality rate is directly related to patients' renal functions: proximately 1% with good renal function, 20% with renal dysfunction, 60% with renal dysfunction and dialysis. Older age (< 70 years), LVD, diabetes mellitus with silent renal dysfunction, preoperative renal dysfunction (creatinine > 2 mg/dL), and LCOS are the major risk factors for postoperative renal failure. Off-pump CABG can be a more appropriate alternative for complete revascularization in patients with chronic renal failure or patients with estimated postoperative renal dysfunction.
5. Deep sternal wound infection carries a mortality rate of 25%. Obesity and diabetes are strong independent risk factors for mediastinitis, whereas reoperation, re-exploration for bleeding, and blood transfusions are other variables. The use of bilateral IMAs does not increase mediastinitis risk, especially with skeletonization technique. However, bilateral IMA harvest must be avoided in obese diabetic women or patients with severe COPD. In spite of all the recent advances in open cardiac surgery, mediastinitis still is an important risk factor for early mortality, but it does not affect the graft patency [54].

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