

Conduits Used in Coronary Artery Bypass Grafting: A Review of Morphological Studies

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There is a significant variety of vascular conduits options for coronary bypass surgery. Adequate graft selection is the most important factor for the success of the intervention. To ensure durability, permeability, and bypass function, there must be a morphological similarity between the graft and the coronary artery. The objective of this review was to analyze the morphological characteristics of the grafts that are most commonly used in coronary bypass surgery and the coronary arteries that are most frequently occluded. We included clinical information regarding the characteristics that determine the behavior of the grafts and its permeability over time. Currently, the internal thoracic artery is the standard choice for bypass surgery because of the morphological characteristics of the wall that makes less prone to developing atherosclerosis and hyperplasia. The radial and right gastroepiploic arteries are the following second and third best options, respectively. The ulnar artery is the preferred choice when other conduits are not feasible.

Keywords: conduits, coronary artery bypass grafting, histology, morphology, permeability

Introduction

Cardiovascular disease is the leading cause of death worldwide, accounting for 31% of all registered deaths, and is expected to continue in this position until 2030.¹⁾ The most common of these is the coronary heart disease or coronary artery disease,^{2,3)} which represents the leading cause of death in developed countries.

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The main etiology of coronary artery disease is atherosclerosis, a multifactorial, chronic inflammatory process. Obstruction of blood flow is caused by plaques formed from fatty deposits in the walls of blood vessels and endothelium. The degree of obstruction of the vessel determines the treatment needed, either pharmacological or surgical.³⁾

Today, surgical treatment is widely used and it may vary from percutaneous angioplasty (coronary stent) to coronary artery bypass grafting (CABG).^{2,4)} This surgery has proven to be one of the most effective and lasting therapies for ischemic heart disease.^{3,5,6)} A lower mortality, better symptoms alleviation, and lower reoperation have been reported when compared to angioplasty.⁷⁾

Arteries or veins may be used in CABG as a graft to redirect blood to an area of the coronary artery, distal to the blockage.⁷⁾ The objectives of this procedure are to improve survival and alleviating symptoms.⁸⁾ The main concern with this intervention is precisely the duration and functionality of the graft used. In order to achieve

this, it is necessary to complete the revascularization using ducts that will remain permeable for all or most of the patient's life.^{4,9)}

There is a wide variety of vascular conduits available for CABG. The most commonly used are as follows: internal thoracic artery (ITA), saphenous vein (SV), radial artery (RA), right gastroepiploic artery (RGEA), and occasionally ulnar artery (UA), splenic artery, and inferior epigastric artery.²⁾ Such diversity of options has caused controversy and a consensus regarding which one is superior has not been fully established.¹⁰⁾

The graft selection for the CABG is the most important factor in patient survival.^{2,6)} This choice has been based on the surgeon's preference and experience, as well as the surgical protocols established by each hospital.¹¹⁾ In order to determine the best choice, the surgeon must consider the patient's past medical history: age, cholesterol levels, smoking, and hypertension, among other comorbidities.^{8,10)} The morphological characteristics of the graft and the coronary arteries are also one of the most important criteria.^{4,10)}

The morphological similarity between the graft and the coronary artery is important in order to promote durability, permeability, and good functioning of the bypass.^{10,12)} The most important morphological features to consider are length, luminal diameter, wall thickness, and histological characteristics of the conduit.^{4,10)}

The objective of this review is to analyze the morphological characteristics of the conduits used in CABG: the SV, ITA, RA, UA, and RGEA. The most frequently occluded coronary arteries used are as follows: anterior interventricular artery (AIA), circumflex artery (CX), and right coronary artery (RCA).^{13–16)} For each vessel, the following parameters are reviewed: length, luminal diameter, thickness of the intima and media, and histological features of the wall. Clinical information regarding the characteristics that determine the behavior of the grafts during surgery and its permeability over time is also provided.

Coronary arteries

The coronary arteries' segments that have a higher incidence of occlusions are AIA, CX, and RCA.^{13–16)} There is insufficient evidence evaluating the specific segments of the coronary arteries where atheromas are most often located, or their size. It is reported that most atheromas occupy the proximal segments,^{13,17)} and these are usually the largest.¹⁷⁾ This is most likely because these segments have a greater luminal diameter. Atheromas'

size is important because the severity of coronary artery disease is one of the factors that determine the graft selection for CABG.¹⁰⁾

The coronary arteries' anatomy and its variants are well described in the literature. The anatomical variations many times influence the method indicated for CABG. The most common is the right coronary dominance, with a prevalence of between 76% and 85%, followed by the balanced circulation with a frequency of 7.5%–17%, and finally left dominance with 6.8%–7.5% prevalence.^{17–19)} Morphological characteristics of each artery from several studies are described in **Table 1**.

There are few studies reporting the length of the coronary arteries, which may vary between populations.^{17,20)} A study in Turkish population reported a mean length of 9.38 ± 1.84 cm for AIA, 6.60 ± 1.53 cm in RCA, and 5.70 ± 1.20 cm in CX.²⁰⁾ In contrast, a study involving a Mexican population reported mean lengths of 15.66 ± 1.12 cm for AIA, 12.69 ± 1.94 cm for RCA, and 8.89 ± 2.11 cm for CX.¹⁷⁾

The luminal diameter is the most studied and irregular parameter. Most studies only analyzed a single segment,^{19–23)} whereas others analyzed the segments that are most often occluded¹⁷⁾ or an unspecified segment (Barry et al., 2007²⁴⁾; Ballesteros and Ramirez, 2008²⁵⁾) (**Table 1**).

The thickness of the intima and tunica media is rarely evaluated (**Table 1**). The AIA, RCA, and CX are muscular arteries, with a tunica media bounded by two distinct internal and external elastic laminae.^{21,24)} The amount of elastic fibers in the tunica media is low, being only 2–7 fibers.¹⁷⁾

Saphenous vein

Favaloro (1968) reported the first CABG using the SV as a graft.^{4,26)} During the first decades, the SV was the most used conduit, as it has sufficient length and diameter, coupled with the absence of atheromas,²⁾ and it is easily available.²⁷⁾ However, because the permeability is compromised due to its adaptive histological changes such as intimal hyperplasia and atherosclerosis,^{5,27,28)} arterial grafts have demonstrated to be superior to venous.^{2,4,27)} Thus, international guidelines recommend arterial conduits, specifically the ITA, as the gold standard.^{2,8,29)}

However, the use of vein grafts has gradually increased in recent years.³⁰⁾ This may be due to the development of the "no touch" vein harvest technique. This procedure involves harvesting a SV with the perivascular tissue intact without direct contact or manipulation of the vein

Table 1 Morphological studies on the coronary arteries that occlude most frequently

Author	Sample	Vessel	Results	
			Luminal diameter (mm)	Tunic thickness of the intima media (μm)
Barry et al., 2003 ²¹⁾	20 cadavers	AIA RCA CX	M: 1.6 (1–3) P: 3.2 (2.5–4.5) U: 2 (1–5.3)	
Unlü et al., 2003 ²⁰⁾	7 cadavers	AIA	M: 2.53 ± 0.86	M: 299 ± 42
	8 autopsies	RCA	M: 1.98 ± 0.67	M: 226 ± 36
	14 patients	CX	M: 1.62 ± 0.44	M: 271 ± 33
Barry et al., 2007 ²⁴⁾	40 cadavers	AIA	U: 1.6 ± 0.3	
		CX	U: 2.2 ± 0.4	
Ballesteros et al., 2008 ²⁵⁾	154 cadavers	AIA	U: 2.94 ± 0.5	
		RCA	U: 3.8 ± 0.52	
		CX	U: 2.71 ± 0.54	
Ballesteros et al., 2011 ¹⁹⁾	221 cadavers	RCA	P: 3.42 ± 0.66 D: 2.0 ± 0.5	
			Men Women	
Ilayperuma et al., 2011 ²²⁾	102 cadavers	AIA	P: 3.96 ± 0.99	P: 3.72 ± 1.18
		RCA	P: 5.99 ± 1.23 M: 5.28 ± 1.45	P: 4.73 ± 1.82 M: 4.32 ± 1.92
		CX	P: 3.94 ± 1.34	P: 3.73 ± 0.78
Aroche et al., 2013 ²³⁾	386 angiographs	AIA	Men P: 3.59 ± 0.69	Women P: 3.68 ± 0.83
		RCA	P: 3.46 ± 0.67	P: 3.16 ± 0.89
		CX	P: 3.24 ± 1.05	P: 3.25 ± 0.88
Martínez et al., 2015 ¹⁷⁾	11 cadavers	AIA	P: 2.37 ± 0.47	P: 354.39 ± 98.72
			M: 1.50 ± 0.31	M: 218.79 ± 113.36
			D: 1.12 ± 0.31	D: 117.59 ± 34.41
		RCA	P: 2.31 ± 0.76	P: 396.31 ± 105.47
			D: 1.81 ± 0.43	D: 305.52 ± 111.08
			P: 2.33 ± 0.57	P: 361.37 ± 132.42
CX	D: 1.51 ± 0.43	D: 227.59 ± 118.11		

This table shows the results of various morphological studies on the coronary arteries that occluded most frequently. AIA: anterior interventricular artery; RCA: right coronary artery; CX: circumflex artery; P: proximal segment; M: medial segment; D: distal segment; U: single segment/unspecified

itself, thus avoiding distension prior to anastomosis,^{31,32)} which can cause intimal and medial hyperplasia, leading to graft failure.³¹⁾

When using conventional or manual dilatation technique, the SV is often stripped of its adventitial layer and distended, causing damage to the wall.³³⁾ The luminal diameter of the vein increases, causing the loss of the characteristic folds in the tunica intima,³¹⁾ as well as modifications in the tunica media morphology and smooth muscle cell distribution.³¹⁾ Also these cells are genetically activated, which lead to an increased and uncontrolled proliferation and migration to the tunica intima, diminishing the graft permeability.³¹⁾

In contrast, when the “no touch” harvesting technique is used, it provides better structural, functional, and mechanical protection of the vein wall, resulting in a

long-term improvement.³³⁾ The morphological characteristics of the vein, such as the luminal diameter,³¹⁾ the collagen in the tunica adventitia,³²⁾ the circular distribution pattern of the smooth muscle cells in the tunica media,³¹⁾ and the endothelium in the tunica intima, remain intact.³²⁾ The *vasa vasorum* and the expression of the nitric oxide synthase in the tunica intima increase, whereas the atherosclerotic process is reduced.³²⁾

Studies using a “no touch” or low manipulation technique report that long-term results are similar and compatible to those of arterial grafts.⁹⁾ Permeability rates using this procedure are of 83% at 16 years compared to an 88% in arterial grafts.⁹⁾

Regarding the morphology of the SV, a Turkish study reported a mean length of 72.42 ± 6.60 cm.²⁰⁾ The luminal diameter varies in proximal, medial, and distal segment

with 5.24 ± 0.62 mm, 3.25 ± 0.51 mm, and 1.67 ± 0.29 mm, respectively.²⁰⁾ The thickness of the media and intima also varies, with 291 ± 35 μ m, 200 ± 31 μ m, and 143 ± 32 μ m, respectively, for each segment.²⁰⁾

The SV has a thin intima covered by a layer of endothelial cells. It is separated from the tunica media by a rudimentary internal elastic lamina, which is discontinuous and irregular. Its tunica media contains two layers of smooth muscle cells, a thick internal layer made up of longitudinal collagen fibers, and a thick outer circular layer.^{34–36)} The internal longitudinal layer is thicker when valves are present.^{35,36)} The adventitia is composed of connective tissue, collagen and elastic fibers, and longitudinal smooth muscle cell fibers.^{34–36)} It also has *vasa vasorum*, which can reach the tunica media.³⁴⁾

Various studies report the changes in the vein's morphology prior to its use as a graft in CABG.^{35,37,38)} The changes reported are as follows: fibrosis of the intima with the presence of elastic fibers, collagen, and smooth muscle cells, causing narrowing of the lumen; elastosis of the internal elastic lamina, and hypertrophy of the longitudinal layer of the tunica media.^{35,37,38)} These changes may have implications for graft failure, contributing to the development of cell proliferation in the intima, thus causing graft occlusion.^{35,37)}

The changes that occur in the intima are associated with the changes in the tunica media; this indicates that there is a common etiology.^{37,38)} Although these injuries are considered part of the aging process, the study by Thiene et al. (1980) analyzed 150 SV prior to CABG, dividing patients by age, and revealed that these changes do not correlate with the age of patients. They also recommended reviewing the morphology of the vein prior to use, to discard useless grafts and use alternative conduits.³⁵⁾ The permeability of the SV is 50%–60% at 10 years^{2,4,28)} and 20% at 20 years.²⁸⁾ Graft failure causes recurrent ischemic symptoms and clinical deterioration, requiring new revascularization procedures, which are less effective and generate higher risks and costs.²⁶⁾

Internal thoracic artery

Vineberg (1946) was the first to use the ITA as a graft in CABG.^{2,39)} Currently, it is considered the standard for CABG and is recognized by cardiothoracic surgeons as the most effective and reliable conduit due to its excellent permeability, lower incidence of adverse events, and greater long-term survival for the patient.^{2,4,5,8,29,40–42)} The higher permeability of this conduit is attributed to the morphological characteristics of the wall,^{5,40–43)} as its

histological structure makes it relatively free of atherosclerosis as well as from intimal hyperplasia.^{29,40–44)}

Both left and right ITAs can be used either in situ or as a free graft.^{5,29)} The left ITA is used more often than the right because of its location and proximity to the heart, allowing for a better anastomosis.²⁾ Using the left ITA to re-establish circulation to the AIA remains unchallenged in the CABG.^{2,5)} When AIA does not need revascularization, it is used to revascularize the most important coronary artery.⁵⁾ The right ITA may be used to revascularize branches of the left coronary or branches of the CX; however, it is inaccessible for hemostasis or verification of permeability. Because of this, it is commonly used to bypass the RCA in its middle or distal segment, or if its length is sufficient, the posterior interventricular artery (PIA).⁵⁾

Morphological studies report that the ITA does not present a uniform structure along its length, and is known as a transitional artery.^{40–43)} This may have implications regarding its use and thus interfere with the results of CABG,⁴⁴⁾ and this is the reason why the morphology of specific segments is important. There are studies that evidence differences between the left and right ITA,⁴²⁾ as well as they report similarities in their structure.⁴⁴⁾

This vessel has a reported length ranging from 14.32 to 19.48 cm.^{4,20,45)} A study by Henriquez et al. using 100 bodies demonstrated that the length difference between the two ATI was minimal, reporting 20.7 cm in the left and 20.1 cm in the right.⁴⁵⁾

Results of various morphological studies of ITA, where the luminal diameter and the thickness of the tunica intima and media are determined, are shown in **Table 2**. The luminal diameter in the proximal segment varies from 2.12 to 2.75 mm and 1.03 mm to 1.75 mm in the distal segment.^{20,46)} Comparative studies of the right and left ITA report a luminal diameter of 1.72 mm and 1.76 mm, respectively.¹²⁾ Although in studies in which unspecified segments were evaluated, the luminal diameter ranged between 1.6 and 2.75 mm.^{4,5,21,24)} In studies in which the artery segment evaluated is not specified, a wall thickness of 350 μ m is reported.^{5,41)}

The amount of elastic fibers in the tunica media varies along with the length of the ITA.^{41,43)} The middle segment is the one with the most elastic fibers present, with nine fibers; the proximal segment has six fibers, and the distal segment three fibers.⁴¹⁾ Comparative studies show that there are significant differences in the amount of elastic fibers between the two ITA, being higher on the left than on the right.⁴²⁾ Other studies that

Table 2 Morphological studies on the internal thoracic artery

Author	Sample	Results		
		Luminal diameter (mm)	Tunic thickness of the intima media (μm)	Number of elastic fibers
Barry et al., 2003 ²¹⁾	20 cadavers	U: 1.5 (1–2.5)		
Unlü et al., 2003 ²⁰⁾	7 cadavers	P: 2.12 ± 0.27	P: 253 ± 43	
	8 autopsies	D: 1.03 ± 0.17	D: 139 ± 37	
	14 patients			
Kneubil et al., 2006 ⁴⁰⁾	18 cadavers		U left: 218.3–257.7	13.1–20.4
Barry et al., 2007 ²⁴⁾	40 cadavers	U: 1.6 ± 0.3		
Ribeiro et al., 2008 ⁴²⁾	18 cadavers		U right: 156–262	10–16
			U left: 205–270	12–21
Borović et al., 2010 ⁴³⁾	42 arteries of autopsies		U: 12.57–22.15	
Appleson et al., 2012 ¹²⁾	7 cadavers	U right: 1.72	U: 0.22	27.20
		U left: 1.76	U: 0.17	30.31
Kinoshita et al., 2014 ⁴⁴⁾	144 segments from 72 patients	U right: 1.60	U: 172	
		U left: 1.52	U: 169	

This table shows the results of various morphological studies of ITA. P: proximal segment; D: distal segment; U: single segment/unspecified

determine the number of elastic fibers in the ITA are shown in **Table 2**.

Histologically, the ITA is an elastic artery,^{5,21,24,43)} which could explain its excellent long-term patency, as it is mentioned that, the more elastic the graft is, the greater its permeability will be over time.¹⁰⁾ The intima is thin and the tunica media is delimited by a thick and well-defined internal elastic lamina.^{5,43)} The tunica media has two sublayers: an internal and an external layer.⁴³⁾ The internal layer is muscular, composed mainly of smooth muscle cells with few elastic fibers that are not well formed.⁴³⁾ The external layer is elastic, composed mainly of well-defined elastic fibers with few muscle cells.⁴³⁾ The compact structure of the internal elastic lamina is a possible explanation for the low incidence of developing intimal hyperplasia.⁴³⁾

The permeability of the ITA is superior to that of all other conduits used in CABG.^{2,5,28,40–42)} The left ITA, when anastomosed with the AIA, has a permeability of 99% at 5 years, 97% at 10 years, 90%–95% at 15 years, and 90% at 20 years.^{2,4,5,28)} When anastomosed with the CX, its permeability is 97% at 5 years, 92% at 8 years, 89% at 10 years,⁴⁾ and 91% at 15 years.⁵⁾ When anastomosed with the RCA, permeability descends to 84% at 15 years.⁵⁾ The right ITA has a permeability of 80%–90% at 10 years when anastomosed with the RCA.²⁾ Other studies report a 91.9% permeability with the AIA, 90.1% with the CX, and 83.1% with RCA.⁴⁷⁾

Radial artery

Carpentier (1973) was the first to use RA for CABG,^{2,4,47–49)} and is currently considered the second best conduit after the ITA.^{4,5,47,50)} In recent years, it has gained popularity as a graft for CABG because of its multiple morphological and surgical advantages that make it superior to other conduits.^{4,5,50,51)}

The features that make it a versatile graft for CABG are as follows: its vast length to reach distal coronary branches and perform multiple anastomoses,^{4,5,47,48,50)} a thickness that makes it comfortable to handle and easy to anastomose,^{4,5,48,50)} a diameter comparable to the coronary arteries,^{4,47,48,50)} its ability to adapt to high blood pressure,⁴⁸⁾ its removal is safe and easy,^{4,5,47,48,52)} and a remarkable permeability at short, medium, and long term.^{2,4,5,47,52)}

On the other hand, the RA does have some disadvantages; the important one is that due to its thick muscular tunica media, it is prone to early spasms.^{4,5,47,48,50,51)} However, the use of specific surgical techniques and pharmacological prophylaxis may prevent it.^{5,47)} Additionally, the prevalence of atherosclerosis and intimal hyperplasia is higher in RA than in the ITA and it can also present calcification in the tunica media (Monckeberg's Sclerosis) with a prevalence of 25%.^{50,51)}

The most widely accepted indication for RA use is revascularization of the second most important coronary artery in patients where the use of both ITA is contraindicated.⁵⁾ Usually, it is anastomosed with the RCA,^{2,4,5)}

Table 3 Morphological studies on the radial artery

Author	Sample	Results		
		Length (cm)	Luminal diameter (mm)	Tunic thickness of the intima media (µm)
Barry et al., 2003 ²¹⁾ Riekkinen et al., 2003 ⁵⁵⁾	20 cadavers Angiographs of 24 cadavers		U: 2.2 (1–2.5) D left: 3.0 ± 0.5 D right: 3.2 ± 0.5	
Unlü et al., 2003 ²⁰⁾	7 cadavers 8 autopsies 14 patients	22.28 ± 3.31	U: 2.20 ± 0.26	P: 321 ± 32 D: 161 ± 43
Appleson et al., 2012 ¹²⁾ Nasr, 2012 ⁵²⁾	7 cadavers 50 cadavers	Men 22.6 ± 21.7 Women 20.9 ± 13.9	U: 2.39 Men P: 3.3 ± 0.72 D: 3.1 ± 0.73 Women P: 3.2 ± 0.66 D: 3.0 ± 0.66	U: 254
Reyes et al., 2013 ⁴⁸⁾	10 cadavers	21.94 ± 3.34	P: 1.48 ± 0.70 M: 1.01 ± 0.35 D: 1.43 ± 0.47	P: 196.16 ± 72.35 M: 148.25 ± 40.40 D: 158.96 ± 45.74

This table shows the results of various morphological studies of ITA. P: proximal segment; M: medial segment; D: distal segment; U: single segment/unspecified

CX, or PIA^{4,5)} and its use in these vessels has been associated with satisfactory clinical and angiographic results.⁴⁾ Less frequently, it has been used to anastomose with diagonal branches or to bypass the AIA.⁵⁾

Complications in the forearm after extraction are rare when adequate preoperative assessment is performed.^{4,5,47,48)} Sensory neurological disorders are rare^{4,5)} with incapacitating symptoms present in less than 10% of patients, with most cases disappearing within days or weeks.⁵⁾

After grafting the RA in CABG, it undergoes functional and morphological remodeling characterized by increased luminal diameter, decreased muscle thickness with a conduit transformation from muscular to elastic/muscular, and initial loss of reactivity; these changes make it even more suitable as a graft for CABG.⁵⁰⁾ It is reported that the main cause of graft failure is spasm or hyperplasia.⁵¹⁾

Results of various morphological studies of the RA, where the length, luminal diameter, and thickness of the tunica intima and media are determined, are shown in **Table 3**. Reportedly, it has a length between 20 and 22.6 cm.^{4,20,46–48,50,52)} The luminal diameter reported in studies that do not specify the evaluated segment varies between 2 and 3 mm.^{12,20,21,47)} The wall thickness reported in studies do not specify the segment evaluated, varying from 254 to 529 µm.^{12,41)}

Histologically, the RA is a muscular artery.^{5,21,24,41)} It has a thin intima presenting mild to moderate hyperplasia⁵⁾ and a thick tunica media with abundant smooth muscle cells.^{4,5,41,47,51)} Reportedly, it has an 18.84% of elastic fibers in the tunica media.¹²⁾ Its internal elastic lamina is well defined and developed²¹⁾ although other studies mention the presence of multiple fenestrations, which would explain their susceptibility to atherosclerosis.^{5,47)} Its *vasa vasorum* does not penetrate the tunica media, assuming it does not require arterial supply, making it ideal for free graft use.⁴⁾

Studies have demonstrated that the RA has comparable clinical results to the ITA when used as a second graft, and has a better outcome when compared to the SV.⁵⁾ Complications are infrequent and it has a lower preoperative morbidity.⁵⁾ It also has a lasting permeability^{2,4,5,47,52)} and does not appear to be influenced by the target conduit when anastomosed.^{4,47)}

It has a permeability of 90%–95% in the first year,^{2,5,50)} 91% at 3 years,⁵⁰⁾ 87%–95% at 5 years,²⁸⁾ 83% at 7 years, 82% at 8 years,⁵⁰⁾ and 72%–84% at 10 years.⁵³⁾ When it is anastomosed with the AIA, permeability is 87% (significantly lower than the ITA), when used with the CX, permeability is maintained at 92% (similar to the ITA), and when used with the RCA or PIA, permeability is maintained at 88% (greater than the right ITA).⁴⁾ In addition, it is reported that 86% of patients were free of angina after 5 years²⁾ and that mortality is less than 1%–2%.⁴⁾

Table 4 Morphological studies on the ulnar artery

Author	Sample	Results	
		Length (cm)	Luminal diameter (mm)
Buxton et al., 1998 ⁵⁴⁾	8 patients	15	U: 2–3
Riekkinen et al., 2003 ⁵⁵⁾	Angiographs of 24 cadavers		U left: 2.4 ± 0.5 U right: 2.5 ± 0.5
Hinojosa et al., 2005 ⁵⁸⁾	10 cadavers	19.02 ± 1.88	P: 2.45 ± 0.09 M: 2.19 ± 0.09 D: 1.96 ± 0.09
Necomb et al., 2006 ⁵⁶⁾	25 patients	18	U: 2.4
Barry et al., 2007 ²⁴⁾	40 cadavers		U: 2.4

This table shows the results of various morphological studies of the AU. P: proximal segment; M: medial segment; D: distal segment; U: single segment/unspecified

Ulnar artery

Buxton et al. (1998) were the first to use UA as a graft in CABG.^{2,4,54)} Its use as a graft is not popular because the RA is preferred; this is due to studies that establish UA as the dominant artery in the forearm.^{2,4,54–56)} It is thought that its removal could result in functional disorders of the hand.²⁾ However, it has been used in surgical procedures of myocardial revascularization surgery and reconstruction with few local implications.⁴⁾

The use of the UA is limited to cases where the use of other conduits is not feasible^{2,56)} or when it is not considered safe to extract the RA.^{4,56)} Likewise, when the RA is the dominant blood supply to the hand, which may be the case in 5%–10% of cases.⁵⁴⁾ Other authors have proven the RA has increased flow and is larger than the UA, that is why it should be considered the dominant artery of the hand.^{4,55,56)} To determine the dominant artery of the forearm, appropriate clinical evaluation should be performed previous to the intervention, in order to have a safe extraction and lower risks.⁵⁶⁾

The UA can be removed from forearm safely, it is similar to the RA in characteristics of length and diameter size, which make it an ideal conduit for coronary graft use.^{56,57)} The biggest concern in relation to its use is the risk of injury to surrounding structures such as the ulnar nerve or ischemia of such structure due to section of the *vasa nervorum*.^{4,56–58)} Another possible complication is the spasm of the artery because like RA, the tunica media is thick and muscular predominance.⁵⁷⁾

Results of morphological studies of the UA, where the length and luminal diameter are determined, are shown in **Table 4**. There is no evidence on the thickness of the intima and media and scarce information about its histological structure, reporting only that it is a muscular artery.^{24,60)}

The use of the UA is safe and sensory deficit is uncommon, plus morbidity is low and there is no evidence of myocardial ischemia.^{4,56)} The permeability is comparable to that of RA.⁵⁷⁾ Because there is limited experience and studies regarding this conduit,^{2,54)} there is a lack of clinical evidence about long-term results, to indicate the effectiveness and permeability of this vessel as a graft in the CABG.^{2,56)}

Right gastroepiploic artery

Bailey et al. (1967) first used RGEA as a conduit for myocardial implementation in 1966.^{2,59)} Sterling Edwards (1973) first used it as a bypass for RCA, but there are no reports on carrying out the process.^{2,60)} In 1984, Pym et al. were the first to report its use for revascularization of the posterior marginal artery and RCA.^{2,61,62)} Due to the satisfactory results, this vessel is still considered an option for CABG.⁶²⁾

The RGEA is considered the third option for CABG.²⁾ It is a very versatile conduit, it provides 20 cm in length, and is capable of reaching all the areas of the heart.⁵⁾ However, there are some concerns in its use: its small size and its propensity to vasospasm.⁶³⁾

The RGEA is mainly used for revascularization of the lower side of the heart,⁵⁾ particularly the PIA,^{5,61)} and appears to be the ideal conduit for this area.⁶¹⁾ It is also used in distal segment of the RCA, and less frequently for marginal branches of the CX and the distal AIA.⁵⁾ It is occasionally dissected and skeletonized to be used as in situ graft, and more frequently left with the gastroepiploic vein and fatty tissue to be used as a pedicle.⁶¹⁾

In most patients, it is used in conjunction with the left ITA and the RA in an attempt to achieve complete revascularization of different coronary vessels.⁵⁾ More commonly, it used as a free graft and can revascularize more

Table 5 Studies on the right gastroepiploic artery

Author	Sample	Results		
		Luminal diameter (mm)	Tunic thickness of the intima media (μm)	Number of elastic fibers
Unlü et al., 2003 ²⁰⁾	7 cadavers	U: 1.62 ± 0.45	P: 274 ± 35	
	8 autopsies		D: 119 ± 29	
	14 patients			
Appleson et al., 2012 ¹²⁾	7 cadavers	U: 1.35	U: 190	21.42 (%)
Van Phung et al., 2012 ⁶³⁾	33 patients	D: 3.8	D: 250	D: 4.2 ± 1.8

This table shows the results of various morphological studies of RGEA. P: proximal segment; D: distal segment; U: single segment/unspecified.

than one artery by one or more side anastomosis.⁵⁾ The anastomosis with the AIA has poor results and should be avoided.⁶⁴⁾

The only absolute contraindication for its use is a previous partial or complete gastrectomy.⁶¹⁾ Abdominal complications due to extraction are rare.⁶⁴⁾ No complications have been reported on the risk of deprivation of blood supply to the greater curvature of the stomach.⁵⁾ One concern is the potential damage of the graft or spasm during abdominal surgery.⁶²⁾ The main mechanism of graft failure is a reduction in intraluminal diameter or occlusion when used for revascularized arteries with low-grade stenosis.⁵⁾

Results of morphological studies of RGEA are shown in **Table 5**. There is limited information on their morphology. It has a length of 19.32–20 cm.^{20,61)} In the proximal segment, diameter varies from 2.5 to 2.7 mm,^{5,41)} 2.2 ± 0.4 mm in the middle segment,⁴¹⁾ and 1.8–3.8 mm in the distal segment, which varies greatly.^{5,41,63)}

In the proximal segment, thickness varies between 274 and 305 μm ,^{20,41)} 290 μm in the middle segment,⁴¹⁾ and 119 and 250 μm in the distal segment.^{20,41,63)} It is a muscular artery, it has an internal elastic lamina with fenestrations and a tunica intima with slight hyperplasia.^{5,41)}

The permeability of the short-term RGEA is comparable to that of ITA, but long term is similar to that of the SV.^{5,64)} There are reports of 97% at 13 months,²⁾ 92%–80% at 5 years,^{2,5)} and 60% at 10 years.⁵⁾ However, it has good permeability, that is, both short and long term when anastomosed with the RCA,⁶⁴⁾ with 98% in the first year, 84% at 3 years,⁵⁾ 80%–90% at 5 years, and 62% at 10 years.⁶⁴⁾

Other conduits

Less frequently, other arteries are used as grafts in CABG. It is resorted to when, for various reasons, the previously mentioned arteries are not available or cannot

be used for revascularization.^{5,65)} Among other conduits used are as follows: inferior epigastric artery, splenic artery, subscapular artery, inferior mesenteric artery, intercostal arteries, and the descending branch of the lateral femoral CA.⁶⁵⁾ The most commonly used of these is the inferior epigastric artery.⁵⁾

Conclusion

There is a wide variety of conduits used as vascular grafts in CABG. Their careful selection is important to ensure its long-term patency. Morphological similarity between the graft and the coronary artery is the most important factor. The features to consider are: as follows length, luminal diameter, wall thickness, and histological characteristics of the vessel.

The most frequently occluded coronary arteries are AIA, RCA, and CX. They are muscular arteries, and their luminal diameter has been the most studied parameter which varies between populations, while the wall thickness varies between 100 and 400 microns.

The standard for CABG is the ITA, due to its excellent long-term results. Its high permeability is attributed to the morphological characteristics of the wall, as an elastic artery that has a low probability of developing atherosclerosis and hyperplasia. Furthermore, luminal diameter and wall thickness are similar to the coronary arteries. The left ITA is the first choice for revascularization of the AIA, whereas the right ITA is used most often for the RCA and PIA.

The second best option is the RA, and is most frequently anastomosed with the RCA, the CX, or the PIA, obtaining satisfactory results. Its main advantage is its wide length and thickness, making it a versatile graft and the luminal diameter is similar to the coronary arteries. Its main disadvantage is its propensity to spasm because of its thick muscular tunica media. The UA is used when

it is not considered safe to extract the RA or when the use of other conduits is not feasible. This vessel has similar morphological characteristics to RA; however, more studies analyzing its permeability and long-term results are needed.

The RGEA is the third best option for CABG. It is mainly used for revascularization of the lower side of the heart, particularly the PIA and the distal RCA. It is a muscular artery; the luminal diameter and wall thickness are somewhat smaller than the coronary arteries. There are few studies about its morphological characteristics and long-term results.

Disclosure Statement

The authors have no conflict of interest to declare.

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