REVIEW

Arterial grafting and complete revascularization: challenge or compromise?

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Purpose of review

Arterial grafting is superior to venous grafting in coronary artery bypass graft surgery with respect to graft patency and long-term patient outcome, but it may be difficult to achieve complete arterial revascularization.

Recent findings

Use of arterial grafts, especially bilateral internal mammary artery grafts, is not common, whereas there are clear indications that it may increase survival. Definitions of complete revascularization are varied and confusing, making study comparisons difficult. Technical challenges in complete revascularization with arterial grafts can be minimized by surgical techniques. Competitive flow in moderately stenosed coronary arteries grafted with arterial conduits may result in reduced patency. While internal mammary arteries may be used in arteries with at least 60% stenosis, radial artery and gastroepiploic grafts are best placed onto coronaries with severe stenosis. Moderate lesions in the left coronary circulation should be bypassed, but right coronary artery lesions can be left untouched as there is minimal progression over time. Complete revascularization may not be necessary or possible in every patient because of technical challenges.

Conclusion

Complete revascularization with arterial grafts presents both technical and physiological challenges. However, with techniques to maximize length of arterial conduits, knowledge of competitive flow and which moderate lesions should be addressed, complete revascularization with arterial grafts can be accomplished in the majority of patients, notwithstanding it may not be possible or even indicated for every patient.

Keywords

arterial grafts, CABG, complete revascularization

INTRODUCTION

As stated by a 29-year-old woman after total arterial coronary artery bypass graft (CABG) surgery ('Doctors always question the scar on my wrist and are astounded to hear that you used an artery in my heart; it makes only sense'), arterial grafts for CABG are intuitively the correct conduit. Just the pressure difference alone between veins (25–30 mmHg) and arteries (mean pressure 70 mmHg) should be evidence enough of arterial superiority. Why then do only 4% of patients in North America [1] and 10% in Europe [2] receive bilateral internal mammary artery (BIMA) grafting? The reasons are complex and many: non-belief of the evidence to date, technical and time demands of use of arterial grafts, fear of deep sternal wound infection [3], lack of benefit beyond a certain patient age, perceived mismatch between arterial graft flow and myocardial demand, and inertia to change. In addition, surgeons find it difficult to completely revascularize patients using only arterial grafts because of technical (limited length of arterial graft available) and physiologic factors (competitive flow when moderately stenosed coronary arteries are grafted).

EVIDENCE FOR IMPROVED SURVIVAL AND GRAFT PATENCY WITH ARTERIAL GRAFTING

As a result of advancements in operative techniques and myocardial protection, operative mortality of

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KEY POINTS

- Arterial bypasses, especially BIMA grafting, portend long-lasting graft patency and improved survival compared with CABG with predominantly venous grafts. Multiple definitions of complete revascularization abound and need careful scrutiny to compare studies.
- Surgical techniques exist to maximize arterial conduit length to facilitate complete revascularization with the finite amount of arterial conduit.
- Arterial conduits to moderately stenosed coronary arteries may suffer from the effects of competitive flow: guides exist for minimizing this problem.
- The moderately stenosed coronary artery behaves differently depending whether it is in the left or right coronary circulation: right-sided lesions do not progress and hence may be left not bypassed, whereas left-sided lesions do progress over time and should be addressed.
- Incomplete revascularization in some patients may be 'reasonable' or 'appropriate'.

CABG has reduced significantly (1% in planned cases) [4] and is no longer in question, but the longevity of the procedure is. As stated by Barner [5], 'Only continued patency of a graft or stent provides benefit.' Long-term venous graft patency is disappointing and has not changed for 44 years: Fitzgibbon *et al.* [6] reported in 1996 a series of 5065 grafts from 1969 to 1994 (25 years' span) with venous graft patency of 50% for at least 15 years, and Tatoulis *et al.* [7] reported in 2011 3238 venous grafts from 1986 to 2008 (22 years' span) with a patency of 50.7% at 15 years.

Use of the internal mammary artery (IMA) began 66 years ago as a myocardial implant by Vineberg and Jewett [8] in 1947. Evidence for superior long-term survival for arterial grafting was reported by multiple authors in the past years. Kelly *et al.*, in a study of 8264 patients (13% BIMA), found that risk-adjusted survival at 10 years was 71% [hazard ratio 0.8; 95% confidence interval (CI) 0.67–1.00] for BIMA grafts, 66% for single IMA grafts (reference group) and 58% (hazard ratio 1.42; 95% CI 1.2–1.7) for no IMA graft. Only the right IMA (no other arterial grafts) conferred benefit [9▪]. In another study with 8622 Mayo clinic patients (overall 12% BIMA), use of multiple arterial grafts compared with left IMA/vein was a strong predictor of survival at 10 (83 vs. 70%) and 15 (80 vs. 60%) years in matched groups ($P = 0.0025$) [10]. Kurlansky *et al.* [11] have reported the longest follow-up to date in a propensity-matched analysis of 4584 patients who underwent CABG through 1972–1994. Survival at 25 years of follow-up was significantly improved in BIMA graft patients as opposed to those receiving only one IMA (29 vs. 16%, respectively; $P < 0.001$) [11].

Bilateral internal mammary artery grafting in diabetic patients has gained little traction because the risk of deep sternal wound complications is particularly high in this subgroup of patients. However, use of two IMA grafts in diabetic patients has been recently shown to also increase late survival, similar to non-diabetic individuals. Puskas *et al.* [12▪] reviewed 3527 patients operated between 2002 and 2010, and showed that there were no increased propensity score-adjusted rates of 30-day mortality and sternal wound complications between the use of BIMA and single IMA grafts in diabetic patients; however, 8-year survival was 87.4% vs. only 60.6% in BIMA and single IMA patients, respectively ($P < 0.001$). Furthermore, Dorman *et al.* [13▪], in a cohort of 1107 consecutive patients with diabetes, showed that median survival of 646 single IMA patients was 9.8 years compared with 13.1 years of propensity-matched patients with BIMA grafts ($P = 0.001$).

Also for diabetic patients with complex disease in the SYNergy between Percutaneous Coronary intervention with TAXus and Cardiac Surgery (SYNTAX) trial, CABG is preferred over percutaneous coronary intervention (PCI) because of fewer major adverse cardiac or cerebrovascular events and less repeat revascularization, in keeping with findings from the Freedom trial [14▪,15].

Radial artery grafts, easier to harvest and use than the right IMA (RIMA), have some attrition beyond the first postoperative year, but remain stable thereafter up to 20 years: at 1.0, 5.4, 8.3 and 13.1 years, respectively, radial artery graft patency is 86.2, 81.9, 81.4 and 81.6% [16]. Because of the susceptibility of radial grafts to the effects of competitive flow (see below), radial grafts should only be constructed in areas of severe stenosis. As stated by Alfieri *et al.* [17] in their paper entitled 'Drug-eluting stents or drug-eluting conduits for multivessel disease', mammary arteries are the very best conduits. Tatoulis *et al.* [7], in a series of 5766 patients with BIMA, reported a 15-year patency of 91.1% for the left IMA, 79% for the RIMA and 50.7% for saphenous vein; 10-year patency for radial artery grafts was 78%. It is important to note that the patency of the right and left IMA is identical when used to the same vessels [7]. Yet, there are still those who remain to be convinced ... The Arterial Revascularisation Trial (ART) trial randomizing 3102 patients to either single IMA or BIMA will be the deciding vote [18].

DEFINITIONS OF COMPLETE REVASCULARIZATION

Incomplete revascularization (ICR) varies from 9 to 39% from study to study [19]. One of the difficulties interpreting the literature on this topic is the many and varied definitions of complete revascularization (Table 1) [20–27]. The 'traditional' definition defines complete revascularization as placement of at least one bypass in all diseased arterial systems and is basically a 'territorial' definition. 'Functional' complete revascularization most often refers to the bypassing of all diseased primary coronary segments, irrespective of size and territory. However, the term 'functional' has also been used to indicate bypasses into all territories except to those infarct areas without viable myocardium [22]. This has led to completely opposite definitions in some papers, in which traditional is called functional [28]. The amount of 'disease' (50% [20] or 70% stenosis [21]) varies among studies as well.

The definitions 'conditional' or 'unconditional' reflect revascularizing vessels of a certain size [>1.5 mm for CABG and PCI in the the Bypass Angioplasty Revascularization Investigation trial and >2.75 mm for PCI in the Arterial Revascularization Therapy Study (ARTS) trial] or location (main or branch) [22]. The definition 'numeric' refers to whether the number of distal anastomoses is either less than, equal to or greater than the number of diseased coronary segments [24]. One definition may be labelled the 'left anterior descending (LAD) artery definition': patients are grouped by whether they have at least two bypasses to both LAD and non-LAD system, at least two bypasses to the LAD, at least two bypasses to non-LAD system or whether no arterial system had multiple bypasses [24]. For the definition 'Index of Completeness of Revascularization (ICOR)', complete revascularization is a ratio of the number performed bypasses divided by the number of preoperatively planned bypasses and should be at least 1 [25]. This definition – because of the necessity of forethought – cannot be retrospectively applied to observational studies. However, to circumvent this, the definition has been extrapolated to be: the total number of distal anastomoses performed divided by the number of diseased coronary vessels defined on preoperative angiography [26,27]. Finally, complete revascularization can be measured by weighting stenoses in different vessels (extent of disease is a continuous variable) and may be 'anatomic' (irrespective of viable myocardium) or 'functional' (using the Jeopardy score to calculate the myocardium at risk after revascularization) [22]. Because of the different techniques by which PCI and CABG achieve complete revascularization, it is

Table 1. Definitions of incomplete vs. complete revascularization

Principal definitions	Description
Traditional	'Territorial' all territories diseased receive at least one graft/PCI (stenosis ≥50% [20] or ≥70%) [21]
Functional	'Territorial' without requirement for non-viable myocardium to be perfused [22]
Functional	Also called 'anatomic', all primary coronary segments irrespective of size or territory (SYNTAX trial is an example of this definition) [23]
Numeric	Number of stenotic vessels = number of distals [24]
'LAD definition'	≥2 distal sites to LAD + another artery
(Number of distal anastomoses to the LAD or other coronary arteries)	≥2 distal sites to LAD
	≥2 distal sites to an artery other than LAD
	<2 distal sites to all arteries [24]
ICOR (Index of Completeness of Revascularization)	Number of bypasses performed/number of bypasses preoperatively planned (should be >1) [25]
	Also, number of bypasses performed/number of stenotic arteries [26,27]
Weighted scoring (continuous variable)	Scoring of stenoses in different vessels at different locations with weighting, disease extent is a continuous variable, treatment is another variable; post treatment score determines completeness of revascularization [22]
Anatomic	Irrespective of viable myocardium [22]
Functional	Post-treatment score based on amount of viable myocardium still at risk by Jeopardy score [22]
Conditional	Conditions include specified vessel diameter or location (main or branch), can apply to any of above definitions [22]

LAD, left anterior descending; PCI, percutaneous coronary intervention.

questionable whether one definition for both PCI and CABG is possible or even advisable. Hopefully, one day, we will reach the utopian goal of no longer needing comparison of PCI and CABG because the role for each will be defined; for example, patients with diabetes [14▪,15], patients with a SYNTAX score above and below 33 and so on [29]. This multiplicity of definitions needs addressing, without which comparison from study to study is difficult and may not be meaningful. Forethought and decision beforehand of vessels potentially treatable by both the cardiologist and cardiac surgeon of the Heart Team (as used in the SYNTAX trial) [14▪], and then comparing with what was done, may be the best way to decide completeness of revascularization.

The residual SYNTAX score is a recently proposed definition to grade the degree of completeness of revascularization, adding more detail to previous dichotomous definitions. It is promising as a predictor of mortality during follow-up after PCI [30▪,31,32▪], but has not yet been validated in a CABG cohort. It will be interesting to see how it performs, particularly since the original core SYNTAX score lacks prognostic accuracy [33].

TECHNICAL CHALLENGES IN ARTERIAL GRAFTING FOR CORONARY ARTERY BYPASS GRAFT SURGERY

When using venous grafts, one can always 'go and get more vein', whereas with arterial grafts there is only so much conduit available. A large heart may require 'creative arterial grafting' in which various segments of arterial conduit are attached to each other to form a composite graft and reach their target. Technical tricks include the following:

(1) Skeletonization of the IMAs [34] adds considerable length and also facilitates sequential grafting because the correct 'lie' of the conduit can be judged accurately when the whole circumference of the IMA is seen (when performing the side-to-side anastomosis of a sequential graft).
(2) The length of an arterial graft is maximized if placed 'as the crow flies', that is, as direct a route as possible to the target. For example, for either the left or right IMA to reach the LAD, one can bring the conduit through a hole in the pericardium (or make a slit) instead of going 'up and over' the pericardial reflection. First pleural tissue is swept away to avoid entering the pleural cavity, then cautery is used to make a small hole in the pericardium, enough to admit two fingers. In order for the RIMA to reach the right coronary artery (RCA) system, pericardial holes are made in different locations depending on the location of the target: for a RIMA graft to the main RCA or postero-lateral branch of the RCA, the pericardial hole is made adjacent to the 'superior vena cava', and to graft the posterior descending artery (PDA), the hole is made near the 'inferior vena cava' (personal communication from Dr Pascal Berdat of Berne, Switzerland, July 2003). This route to the PDA is extra-pericardial (may facilitate re-operation if needed); the IMA seems longer with this route, usually reaches the PDA and allows the 'turn-point' of the IMA to be tethered by the pericardial edge, ensuring a correct lie of the distal segment of the RIMA. This allows no twisting at the heel.

In the authors' experience of almost 10 years of 1047 patients with 98% arterial grafts, by using this technique, the RIMA–PDA was used as a free graft 13% of the time (26/194 RIMA to PDA). For this same group of 1047 patients, a total of 748 RIMA conduits included 309 (41%) RIMA conduits to RCA system and 439 (59%) to left coronary artery (LCA) system. For the RIMA to the circumflex system, the most direct route is usually through a hole in the pericardium just above the superior vena cava and through the transverse sinus to reach the marginal branches. A skeletonized IMA beating against an occluding clip or bulldog wrapped in a vasodilator solution usually lengthens enough to reach most branches of the circumflex system *in situ*. In the authors' experience, for this same group of 1047 patients, the RIMA–LCA system was used as a free graft only 9% of the time (40/439 RIMA-to-LCA system). Although it may be twice as difficult to use the RIMA as the left internal mammary artery (LIMA), patients get close to twice as many grafts at 15 years (90 vs. 50% patent grafts). The radial artery is almost as easy to use as a saphenous vein and in fact may be 'the new saphenous vein'. One must just be cognizant of the native coronary stenosis and use the radial when appropriate (in coronary arteries with 90% stenosis or higher, see below).

COMPETITIVE FLOW AND ARTERIAL GRAFTING

Venous grafts have virtually no resistance (the pressure at the distal anastomosis is nearly equal to the aortic pressure) and hence are less susceptible to the adverse effects of competitive flow [35▪▪]. Arterial grafts 'auto-regulate in response to demand' [36]; flow in an arterial graft will rise and fall as is needed. Arterial grafts have one Achilles heel – competitive flow if grafted into coronary arteries with moderate stenosis. The most severe form of 'non-requirement' results in a 'string sign' – on angiography, the graft looks like an atretic thread attached to the coronary artery. Conversely, arterial grafts increase their diameter over time [35■■] and, in particular, left IMAs have been known to revascularize the whole of the LCA circulation in cases of isolated/predominant left main stenosis (Fig. 1). IMAs are the arterial conduit least affected by competitive flow; generally there is no critical level of stenosis below which graft flow is compromised [5]. Sabik *et al.* [37] studied 2121 IMAs from 1972 to 1999, and found that, although IMA patency diminished as the degree of coronary stenosis decreased, at no particular degree of stenosis was there a sharp decline in patency. Glineur *et al.* [38] showed that composite 'Y' IMA grafting to both the RCA and LCA systems had a negative prognostic influence on graft function, with loss of the graft to the RCA system. Possibly the different diastolic filling of the right (50%) and left coronary arteries (66%) could explain this: the RCA segment fails because two disparate pressure systems are grafted with one inflow.

For the radial artery graft, Barner [5] was the first to identify the relation of native coronary stenosis and radial artery patency; he found that patency was worse in moderate stenosis (≤70%) compared with critical stenosis (≥90%). Shah's review showed radial artery graft patency to be significantly reduced from 90 to 60% when grafts were placed to fewer than 70% stenotic arteries [39]. In the Radial Artery Patency Study, Desai *et al.* [40] found that radial grafts to coronary arteries with stenosis of at least 90% as compared with those with stenosis of 70–89% were associated with a lower rate of occlusion (5.9 vs. 11.8%). Composite grafts using the radial and IMA to the left circulation therefore need to take this into account as well. The right gastroepiploic artery, similar to the radial artery, is recommended to be used only on severely stenotic coronary arteries [41]. Some of these guidelines are difficult to implement for arterial grafting in that the conduit that 'reaches' may not be the most appropriate conduit for that particular coronary [e.g. a long graft (radial) is needed for two branches on the RCA system, but the stenoses are only 70%].

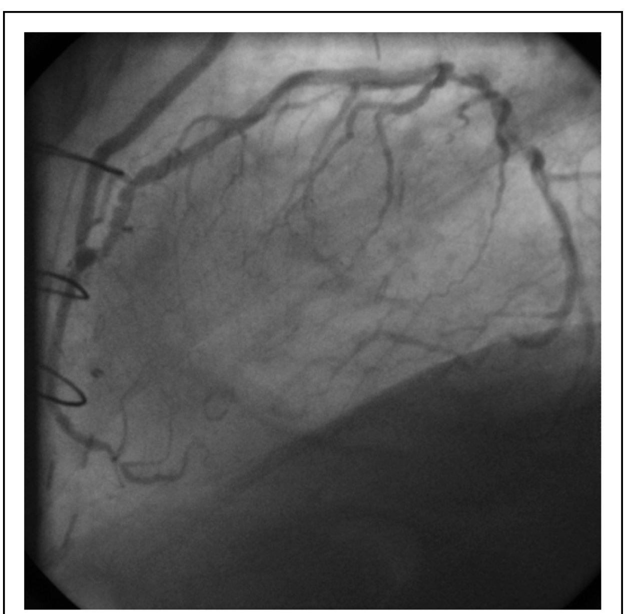

FIGURE 1. LIMA graft supplying all of LCA system in a patient with predominantly left main stenosis. LCA, left coronary artery; LIMA, left internal mammary artery.

WHAT ABOUT MODERATE STENOSIS?

If arterial grafts are better, but are subject to the vagaries of competitive flow, should moderate stenosis be left alone? Hayward *et al.* [42■■] answered this when he studied 386 bypass grafts to moderately (40–69%) stenosed coronary arteries from the Radial Artery Patency and Clinical Outcomes trial. During a mean of 6.2 years follow-up in nonbypassed coronary arteries, moderate lesion progression differed according to location: only one in seven moderate lesions in the RCA showed significant progression (from moderate to severe) compared with one in two for left-sided coronary vessels. Conversely, however, when a moderately diseased coronary artery in the RCA system was bypassed, the native lesions progressed to severe 40% of the time vs. 14% of the time if not bypassed. Competitive flow from grafts seemed to cause greater disease progression in right-sided vessels than in left-sided vessels; as well, right-sided grafts tended to have inferior patency (73.3% at 7 years vs. 83.2% at 8 years; $P = 0.051$). He concluded that it is advisable to bypass moderate lesions of the left coronary system because of the likelihood of progression, but leave right-sided moderate lesions alone, given the low risk of progression if left undisturbed.

The use of fractional flow reserve has been shown to assist in deciding which lesions are best treated by angioplasty [43]; possibly the same may prove to be useful in deciding which moderate lesions should be grafted. With this new knowledge, that which constitutes 'completeness of revascularization' may need to be rethought.

IS COMPLETE REVASCULARIZATION ALWAYS NECESSARY?

Reduced survival after CABG is multifactorial and cannot be attributed solely to incompleteness

Table 2. Comparison of studies with differing amounts of arterial grafting

Grafts	Author, year	Number of patients	Length of follow-up (years)	Survival (ICR) (%)	Survival (CR) (%)	Comparison
Venous grafts only	McNeer *et al.*, 1974	392	2	75%	83	NS
IMA + vein	Mohammadi *et al.*, 2012	476	8	49	54	$P=0.40$
	Kim *et al.*, 2011	514	5	90	87	$-P=0.26$
	Sarno, 2010	567	5	91	93	$P=0.48$
	Aziz, 2009	580	8	34	44	$P<0.01$
	Lattouf *et al.*, 2008	12812	10	∼58[b]–	–∼68[b]	$P<0.001$; HR = 0.85 (95% CI 0.77–0.93)
	Kozower, 2005	500	8	25	39	$P<0.008$
Arterial (more than usual)	Farooq *et al.*, SYNTAX, 2013[a]	1541 (22.7% BIMA)	4	88	92	$P=0.039$
	Vieira *et al.*, MASS II, 2012	198 (36% IMA+radial)	10	–88[b]	–91[b]	NS
	Girerd *et al.*, 2012	6539 (4.4–10.9% BIMA)	6	82	88	$P<0.001$
	Head *et al.*, SYNTAX, 2012[c]	870 (27.6% BIMA)	3	93	94	$P=0.60$
	Rastan *et al.*, 2009	8806 (22–32% TAG)	5	54	61	$P=0.77$
	Kleisli *et al.*, 2005	1034	5	53	82	$P<0.001$

CABG, coronary artery bypass graft; CR, complete revascularization; HR, hazard ratio; ICR, incomplete revascularization; IMA, internal mammary artery; MASS II, Second Medicine, Angioplasty, or Surgery Study; NS, not significant.
[a]In comparison with Head *et al.*, this group also includes patients both in the trial and in the CABG registry.
[b]Estimate from survival graphs in paper.
[c]Includes only trial patients.

of revascularization [4]. Also, not all studies have shown that incomplete revascularization in CABG results in impaired survival [19,21,44,46–48,51] Table 2 shows 13 studies [19,21,27,28,32▪,44–51] comparing completeness of revascularization at follow-up times ranging from 2 to 10 years relating to the amount of arterial grafting.' In the SYNTAX trial with 27.6% BIMA [23,51,52], in the CABG group, no difference in outcomes was seen between incomplete and complete revascularization groups. Incomplete revascularization was identified as an independent predictor of Major Adverse Cardiac and Cerebrovascular Event (MACCE) in PCI (hazard ratio 1.55, 95% CI 1.15–2.08, $P=0.004$), but not CABG patients. Rastan *et al*. spoke about 'reasonable ICR', noting that most often the territory not bypassed involves either the RCA or circumflex territory, which may or may not portend worse outcomes, especially if, as in their study, arterial grafting was more frequent [19]. Taggart [53▪▪] discussed the 'appropriateness' of ICR, noting that inability to completely revascularize often is a marker for more severe and diffuse disease. It is not 'appropriate' to place a bypass graft into an infarct area, or into a small target vessel, risking graft failure and possible infarct.

CONCLUSION

Arterial grafting is thought to be superior for graft longevity and patient survival, and we anxiously await the results of the ART trial to confirm this [18]. The definitions of ICR are as varied as is the incidence of ICR in the literature. Although technically challenging, it is possible to achieve complete revascularization with arterial grafts, especially if one skeletonizes the IMAs and as much as possible follows guidelines correlating the conduit type to level of stenosis in order to avoid competitive flow. Moderate lesions on the RCA system should probably be left alone as they do not progress (one in seven), whereas those in the left coronary system should be bypassed because of their progression over time (one in two). Finally, 'the enemy of good is perfect', and it may not be necessary to achieve completeness of revascularization each and every time.

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Conflicts of interest

There are no conflicts of interest.

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