Perspective

Total arterial coronary revascularization—patient selection, stenoses, conduits, targets

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Graft patency determines prognosis in coronary artery bypass grafting (CABG). Numerous reports over the past 20 years have documented superior patencies and prognosis when multiple arterial grafts are used, yet less than 10% of CABG have multiple arterial grafts. Several conduits have been proposed, with varying degrees of success. Saphenous vein grafts (SVG) begin to fail with intimal hypertrophy and then atheroma after 5 years, with patency rates of 50% to 60% at 10 years, and <30% at 15 years. In contrast, left internal thoracic artery (LITA) patency is >95% at 10 years and >90% at 20 years. The radial artery is extremely versatile and can reach all territories, but is muscular and vulnerable to spasm and competitive flow. Similarly, the right gastroepiploic artery is also muscular, and is best suited to the posterior descending coronary artery, especially in reoperations and is also affected by competitive flow. In addition, bilateral internal thoracic artery grafting (BITA) grafts and total arterial revascularization (TACR) can be performed with identical perioperative mortality (1%) and perioperative morbidity to LITA + SVG. Importantly, survival is superior—85% to 90% at 10 years versus 75% to 80% respectively. BITA/TACR patients also suffer fewer late cardiac events and reoperations, with superior results for older patients, those requiring urgent surgery, diabetics, patients with renal dysfunction and in reoperations. Contraindications to BITA include obesity, insulin dependent diabetics, and severe chronic obstructive airways disease. As such, arterial grafts have better patencies and clinical results. BITA/TACR is often underutilized, but can be achieved in the majority of patients. Opportunities exist to enhance BITA/TACR use in CABG to the potential benefit of our patients.

Keywords: Coronary artery bypass graft; conduits; internal thoracic artery; patient selection

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Introduction

Why total arterial revascularization (TACR)? To give patients the greatest possible long-term benefit of coronary artery bypass grafting (CABG) with the same low perioperative risk and morbidity that is currently being achieved with conventional CABG (operative mortality 1-2%).

Over 95% of all CABG in the USA, and over 90% in the United Kingdom and Australia, have only one arterial graft (1-3). The left internal thoracic artery (LITA) and saphenous vein graft (SVG) remains the standard operation, with SVGs accounting for the vast majority of conduits used. 40-50% of these SVG will be occluded at 10 years and over 75% will be occluded at fifteen years (4). Knowing this, why are SVG predominantly used as the conduit of choice when we know there are other better alternatives available? Are we performing CABG operations that are convenient for the cardiac surgeon rather than being the optimum for the perioperative, and especially, the long-term welfare of the patient?

Through databases developed over three decades, we have huge amounts of information. Possibly, no other operation has been studied as well as CABG. The

consistency of the information renders it reliable, and consistently it suggests that the more arterial grafts performed at the primary CABG surgery, the better the long-term prognosis (1,5-9). While TACR is not necessarily appropriate for all patients, it should be the primary objective in coronary surgery.

Conduits

Saphenous vein grafts

Excellent patency can be achieved in the first five years with saphenous vein grafts. They are unaffected by native coronary artery stenosis (NCAS), however, endothelial and media hyperplasia (5-8 years post-operatively) and subsequent atherothrombosis markedly diminish patency, usefulness and function of SVG (4,10). Attention to harvesting, avoidance of trauma, over-distension, and preservation of vessel wall integrity, and vasa vasorum may contribute to longer-term patency, as may the use of statins. However, current evidence suggests that SVG patency is still problematic at 10 years (4,7). As the mean age of patients undergoing CABG is 65 years, then it follows that by age 75 years, such patients will have lost several grafts and had recurrent events such as myocardial infarction, recurrent angina or death within the decade following the primary CABG.

Left internal thoracic artery to the left anterior descending (LITA-LAD)

Since the publication by Loop *et al*. in 1986 (and other publications around that time), it is universally accepted that LITA is the best coronary graft, and LITA to LAD is the single most important component of any coronary revascularization in reducing recurrent cardiac events, and enhancing survival (10,11). LITA-LAD improves perioperative mortality and can be used, and is strongly recommended, in all situations including emergency revascularisation, older age, and in patients with co-morbid states (diabetes, obesity, renal dysfunction, chronic obstructive airways disease (COAD) (12). The only conditions are that the LITA must not be damaged, is of sufficient size, and has adequate flow to sustain the dependent vessel and myocardium.

The right internal thoracic artery (RITA)

The RITA is biologically identical to the LITA (1,7,13-15). Hence, it is not logical to universally proclaim the LITA as the best conduit, and by virtue of its non-use, infer that the RITA is inferior to SVG. The RITA is usually of greater diameter than the LITA in right handed people, and potentially easier to use.

Bilateral internal thoracic artery grafting (BITA)

BITA has been used since the early 1980s, and numerous reports from centers world over have consistently found similar excellent perioperative and especially long-term results, which are superior to those with LITA-SVG (9,16-22). The recurrent cardiac events are fewer, reoperation rates are lower (50% fewer reoperations for BITA versus LITA at 10 years) and long-term patencies are better (80-90% for RITA versus 50-60% for SVG at 10 years), and survival is superior—with 40-50% fewer deaths (10% versus 20%) over 10 years (16-23).

As the populations' life expectancy is increasing, these facts have profound implications for these patients in our community. That BITA grafting provides better outcomes for patients is unfortunately "an inconvenient truth" (7). So why is not BITA performed in the majority of patients who can obviously benefit? (Indeed our group has been guilty of this as well, as only 35% of our CABG patients have had BITA over the past 30 years, though 85% have consistently had TACR since 2000).

Commonly raised concerns regarding BITA use

Surgeons not trained in RITA harvest: RITA harvest is the same as LITA harvest. As all trainees and surgeons harvest and use the LITA almost universally, then it is a minor step to progressing to harvesting the RITA competently, safely and comfortably.

Not comfortable with the actual use of the RITA to perform coronary grafting: the RITA is usually larger than the LITA in most right handed individuals. For an average male (80 kg, or 170-190 lbs) the RITA has at least a 2 mm internal diameter distally at its bifurcation and at least a 3 mm proximally. The wall is identical or sometimes slightly thicker than that of the LITA.

Uncertainty as to how best to deploy the RITA: *in situ*, free of Y? Anterior or posterior to the aorta to reach the circumflex (Cx)? To the Cx or the right coronary artery (RCA), or posterior descending coronary artery (PDA)? Individual graft or sequential? NCAS and vulnerability to competitive flow? Regardless, patency of *in situ* RITA is identical to free RITA to the same vessel.

Prolonging the operation: approximately a further 30-60 minutes is required.

Concern regarding sternal infection, necrosis, and non-union: this is minimized by skeletonized harvest of the RITA, using precise clip and cut technique, preserving the continuity of the intercostal arteries to the sternum, leaving the endothoracic fascia to cover the mammary bed, appropriate prophylactic antibiotic regimens, and meticulous perioperative glucose management (1,7,24-26). However, there is no doubt that BITA should be avoided in morbidly obese (BMI >40), insulin dependent, diabetic patients, and those with severe COAD (1,7).

Lack of randomized trials: numerous single and multi-institutional observational, propensity matched reports, and meta-analyses support BITA. However, this issue is being addressed by randomized trials as well. The early results show identical perioperative mortality, and morbidity for BITA when compared to LITA (16,27).

While the above listed issues are real dilemmas, their presence does not justify not using BITA.

Pragmatic use of arterial conduits

For surgeons embarking on BITA or TACR, keep it simple—essentially duplicating the LITA-SVG operation, using the RITA as one would use your patients' best quality SVG to the next most important vessel that warrants a bypass graft. Accumulating evidence suggests that the LAD and circumflex territory revascularization should take priority over the RCA (except for a large, dominant, tightly stenosed RCA with multiple, distal branches that supply a large amount of myocardium) (9,28). An *in situ* RITA will reach the intermediate or high first Cx. This can be "trialed" prior to deployment, or prior to cardiopulmonary bypass (CPB). For most surgeons it is more comfortable to run the *in situ* RITA behind the thymus, anterior to the aorta to the circumflex. Passage through the transverse sinus, posterior to the ascending thoracic aorta is possible, but presents challenges in ensuring no rotation, or if there is bleeding (9). If the mid to distal Cx territory is to be grafted, then the RITA should be used in an identical manner as one would a SVG.

The FRITA (and radial artery) proximal anastomosis

To the aorta, constructed in an identical manner to an SVG.

RITA T or Y graft with the LITA

This was described by Tector and others (29). It is the best technique to reach the inferolateral aspect of the heart with the RITA, and allows multiple sequential anastomoses in the circumflex system. It is commonly used in off-pump coronary artery bypass (OPCAB) and is the standard operation in many centers that perform BITA routinely (30,31). Additionally, it has the advantage of potentially completely avoiding the aorta and reducing the risk of embolic stroke (32).

RITA to the right coronary system

Should the RITA be used to the RCA system? The evidence is conflicting. The predominant view is that the RITA should be used as the second arterial graft to the left side (1,4,7,9,13,22,28). However if the circumflex is small, or leads to an infarct, then it is reasonable to use the RITA to the RCA. Whilst it is often tempting to use the RITA to the main RCA near the acute margin, commonly further disease commonly develops over the ensuing 5-10 years, at the crux rendering the RITA effectively useless (1,7,15). In addition there is a greater chance of competitive flow and a "string sign" with a resultant non-functional arterial graft (30,31). Hence, it is preferable to use arterial grafts—including the RITA, to the PDA.

The *in situ* RITA usually does not reach the PDA comfortably. It is preferable to use it as a free graft. This has at least 4 advantages. It will reach comfortably and distally to the desired, optimal anastomotic location without compromise because of the additional length. It avoids future disease at the crux. One can discard the smaller, more spasmogenic distal part of the RITA if there is sufficient length, and it is less likely to be affected by competitive flow.

Guo-Wei He has comprehensively documented the physiology of the ITA, noting a greater tendency for spasm, in the more distal, smaller diameter segment of the ITA (14). Spasm here has a greater effect on the internal diameter.

Alternative deployment of the RITA: RITA-LAD, LITA-Cx

Patency of the RITA to LAD is identical to that of LITA to LAD (94-96% at 10 years) (1,4,7,30).

Advantages include the *in situ* LITA reaching distally into the circumflex system, and the surgeon can check the integrity of the LITA-Cx anastomosis immediately after its construction (for example, hemostasis, lie). Potential disadvantages include that the RITA to LAD may have limited reach, only to the mid LAD, particularly if the heart is rotated to the left-hand side, or if the patient is asthenic,

or has hyperinflated lungs with inferior displacement of the diaphragm and heart. It also precludes sequential anastomosis with a major diagonal branch if that would otherwise have been indicated.

Radial artery (RA)

The RA was introduced in 1973 (Carpentier), but fell into disrepute due to inadequate knowledge and poor treatment, which included internal mechanical dilatation. Fortunately the RA was resurrected in 1992 after important patency observations in angiographic studies 15-20 years later on Carpentier's original patient cohort (33).

Over the past 20 years it has established itself as an important conduit, and for those with experience in its use, it is the second best conduit after the internal thoracic artery. An excellent conduit, up to 22 cm long, usually 2.5 mm internal diameter distally, and appropriate size match for coronaries, usually both RAs are available. It is relatively easy to harvest, the forearm wounds heal well, infection is rare and allows early ambulation in older patients, as leg wounds are avoided. Further, it allows for TACR (34-36). RA dominance, calcification, prior trauma and collagen diseases preclude its use in 5-10% of patients (34).

The length of the RA allows one to reach distally to any coronary vessel and its size and robustness allow sequential grafting. Most surgeons would be as comfortable using the RA (once harvested) as they would an SVG. We prefer to construct the proximal anastomosis on the ascending thoracic aorta (duplicating techniques with SVG), but LITA-RA Y is possible (and often used in OPCAB) with sequential anastomoses in the circumflex system and to the distal RCA/PDA (33,35,36). We reserve this technique for cases with conduit shortage or OPCAB (34).

Spasm prophylaxis is essential for all arterial grafts, but particularly the RA [and the gastroepiploic (GEA)] as the RA has a much thicker, muscular wall than the ITA. We achieve this by 2 mL of intraluminal papaverine solution (30 mg in 30 mL heparinized arterial blood at 37 ℃) when the distal end is disconnected, and store the RA in an identical solution until use. Spasm prophylaxis is supplemented by intravenous nitroglycerine for 24 hours and amlodipine 5 mg daily for 6 months (34).

Pragmatic considerations

Arterial grafts should be anchored to the epicardium with 6-0 sutures to avoid rotation along the conduit's longitudinal axis, and protect against displacement by the lungs.

The simplest and most failsafe way of achieving total arterial coronary revascularization (TACR) is by LITA-LAD, free RITA-Cx, RA-PDA, using exactly the same technique as one would use for SVG. Alternate (but more complex) means of achieving TACR include, LITA-RITA Y or T graft, LITA-RA Y or T graft, LITA and bilateral RAs, bilateral ITA and right GEA, LITA + RITA-RA extension (31,32). We achieve TACR using one graft to one territory, hence multiple inflows, on CPB, single cross clamp for all distal and proximal anastomoses using antegrade and retrograde blood cardioplegia (20 degrees C), achieving a myocardial temperature of 25 C with further retrograde doses after each anastomosis.

Native coronary artery stenosis (NCAS) and competitive flow

Much has been learnt about this over the past 20 years. SVGs are unaffected by NCAS nor by competitive flow irrespective of the degree of NCAS (50-100%).

All arterial grafts are affected. ITA conduits less so, with patency reductions noted at NCAS <60%. RA and RGEA are extremely vulnerable, and the best patency rates are achieved when NCAS is >80% (preferably >90%) (34,37,38). The assessment of NCAS is subjective and has confounded the literature. How does one compare an 80% stenosis in a 5 mm diameter, dominant RCA, to an 80% stenosis in a 2 mm Cx? More appropriate and objective is the concept of residual coronary artery diameter, at the stenosis. It is likely that 1 mm is the threshold for significant influence on arterial graft patency (39).

It follows that ITA can be used for important vessels such as the LAD or a large Cx when the NCAS is >60%, preferably >70%. The RA and the RGEA should be reserved for vessels with NCAS >80% (preferably >90%) and that the main RCA should be avoided with preference for grafting the PDA or posterolateral/left ventricular branches (if appropriate) to minimize the effects of competitive flow (40,41).

Patients

There is a common view that TACR is unnecessarily complex with longer anesthetic and recovery times, and may not offer any benefit in some patient sub-groups—older patients, those with left ventricular dysfunction, diabetes, renal dysfunction or established renal failure.

These arguments were also used over 25 years ago regarding the use of the LITA to the LAD in elderly patients (>70 years) and those in urgent or emergency settings—and were refuted by the subsequent evidence (9,23). Similarly, conservative arguments against TACR are being gradually eroded by the accumulating evidence.

In the University of Melbourne Hospitals, after risk adjustment, in almost 3,000 patients 70 years or older with CABG for triple vessel disease (TVD), those with TACR had a hazard ratio of 0.85 (range, 0.72-0.99), i.e., 15% less chance of dying over the next 10 years compared to LITA/SVG. Other groups that perform TACR have also reported improved survival in all patient age cohorts, including in older patients (5,6,8,17,35).

In the Australian population, at age 60, a further 23-26.5 years can be expected based on national survival statistics. At age 70, males can expect to live a further 15 years and females 18 years. Assuming patients of these ages having CABG for coronary artery disease, a 15% reduction in mortality translates to a 3.3-3.8 years of additional life for a 60 year old and 2.2-2.7 years for a 70-year old. Hence age should not be a barrier to multiple, or TACR.

Patient comorbidities

Past concerns regarding deep sternal would infections (DSWI) and mediastinitis in patients undergoing BITA have been well founded. However, techniques to deal with these have drastically reduced these problems. These include prophylactic antibiotics well before the skin incision, skeletonization of the ITAs, reduced retrosternal/ITA bed trauma, preservation of the intercostal blood supply to the sternum, meticulous perioperative glucose management (insulin infusions during CPB and for the first 24-48 hours postoperatively maintaining a blood glucose of <10 mmol/L) (1,7,42). Furthermore, not requiring SVG avoids inadvertent potential, cross contamination from the groin, thigh or leg.

Skeletonization of the ITA (and RA) increases the diameter, length, and hence, versatility of arterial conduit use. Recent evidence suggests that DSWI is no different with skeletonized BITA *vs*. LITA (16,24,42). Diabetic patients that require myocardial revascularization have a better prognosis with CABG *vs*. PCI and are prognostically better off again with BITA/TACR as opposed to LITA/SVG (24,42-44).

In patients with known preoperative renal dysfunction, although counter-intuitive (as outcome should be determined by the renal rather than the cardiac problems), emerging evidence suggests that BITA/TACR can be performed with low perioperative mortality and morbidity (similar to LITA/SVG), and yet may have further prognostic advantages in these patients (45,46).

In patients with prior valve surgery now requiring CABG, we follow the principles and strategies discussed above. In patients requiring replacement of prior, or needing additional grafts, arterial grafting is important if not essential. The best SVG has already been used and therefore not available. Usually two RAs, the RITA and the RGEA are all available, and are better conduits than SVG, particularly the remaining SVG (if any). Time and patience are required to harvest the required grafts and perform appropriate revascularization (47).

Special patient situations in reoperative CABG

If there is already an excellent LITA to LAD, further CABG will not achieve an additional prognostic benefit (48). Redo CABG should only be performed for severe, uncontrolled symptoms.

A diseased, but patent, SVG presents a dilemma, particularly to the LAD. To completely replace this with an ITA may result in short-term, extremely important hypoperfusion, perioperative anterior infarction, and even death. To leave a diseased, patent SVG may lead to competitive flow with and failure of a new arterial graft. Some advocate replacing an essential, patent, diseased SVG with another SVG. Such dilemmas are usually resolved by the surgeon's own experience.

Patients with an intact LITA, whether previously placed, or placed at the time of secondary surgery, do better perioperatively, and in the long term. Additionally those where TACR, or further arterial grafts are performed at reoperation do better over 10 years than those where only supplementary vein grafts are used.

Targets

Unfortunately there is very little objective data relating to targets. Descriptions of coronary vessel characteristics such as size, wall quality, plaque volume, myocardial viability and mass, are all subjective and qualitative. Even a basic feature such as the internal diameter of a coronary artery has not been objectively defined. Hence, grafting practice is determined by experience, personal and institutional bias.

There are many unresolved questions. Should coronary arteries of <1.5 mm internal diameter, those supplying

infarcted areas, and those with diffuse distal disease, be grafted? Will it make any difference? If grafted, what with? Are there any benefits to placing more than one graft (particularly arterial grafts) into each coronary territory? Is there still a role for extensive coronary endarterectomy? Despite 55 years of coronary surgery practice, these questions remain unresolved.

Contra-indications to BITA/TACR and other conduits

There are probably no absolute contra-indications to BITA/TACR. However, we avoid BITA in grossly obese (BMI>40), insulin dependent, diabetics or those with severe COAD. Despite our best efforts, morbidly obese patients present a challenge. TACR should still be a goal, and achieved with LITA and one or two radial artery grafts. Patients with severe COAD are at great risk of coughing, and sternal dehiscence, regardless of the sternal closure method is used, but again TACR can be achieved with a combination of LITA and radial, and RGEA if appropriate.

Occasionally the ITA, RA or RGEA may be relatively small with poor flow. If due to spasm, this can be overcome, however if it is natural, caution is required to avoid hypoperfusion. Calcification in a RA, (<5% cases) may preclude its use. Hence, it is wise to check with ultrasound, or by exposing the distal 2-3 cm of the conduit first to ensure its integrity.

Target territory

Controversy surrounds grafting a vessel supplying extensively infarcted/scarred myocardium. Should one graft at all, and if so, would an arterial graft really make any difference? Our practice would be to not graft an area that is true complete scar, thinned out, particularly as measured on echocardiography (LV wall <5 mm thickness).

Moderate right coronary artery stenosis

This has been discussed above, but a special scenario is that of a relatively young patient (<70 years) with a 50-60% stenosis in a large, dominant, RCA. We would leave this alone, and subsequently treat it on its merits, should future symptoms relating to this vessel develop.

Mode of arterial graft failure

Spasm is the Achilles heel of arterial grafts. It is most prevalent peri-operatively, but can occur days, weeks and even months later. In addition at least 3 other patterns of arterial graft failure occur. Complete occlusion which occurs early and is likely due to a technical mishap. Localized stenosis—the cause is usually unknown, possibly due to local trauma, or a local vascular wall abnormality not recognized at harvest. Thirdly and importantly, string signs where the arterial graft remains patent, but ineffectual, are due to competitive flow. Such free grafts do not "reopen" when the native coronary occludes, although there are reports of *in situ* LITA grafts doing so. Arterial grafts, however, never become atheromatous (1,4,7,17,48).

Recommendations

TACR is preferred, and can be achieved in over 80% of patients. We prefer to achieve this via BITA and radial artery grafting, or LITA and bilateral radial arteries, with the occasional use of the RGEA. We use the two ITA grafts on the two best coronary vessels according to size, and ischemic myocardium subtended (usually LAD and Cx territories) and the RA to the distal RCA territory because of its usual, lesser importance, and ease of reach of the RA, being significantly longer than the free RITA. We tend not to graft vessels <1 mm, nor those supplying significant areas of true scar and thinned out LV wall. We do not hesitate to leave moderate lesions particularly in the RCA in younger patients. Spasm prophylaxis for arterial grafts is essential.

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