The history of arterial revascularization: from Kolesov to Tector and beyond

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Coronary artery bypass grafting (CABG) is the one of the most effective revascularization strategies for patients with obstructive coronary artery disease. Total arterial revascularization using one or both internal thoracic and radial arteries has been shown to improve early outcomes and reduce long-term cardiovascular morbidity. Although CABG has evolved from an experimental procedure in the early 1900's to become one of the most commonly performed surgical procedures, there is still significant variation in grafting strategies amongst surgeons. We review the history and development of CABG with a particular emphasis on the early pioneers and the evolution of arterial grafting.

Keywords: Coronary artery disease (CAD); coronary artery bypass surgery; radial artery (RA); internal mammary artery; total arterial graft

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Introduction

It has been just over 100 years since Alexis Carrel first described the concept of operating on the coronary circulation (1). Over this time coronary artery bypass grafting (CABG) has gone through three distinct eras in its evolutionary journey. The first, or "experimental", period was dominated by visionaries in our field who pioneered, developed and established direct coronary surgery in clinical practice. The second, or "vein graft", era was when the use of the saphenous vein graft (SVG) as an aorto-coronary bypass graft dominated and routine coronary surgery became an important and effective treatment for the management of obstructive coronary disease. The final and current era is that of "mixed venous and arterial grafting". Along with an improved understanding of the limitations of the saphenous vein, we have recognized the benefits of arterial grating with the internal thoracic (ITA) and radial arteries (RA).

Such understanding has led to significant variations in surgical practice worldwide. Whilst the majority of surgeons continue to perform the traditional operation of left ITA (LITA) to the left anterior descending artery (LAD) supplemented with SVG grafting to other coronary territories, an increasing number of surgeons are maximizing the use of arterial grafts, when possible, to all coronary territories. Coronary artery bypass grafting has been shown to be superior to percutaneous coronary intervention (PCI) and is established as the standard of care for treating patients with multi-vessel coronary artery disease (CAD) (2,3). However, despite evidence that PCI is associated with a long term increase in cardiovascular morbidity and need for repeat revascularization, cardiac surgeons still compete with a procedure which offers a quick and minimally invasive alternative to open surgery.

Total arterial revascularization (TAR) has been shown to improve survival and reduce morbidity in patients with triple vessel disease (4). Even in patients receiving vein grafts, addition of a second arterial conduit, particularly on the left system, confers a significant survival advantage (5). By using the ITA and radial arteries it is possible that TAR can be performed in the majority of patients with reproducible and excellent outcomes. Despite the evidence for arterial grafting and its increasing use, it is often the historical outcomes of

LITA coupled with SVG grafting that are most commonly quoted in discussions comparing PCI to surgical therapies. It is becoming increasingly important that we report early and long term results with contemporary arterial grafting techniques and use these results as the new benchmarks with which PCI is compared. This review will detail the early history of coronary surgery, the evolution of arterial grafting, and some of the current controversies in this field.

The early evolution of coronary artery bypass grafting

Alexis Carrel was one of the first surgeons to fully appreciate the relationship between anginal symptoms and obstructive coronary artery disease, which led him to perform the first coronary artery bypass procedure. In 1910 he described a series of canine experiments which he hoped would treat coronary artery disease by creating a "complementary circulation" for the diseased native coronary arteries (1). Carrel subsequently used the innominate and carotid arteries to achieve the first aorto-coronary bypass grafts. Despite this early description of CABG, surgeons were unable to translate these techniques successfully to humans due to a lack of technology and tools to operate on the unsupported beating heart.

The LITA was used in humans as early as 1945 by Arthur Vinberg, who, instead of anastomosing the LITA to the LAD, implanted it directly in the myocardium of the left ventricle (6). The "Vinberg Procedure", as it has become to be known, had variable success but often led to symptomatic improvement. With the advent of direct coronary anastomosis the Vinberg procedure is now infrequently performed. However, there are some recent reports of coronary collateral patency of the LAD as late as 30- (7) and 35-years (8) following intra-myocardial LITA implantation. Interest in the Vinberg procedure has been rekindled as of late with experimental studies combining intramyocardial implantation of the LITA with intra-myocardial stem cell therapy as a treatment for end stage inoperable CAD (9).

In 1952, Demikhov described the use of the LITA to directly graft the LAD in dogs, with graft patency confirmed for up to 2-years (10). Similar early success with the use of the ITA was reported by Canadian surgeon Gordon Murray (11), along with other surgeons including Sabiston (12) and Goetz (13).

Well aware of the vital importance of his predecessors' contributions to direct coronary revascularization, Vasilii I. Kolesov gave credit to Demikhov, Murray, Goetz, and Pronin in his first article reporting successful clinical CABG (14). In Kolesov's early animal studies, he used a modified collapsible cannula to create an anastomosis between the ITA and a coronary artery without interruption of coronary blood flow. Eight dogs underwent follow-up for as long as 19-months, and the patency of the anastomosis was demonstrated in all animals. On 25 February 1964, the same year that Spencer performed the first LITA anastomosis to the LAD in the US (15), Kolesov performed the first successful CABG using the suture technique. With specially designed magnifying glasses and scissors, he grafted the LITA to the left circumflex artery in a patient, who remained free of angina during 3-years of follow-up (16). He was also the first surgeon to use coronary stapling clinically and to advocate for the use of off-pump CABG (OPCAB). In the early 1960s, Kolesov conducted a study on artificial circulation, concluding that while cardiopulmonary bypass was safe and reliable for use during open heart surgery, the global inflammatory response following extracorporeal circulation was too great to justify its use for CABG. By the end of the 1960s, the extracorporeal circulation technique was as well established in Kolesov's clinic as anywhere else in the world. Kolesov continued to perform CABG without extracorporeal circulation, believing in the superiority of the off-pump technique. In his own practice, between 1964-1974, only 18% of his CABG procedures were performed on pump. In the late 1970s, Kolesov demonstrated both the excellent patency rates and functional results of CABG using angiography (17). Upon his retirement in 1976, Kolesov published a monograph devoted entirely to CABG. After retirement, he continued his long-term follow-up studies.

Up until the late 1950s, the main obstacle to the evolution of CABG surgery was an inability to image the coronary tree and link symptoms with specific patterns of obstructive coronary disease. On October 30th 1959, Mason Sones of the Cleveland Clinic inadvertently performed the world's first coronary angiogram. While undertaking an aortogram on a 24-year-old man with rheumatic heart disease he accidently injected contrast into the right coronary artery (18). This led to the birth of coronary angiography and intense interest in coronary imaging, which generated a greater understanding of coronary anatomy.

The ability to image the coronary arteries allowed Sones and his colleagues, including Donald Effler and Rene Favalaro, to describe two distinct patterns of CAD, namely proximal and diffuse obstructive disease. The Cleveland group initially advocated alternative management strategies for these two patterns, recommending localized patch grafting for proximal disease and the Vineberg procedure for diffuse disease (19). Interestingly, in 1966 Favalaro reported to have performed bilateral internal thoracic artery (BITA) grafting using the indirect Vinberg technique where the RITA was placed in the left ventricle (LV) parallel to the LAD and the LITA in the lateral wall of the LV between the branches of the circumflex and right coronary arteries with good clinical result (19).

Whilst the Cleveland Clinic reported reasonable results with the indirect Vineberg technique they had a high mortality rate (11 of 14 patients) with the proximal patch graft technique. The high mortality associated with direct coronary patching led to the use of the saphenous vein. Initially, in May 1967, the saphenous vein was used in an end-to-end fashion to replace an occluded segment of the right coronary artery and then soon after as a free aorto-coronary bypass graft to the LAD (19). By October 1967 Favolaro reported the use of the saphenous vein graft in direct coronary surgery in 180 patients (20). This was an important landmark in the birth of modern coronary surgery. Although the origins of coronary surgery began with the arterial graft, the saphenous vein, with its technical ease of harvest, its robust handling characteristics and its versatility as an aorto-coronary graft, simplified the conduct of the operation and allowed for widespread reproducibility.

However, even in the early days of saphenous grafting it was recognized that the saphenous vein was prone to failure, with pathological reports of intimal and medial thickening and graft thrombosis (21). Over time it has become apparent that because of accelerated intimal hyperplasia and premature atherosclerosis, the SVG has a significantly lower patency than its arterial counterparts (22). In combination with the excellent outcomes seen with widespread introduction of ITA grafting, the limitations associated with the SVG have fueled the interest in arterial grafting in contemporary surgical practice.

The introduction and subsequent revival of the radial artery

Alain Carpentier first used the RA in 1971 (23). However, within 2 years of adopting the RA there were reports of early failure rates (24) and significant intimal hyperplasia (25), which resulted in almost complete abandonment of its use as a graft. Techniques of early RA harvest, particularly skeletonization, resulted in vessel trauma and spasm. When this was combined with the use of mechanical dilatation it likely led to endothelial injury and subsequent early graft failure.

Due to the early inferior patency rates as compared to the SVG, the RA remained a "forgotten conduit" until its use was reported again by Christophe Acar in 1992 (26). In this later experience Acar and colleagues used a more refined "no-touch" method of graft harvesting and used pharmacological rather than mechanical vasodilatation to overcome RA spasm. It was through this better understanding of graft physiology and protection of the endothelium that Acar was able to demonstrate 100% RA patency on early postoperative angiography (26).

Further reports of excellent outcomes with the RA (27,28) coupled with a number advantageous characteristics (for example, ease of harvest, ability to reach all coronary territories, size match with the coronary arteries, uniform caliber along length of graft) led to the widespread adoption of the RA as the second or third arterial graft of choice. A number of randomized trials have compared the RA to the SVG or the free right internal thoracic artery (FRITA) predominately as the graft of choice to the best non-LAD target. Both the RAPS (29-31) and the RSVP (32) studies showed the RA to have superior patency on 5-year angiographic follow-up. In contrast, the short term VA cooperative study by Goldman and colleagues (33) and our own mid-term results from the RAPCO study suggested comparable patency rates between the RA, SVG and FRITA (27,34-37).

The excellent patency of the SVG seen in these compared to historical reports (22) may possibly be explained by the meticulous selection, atraumatic harvest and pharmacological preparation and storage prior to grafting in contemporary practice (38). Coupled with improved post-operative medical management and secondary cardiovascular protection measures the SVG may prove to be a reasonable graft choice at least in mid-term follow-up. However, as vein graft patency declines dramatically in the 5-10 year period following surgery (39), it may be that final reports of long-term follow-up may yield superior results with the RA.

Finally, the RA appears to have other significant advantages when compared to the SVG. RA harvest allows for quicker and easier ambulation following surgery and is associated with fewer wound complications and higher patient satisfaction in both the short- and long-term (40-42). These clinical outcomes must not be forgotten, as they are often extremely important to patients.

The internal thoracic artery

While the ITA was routinely used by surgeons as early as the 1970s, it was not until the mid-1980s that the significant influence its use had on clinical outcome was recognized. Floyd Loop and the Cleveland Clinic group were the first to report improved clinical outcomes with the use of the ITA when compared to vein grafting alone (43). They showed that ITA use was associated with improved survival, reduced risk of myocardial infarction, reduced risk of hospitalization and a reduced requirement for repeat revascularization over 10 years. With increasing use of the ITA it also became apparent that it was not only associated with a long-term survival advantage but also with improved early outcomes and a reduction in early peri-operative death. This finding was seen in both low- and high-risk individuals (44).

Following the obvious benefits of single ITA grafting to the LAD many groups postulated that two ITAs would further improve outcomes (45). A sentinel paper by the Cleveland group in 1999 confirmed that BITA grafting was associated with greater survival and reduced need for repeat revascularization when compared to single ITA grafting (46). Furthermore, *in situ* ITA grafts were shown to have a superior patency when compared to free ITA, RA and SV grafts (47-49), although it was not clear what the best configuration would be for bilateral ITA grafting. Many groups, including our own, reported suboptimal results when an *in situ* RITA was grafted to the right coronary system (50) and equivalent patency rates when comparing a free ITA and the RA grafted in a non-LAD territory (51). It is likely that the best outcomes from BITA grafting are seen when the ITAs are used to graft the left system and the right coronary supplemented with a radial graft.

Despite the almost universal use of the LITA and evidence to suggest improved outcomes with BITA grafting (52), RITA harvest and BITA grafting is performed worldwide in the minority of CABG operations [approximately 4% in the US (53) and 11.5% in Australia (54)]. There are a number of perceived disadvantages to BITA grafting, including the increased length of operative time and the requirement for an *in situ* RITA to cross the midline or to go through the transverse sinus to reach the LAD or circumflex systems. Probably the most frequently cited reason for not using BITA is the increased risk of sternal wound breakdowns. It is apparent that in certain groups harvesting bilateral ITAs may lead to an increased risk of sternal wound problems from sternal devascularization and surgical trauma associated with harvest. This is particularly apparent in those with severe airways disease, the obese and in diabetics (55).

The use of a skeletonized harvest technique, however, has been shown to reduce the risk of sternal wound complications (56). Many groups have reported no significant increase in the risk of sternal problems in BITA grafting using a skeletonized technique in higher risk patients (including diabetics) when compared to a standardized single pedicled ITA (57). Despite this there remain concerns about sternal devascularization with BITA grafting, and the 1-year results from the ART trial have shown a minor increase (1.3%) in sternal wound problems when both ITAs are used (58). The inconsistent use of skeletonization, coupled with concerns of wound problems, have contributed to variable uptake in the BITA grafting technique.

Refining the technique of total arterial revascularization

Other arterial grafts, including the gastroepiploic, inferior epigastric, and ulnar arteries, have been employed by many groups. However the ease of harvest and the excellent clinical results associated with RA and ITA use means that these conduits are rarely used. They are mostly chosen when there is a paucity of conduit options or by enthusiasts who require an additional arterial conduit to achieve TAR in selected patients. A number of auxiliary arterial grafting techniques pioneered by surgeons such as Barner (59) and Tector (60,61) have facilitated the extent and use of arterial conduits. These include sequential grafting, T- and Y-grafting, graft extension techniques in various combinations, and are described later in the 'Art and Techniques' section of this issue.

The future of total arterial revascularization

The SYNTAX trial is probably the most important contemporary trial that will influence the future practice of coronary surgery. SYNTAX has shown us in both a randomized and a real world setting that CABG is superior to PCI in the management of patients with all but the simplest patterns of coronary artery disease (62). This has already prompted the European Society of Cardiology and the European Society of Cardiothoracic Surgeons to adopt CABG as a Class 1A recommendation, favored over PCI, for most patterns of CAD (2). If, as surgeons, we adopt a strategy of optimizing and maximizing the use of arterial grafts to improve outcomes we will hopefully see even stronger recommendations for surgery in future guidelines and reinforce CABG as the preferred and recommended treatment for most forms of CAD.

The ART trial is the largest randomized study (over 3,000 patients) to date designed to compare outcomes in single versus bilateral ITA use (63). The preliminary reported 1-year results have suggested similar outcomes in the single and bilateral ITA groups but with a small increase (1.3%) in the need for sternal reconstruction in the BITA cohort (58). The final 10-year outcomes from the ART trial will indicate whether the survival benefits and reduction in cardiovascular events in the BITA group will justify the routine use of both ITAs.

With an ageing and increasingly complex cohort of patients undergoing CABG it remains to be proven if there is are significant advantages to BITA grafting and TAR in older patients. Debate already exists as to what age the advantages of TAR (and in particular BITA grafting) loses effect. While it is apparent that the use of at least one ITA graft improves survival even in octogenarians (64), the advantages of BITA grafting appears to reduce with advancing age (65). For these reasons some groups suggest that there is no benefit to using both ITAs in patients over 70 years of age (66). Longer follow-up and increased experience and reporting will dictate the use of these techniques in the elderly group of patients.

Total arterial, anaortic OPCAB grafting is being advocated by many groups as the optimal operative strategy for coronary revascularization. In a recent meta-analysis there has been a suggestion that anaortic OPCAB is associated with a reduction in neurological events due to avoidance of aortic manipulation (67). When coupled with the survival advantage associated with TAR it is an attractive alternative to conventional on-pump surgery. However, due to a concern regarding reduced patency rates with OPCAB surgery (68,69), this technique has not gained widespread acceptance and many surgeons limit its use to patients with heavily calcified aortas in whom the risk of stroke with clamping is the greatest.

Radial access coronary angiography (RA-CA) is exerting a major influence on the use of the RA in our current surgical practice. Cardiology literature has shown that RA-CA is associated with decreased mortality in patients with ST-elevation myocardial infraction and is associated with fewer vascular complications when compared to the trans-femoral route (70). However, from a surgical perspective RA-CA has significant adverse effects on the RA and is associated with increased intimal and medial thickness and intimal hyperplasia (71), abnormal endothelial responses (72) and causes occlusion and stenosis of the RA (73). Worryingly, these findings are not limited to the access point in the RA and appear to affect its entire course (74). Also, if the RA is used as a graft following RA-CA it demonstrates significantly reduced rates of patency even on short-term follow-up (75). Where possible we avoid the use of the RA following RA-CA. However, how the increase in the rates of RA-CA influences future practice, and in particular, the use of bilateral RAs, remains to be seen.

Although the birth of coronary surgery began with early pioneers experimenting with the arterial graft, the widespread adoption of the SVG caused its use to decline. We have now come full circle as we acknowledge the limitations and failures associated with the SVG and the many advantages of arterial grafting. To cement CABG as the preferred treatment for patients with CAD we must ensure that we continue to design and report the results of high quality, surgically driven studies that will allow us to select the optimal grafting strategy and ensure excellent clinical outcomes for those who require coronary revascularization.

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