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Is total arterial coronary artery bypass grafting the next step forward?

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Abstract

Total arterial coronary artery bypass grafting (TAR) has emerged as a superior strategy in coronary revascularization due to its ability to enhance long-term graft patency and reduce postoperative adverse cardiac events compared to traditional saphenous vein graft (SVG)-based approaches. While coronary artery bypass grafting (CABG) remains the cornerstone for treating multivessel coronary artery disease, its historical reliance on SVG has been increasingly challenged by the recognized durability and superior clinical outcomes associated with arterial grafts, such as the internal mammary artery (IMA) and radial artery. This article highlights the advantages of TAR over both single arterial grafting (SAG) and multiple arterial grafting (MAG), emphasizing its potential to eliminate the long-term vulnerabilities associated with venous conduits. However, the adoption of TAR faces significant barriers, including perceived technical complexity, increased operative duration, and concerns over complications such as deep sternal wound infections, particularly when bilateral IMA grafts are used. In contrast, MAG represents a transitional approach that incorporates arterial grafts alongside SVG to mitigate these challenges, offering surgeons flexibility while advancing toward arterial revascularization. Despite growing evidence favoring TAR, its widespread implementation is limited by a lack of large-scale randomized trials and logistical challenges in training and execution. This article provides a balanced discussion of the benefits and limitations of TAR, exploring its role in contemporary CABG practice and its potential to redefine coronary revascularization strategies.

Keywords: Coronary artery bypass grafting, total arterial revascularization, multiple arterial grafting, survival outcomes, radial artery, internal mammary artery, saphenous vein graft

THE EVOLUTION OF CORONARY REVASCULARIZATION

Coronary artery disease (CAD) remains the leading cause of death around the world[1], characterized by atherosclerotic plaque formation and rupture, leading to eventual myocardial ischemia and infarction[2]. Since 1990, deaths from acute myocardial infarction have fallen by 50%, owing to continued developments in percutaneous coronary intervention (PCI) and coronary artery bypass grafting (CABG) as primary interventions for CAD and acute coronary syndromes[2]. Despite improvements in mortality risk, the prevalence of CAD will continue rising due to an aging population, demanding continued innovation and evolution in primary treatment modalities[3].

Worldwide, CABG is the most frequently performed cardiac surgery procedure, with approximately 400,000 procedures completed annually in the United States[4]. CABG has an extensive history, with the 1960s marking a “renaissance” period in its development. The first major successful procedure on a human was performed in 1960 by Robert Goetz with a right internal mammary artery (RIMA) to right coronary artery (RCA) graft in a male taxi driver. Russian surgeon Vasili Kolesov completed the first off-pump bypass surgery with a pedicled RIMA to RCA graft, and was later dubbed the “father of off-pump CABG”[5]. New York surgeon George Green performed the first left internal mammary artery (LIMA) to left anterior descending artery (LAD) in 1968, which has remained the gold standard in modern practice[6]. It was also at this time that Argentine surgeon Rene Geronimo Favaloro pioneered the end-to-side anastomosis with the saphenous vein graft (SVG), and used this technique in conjunction with bilateral or single internal mammary artery (IMA) grafting[4]. By 1985, the propensity of SVG to develop accelerated atherosclerosis became readily apparent, compared to the IMA graft which showed ongoing disease-free patency[7]. It was then reported by Loop *et al.* in 1986 that patients with LIMA grafts (with supplementary SVG) demonstrated significantly better survival, compared to patients who exclusively received SVG[8]. The use of the radial artery (RA) conduit was first reported by Carpentier[9] in 1972, but was quickly abandoned due to poor initial graft patency, though relevant evidence was not formally reported in literature. Inferior patient outcomes and accelerated atherosclerosis with the use of SVG prompted the revival of the RA conduit by Acar[10] in 1992, with promising graft patency results, which have been replicated by other centers into the 21st century[11-16]. RA grafting reduces the risks of myocardial infarction, all-cause mortality, and repeat revascularization compared to SVG[17-20]. Despite this development, approximately 95% of CABG procedures worldwide continue to supplement LIMA-LAD grafts with the use of the SVG in circumflex (Cx) and RCA territories[20,21]. The gastroepiploic artery (GEA) is an additional arterial conduit first used in 1973[4], which has also since demonstrated patency rates superior to SVG[22-24]. However, it is rarely used outside of Asia in conventional practice[4]. Recently, robotically assisted CABG procedures have occurred with increasing frequency, potentially carving the landscape of the future practice of cardiothoracic surgery. However, procedures of this nature currently only account for less than 1% of CABG performed in the U.S.[25], owing to the challenges of surgeon training, longer operative duration, and greater cost of delivery[26].

Since the first successful LIMA-LAD graft by surgeon George Green in 1968[6], this configuration has remained the “gold standard”, described as the most important primary coronary graft[27]. Since CABG is recommended over PCI in patients with multivessel or anatomically complex CAD[28], a supplementary conduit is often required to revascularize the other non-LAD targets[28,29]. The selection of additional conduits has remained a controversial topic among cardiothoracic surgeons from different continents[20]. The use of supplementary SVG has remained prevalent since its introduction by Favaloro[4], constituting up to 80% of conventional CABG practice[30], making it the most frequently used conduit worldwide[20]. The use of bilateral internal mammary artery (BIMA) conduits as a method of exclusive use of arterial grafts, referred to as total arterial revascularization (TAR), has demonstrated superior patency and survival compared to non-TAR, but this approach is often avoided due to deep sternal wound infections (DSWI) associated with IMA harvestings[1,31]. This complication has, in part, resulted in the extensive use of the RA conduit in most TAR approaches to grafting[1], commonly reported in centers outside North America. The 15-year outcomes of the radial artery patency and clinical outcomes trial (RAPCO) demonstrated that the RA as a second choice conduit was associated with superior patency, survival, and reduced major adverse cardiovascular events (MACE), compared with RIMA and SVG[32]. These improved long-term outcomes have led to the American Heart Association's (AHA) recommendation that the RA should be used as a secondary conduit over both RIMA and SVG[33]. While this is an encouraging development, our institutional experience suggests that the RA conduit is equivalent to any IMA graft and should therefore be considered alongside the LIMA in conduit selection, rather than exclusively as a secondary option. From our data, we observed equivalent patency and perfect patency between these conduits[15,34], with both displaying preserved perfect patency status and resistance to the development of atherosclerosis from our observations with serial angiography[16]. Few other studies have directly compared RA with IMA grafts, leaving a potential evidence gap.

CABG OR PCI

The primary objective in treating CAD is to restore or improve perfusion to ischemic or undersupplied myocardial tissue[35]. PCI achieves this through angioplasty to dilate the site of primary stenosis within a native coronary artery, subsequently maintaining vessel patency with the deployment of a drug-eluting stent[3,35]. However, PCI is inherently limited to addressing the localized "site of disease", a strategy often referred to as a "spot intervention"[36]. By contrast, CABG offers a distinct revascularization approach, where grafts are placed distal to the stenotic or occluded coronary segment, thereby creating an alternative route for myocardial blood supply that circumvents areas of diffuse coronary pathology[1].

In patients undergoing PCI, complications such as in-stent restenosis remain prevalent and are a leading cause of recurrent myocardial infarction and increased mortality, risks that are notably reduced in patients receiving CABG[1,3,35,36]. The long-term success of CABG is primarily dependent on the patency of the grafts distal to the diseased segment, which are unaffected by the progression of proximal native coronary artery disease[35]. This fundamental difference in the mechanisms of revascularization is reflected in clinical outcomes, as demonstrated by several randomized controlled trials (RCTs). For instance, the 5-year SYNTAX trial revealed that PCI was associated with a higher incidence of myocardial infarction, all-cause mortality, and major adverse cardiac and cerebrovascular events (MACCE) compared to CABG[37]. Similarly, the FREEDOM trial showed that in patients with diabetes and multivessel disease, CABG significantly reduced mortality and myocardial infarction rates at 5 years post-intervention[38]. Furthermore, a recent meta-analysis of 11 RCTs comparing PCI and CABG at 5-year follow-up found higher incidences of all-cause mortality, myocardial infarction, and repeat revascularization in the PCI cohort[39]. It is worth noting that saphenous vein grafts have a pronounced tendency to develop aggressive atherosclerosis in the proximal coronary artery, often leading to chronic total occlusion of the native vessel. This complication can pose considerable challenges for subsequent PCI revascularizations in the event of a graft failure[40].

Given these findings, current guidelines from the American Heart Association (AHA) recommend CABG over PCI for the majority of patients with chronic CAD, particularly those with significant left main disease, high anatomical complexity, or multivessel disease, as CABG provides more substantial survival benefits[33]. This recommendation is especially relevant in diabetic patients with complex CAD, as CABG minimizes the risks of mortality and the need for repeat revascularization. PCI is generally relevant for patients who are poor surgical candidates or diabetic patients with less complex CAD to reduce postoperative recovery time.

SHIFT TOWARD ARTERIAL REVASCULARIZATION

The conventional CABG configuration utilized in 95% of procedures globally is single arterial grafting (SAG), which relies on the SVG as supplementary conduits alongside the LIMA to the LAD. However, the growing body of evidence has prompted a paradigm shift toward favoring the increased use of arterial grafts. The recognized durability of arterial grafts, in contrast to the atherosclerotic susceptibility of SVGs, which are associated with a high rate of late graft occlusion and, therefore, adverse clinical outcomes, has promoted this change[19,41]. A systematic review of individual patient-level data from six randomized trials reported a 56% relative reduction in graft occlusion rates in RA compared against SVG (hazard ratio [HR], 0.44; 95% confidence interval [CI], 0.28 to 0.70; $P < 0.001$). The superior long-term patency translated into a significantly reduced risk of death, myocardial infarction, and repeated revascularization (HR 0.67; 95%CI: 0.49-0.90; $P = 0.01$)[42]. Similar improvement in long-term patency and clinical outcomes has also been observed in internal mammary artery conduits compared to SVG with 10-year follow-ups[15,43].

As a result, conduit selection in CABG has evolved, with the primary goal of either completely avoiding or reducing the use of SVG from routine practice by using more arterial grafts[1,44]. The current trend in the surgical community favors the latter option, which increases the frequency of arterial graft use with or without concomitant SVG[1,4,41], a practice referred to as multiple arterial grafting (MAG). This differs from TAR, which exclusively uses arterial grafts, completely omitting SVGs[45].

TAR: A PURSUIT OF OPTIMAL LONG-TERM REVASCULARIZATION

TAR, a technique aimed at achieving complete arterial revascularization, has garnered attention for its potential to deliver superior long-term graft longevity, offering an alternative approach to challenge conventional CABG practices. Our multinational retrospective analysis of 127,565 risk-adjusted patients revealed a significant reduction in all-cause mortality associated with TAR compared to non-TAR (HR 0.78; 95%CI: 0.72-0.85; $P < 0.001$). A Bayesian meta-analysis confirmed these findings by indicating a 99.9% probability that TAR is the superior grafting strategy[21]. Similarly, a comparison conducted by Rocha *et al*. demonstrated that compared to vein-graft-dependent operations, TAR was associated with improved long-term freedom from major adverse cardiac and cerebrovascular events (HR 0.78; 95%CI: 0.68-0.89), further supporting its clinical benefits[46]. The consistently observed survival difference is likely attributed to the complete avoidance of the problematic venous conduit, positioning TAR as an optimal long-term solution when technically feasible based on the patient's specific clinical circumstances. The recently launched Total Arterial (TA) Trial in Australia is a multicenter, randomized controlled trial designed to address the comparative outcomes of isolated TAR *vs*. non-TAR procedures. The trial aims to enroll 1,000 patients across 17 sites. To ensure generalizability, all aspects of intraoperative, perioperative, and postoperative management will follow the usual practices of the treating team, with the exception of the randomized treatment allocation. The primary endpoint of the trial is the number of perfectly patent grafts at 24 months, assessed using CT coronary angiography (CTCA). Secondary endpoints include CTCA at three months to evaluate the impact of competitive flow, clinical outcomes such as major adverse cardiac events (MACE), all-cause mortality, postoperative quality of recovery as measured by the postoperative Quality of Recovery Scale (PostopQRS), and a comprehensive health economics analysis to assess cost-effectiveness. This study is expected to provide robust evidence that may significantly impact existing clinical guidelines, ensuring that treatment protocols are grounded in the most reliable and current data[47].

Despite the growing body of positive evidence, broader adoption of TAR has encountered several challenges: (1) the perceived technical difficulties associated with arterial graft harvesting and revascularization; (2) concerns about increased postoperative complications, such as sternal wound infections, particularly when bilateral internal mammary arteries are utilized; (3) the perceived longer operation times; (4) the absence of a large-scale prospective randomized trial to provide definitive, unbiased evidence; and (5) a lack of financial incentives for surgeons, given the perception of longer and more complex operations. These limitations are perceived to be more pronounced in TAR than for MAG techniques, therefore restricting its global implementation. MAG, on the other hand, may serve as a transitional approach, balancing innovation with the learning curve of surgical execution, by offering the flexibility to incorporate SVG for surgeons who may not yet have complete confidence in performing full arterial grafting. TAR is a strategy to eliminate SVG - the conduit known to predictably fail - and its attainment is not dependent on the number of grafts, but rather, the number of venous grafts being zero.

MAG: A TECHNIQUE OF TRANSITION

While TAR advocates for an all-arterial approach, MAG represents a transitional alternative, allowing surgeons to combine multiple arterial conduits with the selective use of SVG if needed. This approach is especially relevant to surgeons who are unfamiliar with using more than one arterial graft. Recent data from the Society of Thoracic Surgeons Adult Cardiac Surgery Database shows a steady rise in MAG usage over the past several years, with the frequency of MAG increasing from 14.3% in 2020 to 15.9% in 2021[41] largely driven by accumulating evidence from MAG *vs*. SAG comparisons, which consistently favor the use of additional arterial conduits due to their superior long-term patency compared to vein grafts. A propensity-matched investigation from British Columbia documented that MAG substantially reduced the risk of mortality (HR 0.79; 95%CI: 0.72-0.87) and myocardial infarction (HR 0.63; 95%CI: 0.47-0.85) in comparison to SAG at 15 years postoperatively[48]. Another analysis conducted by Locker *et al.* involving 8,622 patients with multivessel disease also reported a 35% improvement in survival after 15 years of follow-up[49]. These clinical benefits have also been observed in female, diabetic, and elderly patients[50-52] with more complex coronary disease profiles, underscoring the important function of MAG in a diverse range of patient populations. The ROMA trial is expected to provide definitive evidence on whether multiple arterial revascularization offers significant clinical advantages over single arterial grafting[53].

THE COMPETING STRATEGIES OF MAG AND TAR

Despite a growing trend toward MAG, approximately 95% of patients globally continue to receive ≥ 1 SVG in standard CABG procedures[21]. While MAG is gaining wider recognition, MAG still relies on the use of SVG, which can be considered a “ticking time bomb” for patients with a propensity to develop late atherosclerotic occlusions. These occlusions may unpredictably result in severe cardiac complications and the need for repeat revascularization.

Our recent retrospective observational cohort study demonstrated a significant reduction in late mortality (HR 0.85; 95%CI: 0.80-0.91; $P < 0.001$) among patients receiving TAR compared to those undergoing MAG that included the use of SVG[1]. Notably, the survival benefit associated with MAG diminished when the analysis accounted for the inclusion of SVGs, indicating that the presence of venous grafts substantially limits the advantages of MAG. A meta-analytic investigation by Yanagawa *et al.* further confirmed a significant reduction in all-cause mortality with TAR compared to MAG, based on matched observational studies[54]. The Arterial Revascularisation Trial[55] remains the largest multicenter unblinded RCT in this field, enrolling 3,102 patients who were assigned to either bilateral or single IMA grafting. The primary intention-to-treat analysis found no difference in all-cause mortality at the 10-year follow-up, likely influenced by the high crossover rate (16.4%) and the use of supplementary SVGs in both groups. A subsequent post hoc comparison of MAG and TAR *vs*. SAG demonstrated improved survival with both techniques, though TAR appeared to offer even greater advantages, further emphasizing the potential benefits of entirely avoiding venous conduits[56]. It is important to recognize that the conclusions drawn from observational or post-hoc studies are limited by selection bias, residual confounding, and the absence of randomization. These factors may influence the observed advantages of TAR over MAG and highlight the need for a cautious interpretation of the findings.

Approximately 95% of patients worldwide continue to receive at least one SVG in standard CABG practice, underscoring the significant work still needed to advance the shift toward arterial-based revascularization strategies. Although the adoption of MAG is steadily increasing, the persistent reliance on SVG highlights the ongoing need to optimize graft selection and further refine surgical techniques[21].

CONCLUSION

The evolution of coronary revascularization from its inception to contemporary practice underscores significant advancements and ongoing challenges in managing CAD. While PCI has seen remarkable innovations, such as drug-eluting stents, its limitations in addressing diffuse coronary pathology highlight the enduring relevance of CABG. The historical and current reliance on saphenous vein grafts in CABG, despite their known long-term vulnerabilities, stresses the necessity of advancing arterial grafting techniques. Total arterial and multiple arterial revascularization techniques have emerged as superior strategies due to their enhanced patency and survival benefits, demonstrating particularly promising outcomes in diverse patient populations. However, the widespread adoption of TAR is hindered by technical challenges and the risk of complications like deep sternal wound infections, which are less prevalent in MAG, making it a practical interim strategy. Future research should focus on conducting large-scale prospective randomized trials to solidify the evidence base, providing clear guidelines for conduit selection that could shift global practice toward exclusive arterial revascularization.

DECLARATIONS

Author's contribution

Conceptualization, manuscript writing, manuscript review: Ren J
Manuscript writing: Siderakis C
Conceptualization, supervision, manuscript review: Royse C
Manuscript writing: Hwang B
Conceptualization, supervision, manuscript writing, manuscript review: Royse A

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Not applicable.

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Not applicable.

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