European Journal of Cardio-Thoracic Surgery 2023, 64(2), ezad163
https://doi.org/10.1093/ejcts/ezad163

REVIEW

Cite this article as: Gaudino M, Bakaeen FG, Sandner S, Aldea GS, Arai H, Chikwe J *et al*. Expert systematic review on the choice of conduits for coronary artery bypass grafting: endorsed by the European Association for Cardio-Thoracic Surgery (EACTS) and The Society of Thoracic Surgeons (STS). Eur J Cardiothorac Surg 2023; doi:10.1093/ejcts/ezad163.

Expert systematic review on the choice of conduits for coronary artery bypass grafting: endorsed by the European Association for Cardio-Thoracic Surgery (EACTS) and The Society of Thoracic Surgeons (STS)

Mario Gaudino [a,*], Faisal G. Bakaeen[b], Sigrid Sandner [c], Gabriel S. Aldea[d], Hirokuni Arai[e], Joanna Chikwe[f], Scott Firestone[g], Stephen E. Fremes[h], Walter J. Gomes [i], Ki Bong-Kim[j], Kalie Kisson[g], Paul Kurlansky [k], Jennifer Lawton[l], Daniel Navia[m], John D. Puskas[n], Marc Ruel[o], Joseph F. Sabik[p], Thomas A. Schwann[q], David P. Taggart[r], James Tatoulis [s], and Moritz Wyler von Ballmoos[t]

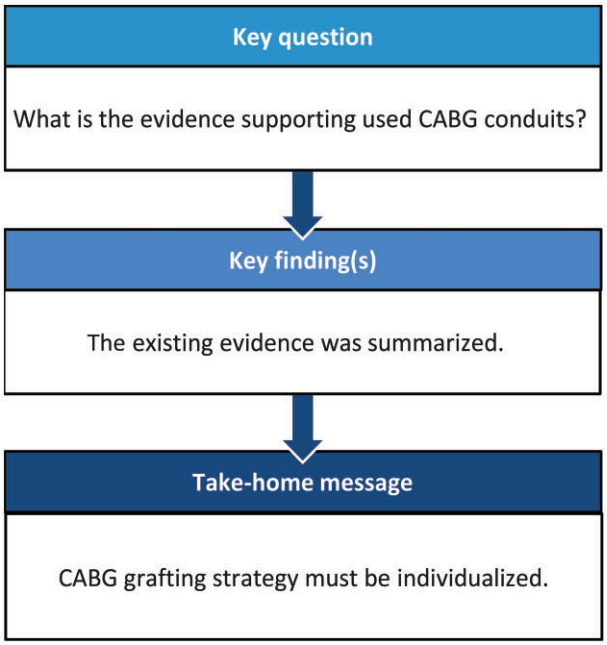
[a] Department of Cardiothoracic Surgery, Weill Cornell Medicine, New York-Presbyterian Hospital, New York, NY, USA
[b] Department of Thoracic and Cardiovascular Surgery, Cleveland Clinic, Cleveland, OH, USA
[c] Department of Cardiac Surgery, Medical University of Vienna, Vienna, Austria
[d] Division of Cardiothoracic Surgery, University of Washington School of Medicine, Seattle, WA, USA
[e] Department of Cardiovascular Surgery, Graduate School of Medical and Dental Science, Tokyo Medical and Dental University (TMDU), Tokyo, Japan
[f] Department of Cardiac Surgery, Smidt Heart Institute, Cedars-Sinai Medical Center, Los Angeles, CA, USA
[g] The Society of Thoracic Surgeons, Chicago, IL, USA
[h] Schulich Heart Centre, Sunnybrook Health Sciences Centre, and the Institute of Health Policy Management and Evaluation, University of Toronto, Toronto, ON, Canada
[i] Cardiology and Cardiovascular Surgery Disciplines, São Paulo Hospital, Escola Paulista de Medicina, Universidade Federal de São Paulo (Unifesp), São Paulo, SP, Brazil
[j] Cardiovascular Center, Myong-ji Hospital, Gyeong-gi-do, Republic of Korea
[k] Division of Cardiac Surgery, Department of Surgery, Columbia University, New York, NY, USA
[l] Division of Cardiac Surgery, Department of Surgery, Johns Hopkins University, Baltimore, MD, USA
[m] Department of Cardiac Surgery, ICBA Instituto Cardiovascular, Buenos Aires, Argentina
[n] Department of Cardiovascular Surgery, Mount Sinai Saint Luke's, New York, NY, USA
[o] Division of Cardiac Surgery, University of Ottawa Heart Institute, Ottawa, ON, Canada
[p] Department of Surgery, University Hospitals Cleveland Medical Center, Cleveland, OH, USA
[q] Division of Cardiac Surgery, Baystate Health, Springfield, MA, USA
[r] Department of Cardiac Surgery, John Radcliffe Hospital, University of Oxford, Oxford, UK
[s] Department of Cardiothoracic Surgery, Royal Melbourne Hospital, University of Melbourne, Melbourne, Australia
[t] Division of Cardiothoracic Surgery, Houston Methodist DeBakey Heart & Vascular Center, Houston, TX, USA

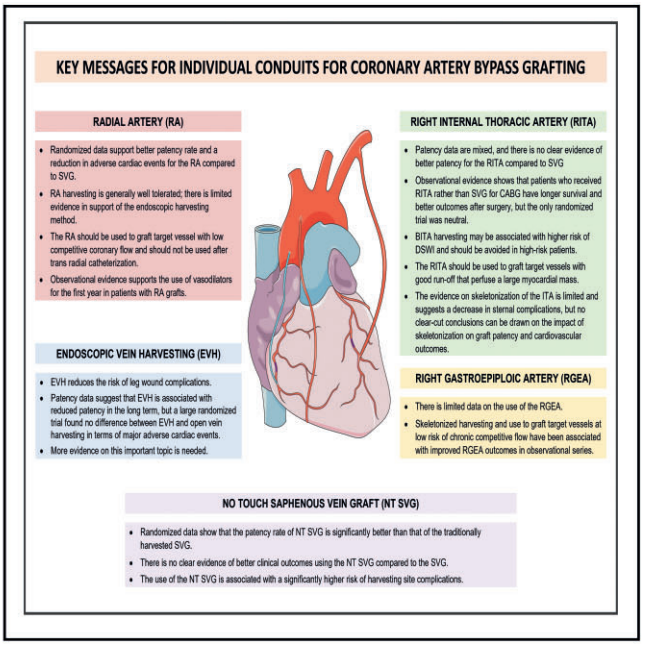
* Corresponding author. Department of Cardiothoracic Surgery, Weill Cornell Medicine, New York-Presbyterian Hospital, 525 E 68th St, New York, NY 10065, USA. Tel: +1-212-7469440; fax: +1-212-7468080; e-mail: mfg9004@med.cornell.edu (M. Gaudino).

Received 4 January 2023; received in revised form 10 March 2023; accepted 20 April 2023

Preamble: The finalized document was endorsed by the EACTS Council and STS Executive Committee before being simultaneously published in the *European Journal of Cardio-thoracic Surgery* (EJCTS) and *The Annals of Thoracic Surgery* (The Annals) and the *Journal of Thoracic and Cardiovascular Surgery* (JTCVS).

This article has been co-published with permission in the *European Journal of Cardio-Thoracic Surgery, The Annals of Thoracic Surgery, and the Journal of Thoracic and Cardiovascular Surgery*. All rights reserved. © 2023 European Association for Cardio-Thoracic Surgery, The Society of Thoracic Surgeons, and the American Association for Thoracic Surgery. The articles are identical except for minor stylistic and spelling differences in keeping with each journal's style. Any of the three citations can be used when citing this article.





ABBREVIATIONS

ART	Arterial revascularization trial
BITA	Bilateral internal thoracic artery
CABG	Coronary artery bypass grafting
CCB	Calcium channel blockers
CI	Confidence interval
CON SVG	Conventional saphenous vein graft
DSWI	Deep sternal wound infection
EVH	Endovascular vein harvesting
GEA	Gastroepiploic artery
HR	Hazard ratio
IRR	Incidence relative risk
ITA	Internal thoracic artery
LITA	Left internal thoracic artery
LAD	Left anterior descending
MACE	Major adverse cardiovascular events
MI	Myocardial infarction
MLD	Minimal lumen diameter
NMA	Network meta-analysis
NT SVG	No touch saphenous vein graft
OR	Odds ratio
OVH	Open vein graft harvesting
PICO	Population, intervention, comparator, outcomes
RA	Radial artery
RAO	Radial artery occlusion
RAPCO	Radial artery patency and clinical outcomes
RCA	Right coronary artery
RCT	Randomized control trial
RITA	Right internal thoracic artery
RGEA	Right gastroepiploic artery
SV	Saphenous vein
SVG	Saphenous vein graft
TRC	Transradial catheterization

INTRODUCTION

Coronary artery bypass grafting surgery (CABG) is the most common cardiac surgery operation in the USA and worldwide [1]. The first choice of conduit and standard of care is use of the left internal thoracic artery (LITA) to the left anterior descending (LAD) artery. While the saphenous vein graft (SVG) remains the most commonly used conduit for multivessel CABG, there is a variety of arterial conduits and technical variations of the SVG that may also be used for the operation. Individualization of the grafting strategy to the anatomic and clinical characteristics of each patient, as well as to the operating surgeon's experience and comfort with the different conduits, is key to the success of the operation. This document reviews and analyzes the existing evidence for the use of conduits for CABG.

METHODOLOGY

The leadership of the Society of Thoracic Surgeons (STS), American Association for Thoracic Surgery (AATS) and European Association for Cardio-Thoracic Surgery (EACTS) nominated a group of experts to systematically review the data on use of conduits in CABG as a comprehensive, international document. This paper reflects the opinion of the nominated authors as to how to approach and perform conduits selection in CABG.

Each of the members of the writing committee submitted conflict of interest disclosure forms, which were then reviewed by the co-Chairs of this document, the STS Joint Guideline Steering Committee and STS staff before confirmation for potential conflicts from relevant relationships with industry.

The writing committee then developed 5 questions for systematic review in the Population, Intervention, Comparator and Outcomes (PICO) format primarily related to comparisons of different grafts to the conventionally harvested SVG and to the use of endoscopic vein harvesting (EVH). The PICO questions were sent to a research

librarian in January 2021 to develop a strategy to identify relevant articles published in English with no time restrictions. Reference lists were manually scanned for additional relevant results. After duplicates were removed, this strategy resulted in 1009 potentially relevant abstracts, which were screened by 2 authors (S.F. and K.K.). A total of 166 articles met the inclusion criteria.

The primary reasons for exclusion were invalid patient populations (e.g. those receiving percutaneous coronary intervention), a focus on non-clinical outcomes and inadequate study design (e.g. lack of a comparison group or expert review). Two authors (S.F. and K.K.) developed an evidence table of the relevant papers and rated the studies for risk of bias. The Newcastle–Ottawa scale was used for observational studies, and a custom-made checklist was used for randomized control trials (RCTs) and meta-analyses.

Ethics statement

Ethics approval was not requested as no individual patient data were included.

Left internal thoracic artery to left anterior descending

The LITA-LAD anastomosis represents the universally accepted gold standard for CABG. In the USA, it is the only recognized CABG quality metric related to the technique of the procedure. The evidence in support of the use of the LITA to graft the LAD is based on observational studies from the '80s and '90s showing better patency rate and clinical outcomes compared to the SVG, as well as on the unique morphologic and biological properties of the LITA [2–4]. While no appropriately powered RCT has formally tested the LITA-LAD hypothesis, there is no professional nor individual equipoise in the surgical community for such a study.

RADIAL ARTERY

Patency

Multiple RCTs and meta-analyses of RCTs have reported an improved patency rate for the radial artery (RA) compared to the saphenous vein (SV) at mid- and long-term follow-up [5, 6].

An individual participant data meta-analysis of 6 RCTs found that the use of the RA rather than the SV was associated with a statistically significant reduction in graft occlusion [hazard ratio (HR) 0.44, 95% confidence interval (CI) 0.28–0.70; $P < 0.001$] at a mean follow-up of 4.2 years [7]. It is important to note that the RAs were used to bypass mainly circumflex arteries with severe stenotic lesions with very few patients receiving radial grafting to the right coronary system. While these RCTs include a relatively limited number of patients for a procedure as common as CABG, the reported benefit is consistent starting in as few as 4 years [8].

Long-term clinical outcomes

Several observational series have found improved short- and long-term outcomes in patients who received the RA rather than the SV as the second conduit. In a meta-analysis of 14 adjusted observational studies (20 931 patients), the use of the RA was associated with a 26% relative risk reduction in mortality at 6.6-year follow-up [9].

The aforementioned analysis of 6 RCTs also reported superiority for the RA in the composite outcome of death, myocardial infarction (MI) and repeat revascularization at 5 years follow-up (HR 0.67, 95% CI 0.49–0.90) [7]. When the follow-up of the same database was extended to 10 years, use of the RA was associated with a statistically significant reduction in the incidence of the composite of death, MI or repeat revascularization (HR 0.73, 95% CI 0.61–0.88) and of the composite of death or MI (HR 0.77, 95% CI 0.63–0.94); a *post hoc* survival benefit for patients receiving the RA was also found, although the absolute benefit was small (HR 0.73, 95% CI 0.57–0.93) [10].

A Veteran Administration trial of 757 patients found no difference in patency rate at 1 year between the RA and the SV [odds ratio (OR) 0.99, 95% CI 0.56–1.74] and no difference in survival at 14.6 years of follow-up (HR 1.12, 95% CI 0.91–1.38) [11, 12]. No data on cardiac events were available. The Radial Artery Patency and Clinical Outcomes (RAPCO) trial found better patency rate at 10 years for the RA compared to the free right internal thoracic artery (RITA) (HR 0.45, 95% CI 0.23–0.88) and the SV (HR 0.40, 95% CI 0.15–1.00) [13]: at 15 years of follow-up, the rate of the composite of death/MI and repeat revascularization were significantly lower in the RA arm (HR 0.74, 95% CI 0.55–0.97 vs the RITA and HR 0.71, 95% CI 0.52–0.98 vs the SV).

Hand function

It is generally accepted that assessing the adequacy of ulnar collateral circulation should always be performed before RA harvesting—assessing RA morphology by ultrasound allows also detection of potential calcification and measurement of the RA diameter. Comparative studies on different methods of evaluation are lacking, but the clinical Allen test is highly operator dependent and is best complemented by an objective assessment [14]. The site of harvesting should be the one with better ulnar compensation and artery quality—there is no evidence to support the concept that the artery should be harvested from the non-dominant arm although this has been the logical default approach. Harvesting of the RA is generally well tolerated; while arm paresthaesia and pain have been reported, symptoms are generally transient and self-limited [15], although long-term complications in some studies have been as high as 9% [16]. Ischaemic hand complications, or changes in arm grip strength or dexterity are extremely rare, although there may be a publication bias.

Vascular diseases of the upper extremities are generally considered a contraindication to RA harvesting. Previous forearm trauma is a relative contraindication, especially if operative repair was needed, as well as previous surgery on the forearm or the wrist.

In patients with chronic renal failure the potential benefits of using the RA for CABG must be weighed against the possible need for an upper arm arteriovenous fistula for dialysis, but evidence is lacking.

Proximal anastomosis

The RA can be anastomosed directly onto the aorta or to another conduit, typically the internal thoracic artery (ITA) as a Y or T graft—other configurations have been described but are seldom

used [17–19]. Most of the available evidence on the RA is based on aorta-anastomosed grafts, while some studies have indicated higher radial graft patency with the aortic anastomosis approach [20, 21], other data did not reveal a difference [22–25]. The aortic anastomosed configuration is probably less at risk of failure due to competitive flow [26].

From a technical point of view, concerns relating to high wall tension resulting from anastomosis of the RA directly onto the aorta have led some surgeons to craft a short interposition segment of SV, to which the RA is connected in end-to-end fashion. Whether this configuration negates some of the benefits of using the RA is not known.

Overall, data are currently insufficient to provide meaningful guidance on a preferred anastomotic technique.

Target vessel selection

Three factors are commonly considered: the degree of proximal coronary artery stenosis, the myocardial territory to be grafted and the size of the target vessel. There is ongoing controversy as to whether the RA should be used to graft target arteries with ≥90% proximal stenosis or ≥70% stenosis. In the RAPCO trial, grafted arteries required at least 70% proximal stenosis and a minimum diameter of 1.5 mm [13]. Similar inclusion criteria were used in the Radial Artery Patency Study (RAPS) [27]. Only 21 late radial graft failures occurred in RAPCO, therefore limiting correlational analyses. Observational series, often long-term, have showed that ≥90% proximal target stenosis correlates with better graft patency than ≥70%, and a right coronary territory target with lower patency, a finding observed with most arterial grafts [23, 28–31]. Limited information exists on ideal target vessel size, as trial patients were often selected to meet a minimum size. It is possible but unproven that the RA in comparison with a SVG, may be particularly suitable on small coronary targets—especially those with a high degree of proximal stenosis—due to the RA's more favourable match.

The Impact of Preoperative Fractional Flow Reserve on Arterial Bypass Graft Function (IMPAG) trial provided information on composite radial grafts, whereas a fractional flow reserve cut-off of 0.78 was predictive of anastomotic functionality at 6 months; however, most of the grafts used in IMPAG were ITA, not RA, grafts [17]. Available data remain susceptible to expertise, selection, recall, and publication biases.

Harvesting method

The RA can be harvested in open fashion or endoscopically, the latter typically performed through small incisions at the distal and proximal ends of the *in situ* conduit. While open harvest is not usually associated with major pain locally, its incision is long and can be unsightly. Endoscopic harvesting involves a learning curve and may be associated with harvest-related spasm, less thorough clipping of branches and endothelial dysfunction [32]. Patient satisfaction, however, appears enhanced by endoscopic harvesting [33]. Both techniques have been shown to be safe in expert hands [31, 34, 35].

Randomized data are sparse, involve small series and reveal short-term outcomes only. Most of the published RA trials employed open harvesting which, consequently, should be considered the standard. Available evidence with endoscopic radial harvest may be fraught with major expertise, selection, recall and publication biases and no clear conclusion on RA patency and outcomes using the endoscopic technique can be drawn.

Transradial catheterization

Previous catheterization of the RA is a contraindication to RA use for CABG, as there is evidence that the patency rate of RA grafts used for transradial procedures is significantly reduced compared to non-catheterized grafts [36] and it is known that transradial catheterization (TRC) produces significant endothelial damage [37].

After TRC complete radial artery occlusion (RAO) may occur in up to 38% [38]. Measures to reduce RAO include, smaller hydrophilic sheaths, nitroglycerine solution flushes and larger doses of heparin. Nevertheless, most current RAO rates are between 3% and 10% [39, 40]. Recanalization occurs but it may take months, or the RAO may remain permanent [38–40].

5F and 6F sheaths used for TRC are 7–10 cm long and the guidewires and catheters progressively traumatize the RA endothelium. Ultrasound, intravascular ultrasound [41] and optical coherence tomography studies [42, 43] have documented intimal tears in 37–80%, media dissection in 10–37% and an increase in intima and media thickening, a marker of RA endothelial and vascular wall trauma, and a precursor to atherosclerosis [41–43].

Histological and immunohistochemical examination of TRC-RA distal segments showed endothelial damage in all samples, with changes most pronounced if the instrumented RA was used within 24 h, still persisting though less prominent after several months [36, 37, 44, 45].

Excessive intimal hyperplasia in 68–73%, periarterial inflammation in 33%, fat and tissue necrosis in 26% were additional sequalae, most prominent in the 3 cm immediately upstream from the RA puncture, becoming less severe and less frequent proximally. These changes were not present in the non-instrumented RA [44, 45].

The diameter of the TRC-RA suffers a 10% reduction, most apparent in the distal 3 cm, which persists beyond 6 months [36, 37, 46]. As most RA punctures for TRC are 3–5 cm above the wrist [38], and the vascular trauma affecting the most distal 3 cm adjacent to the puncture, 6–8 cm of a 20 cm length RA may be 'unavailable' for use as a conduit—confining any potential instrumented RA use to a proximal coronary or as a Y graft. However, endothelial damage and dysfunction may not be confined to the distal portion of the artery, and the effect on graft patency is unknown.

Flow mediated dilatation assessed by ultrasound using the other RA as a control shows a significant 10% reduction compared to preinstrumentation and to the control, lasting up to 1 year after TRC [36, 37, 39, 47]; longer follow-up have not been investigated and there is no evidence that endothelial function ever return to normal.

Nitrate-mediated vasodilatation is also impaired—maximally impaired early after TRC. The impairment gradually lessens over the next 9–26 weeks [37, 46–51]. Endothelium dependent vasodilation is also impaired for up to a year [37].

Instrumented RAs used in CABG have reduced patency in the only 2 published studies: 70% patency for TRC–RA versus 98% in pristine RAs 1 month postoperatively ($P = 0.017$) [36], and a markedly reduced patency for TRC-RAs (59% vs 78%) at 18 months [52].

Calcium channel blockers

Prevention of perioperative RA spasm is key for successful RA grafting. Perioperative regimens, though varied, are well

established and include topical and intraluminal RA papaverine, nitroglycerine, nitroprusside, diltiazem, verapamil, milrinone and phenoxybenzamine [53, 54].

Some surgeons also use intravenous nitroglycerine or intravenous calcium channel blockers (CCBs) during surgery and for the first 12–24 h [53, 54]. The optimum CCBs may be nifedipine and amlodipine. Both are up to 30 times more efficacious than diltiazem [55, 56] whereas verapamil depresses myocardial function and conduction. There is less agreement regarding potential benefits of longer-term use of nitrates and CCBs.

There is no study evaluating the subacute or chronic use of oral or topical nitrates with respect to graft patency (including RA) and survival post CABG. Early small observational and randomized trials of postop CCBs (up to 12 months) reported inconsistent outcomes. However, most were underpowered, and used various CCBs.

In postoperative RA angiograms, areas of localized RA stenosis that dilated instantly with intragraft nitroglycerine were occasionally noted [57]. The meta-analysis of RCTs of RA versus SVG as a second graft by Gaudino *et al*. [58] showed significantly improved outcomes for death, MI, revascularization and patency in those patients taking CCBs for at least 12 months postoperatively, although a treatment allocation bias may be present.

CCBs reduce preload, afterload and blood pressure. These actions may also contribute to better long-term outcomes. Drawbacks of CCBs, especially amlodipine are potential for headache, and mild peripheral oedema (up to 20%) [54, 57]. The use of CCB may also prevent the use of other important secondary prevention therapies (beta-blockers, angiotensin-converting enzyme-inhibitors).

Bilateral radial artery use

Few reports exist regarding the use of bilateral radial arteries (BRAs), mostly in cases of redo CABG, and conduit shortage [32, 33]. Due to the increasing use of TRC and its potential clinical benefits, the use of bilateral radial artery should be balanced with the potential need for percutaneous coronary imaging or interventions [59].

Key messages

- Randomized data support better patency rate and a reduction in adverse cardiac events for the RA compared to SVG.
- RA harvesting is generally well tolerated; there is limited evidence in support of the endoscopic harvesting method.
- The RA should be used to graft target vessel with low competitive coronary flow and should not be used after TRC.
- Observational evidence supports the use of vasodilators for the first year in patients with RA grafts.

RIGHT INTERNAL THORACIC ARTERY

Patency

Benedetto *et al*. [8] in a network meta-analysis (NMA) of 9 RCTs comparing angiographic outcomes of second conduits in CABG showed that when the analysis was restricted to 6 RCTs with ≥4 years of angiographic follow-up, the SVG ($n = 377$) was significantly associated with a 4-fold increased risk (OR 0.25, 95% CI 0.05–0.78) of functional graft occlusion when compared with the RITA ($n = 145$). In a rank probability analysis that also included the RA and the gastro-epiploic artery (GEA), the RITA achieved the highest probability (74%) to be the best conduit. More recently, however, Gaudino *et al*. [6] conducted an updated NMA of 14 RCTs that included 3396 patients and 3651 grafts from 5 additional studies comparing the angiographic patency of the RITA, RA, GEA, conventional SVG (CON-SVG) as well as the no-touch SVG (NT-SVG). The patency rates of the CON-SVG ($n = 1362$) and RITA ($n = 399$) after a mean angiographic follow-up of 5.1 years were 81.8% (95% CI 74.8–87.3) and 90.9% (95% CI 72.1–97.5), respectively. The RITA was not associated with a significantly lower rate of graft occlusion compared with the CON-SVG [incidence relative risk (IRR) 1.02, 95% CI 0.39–0.78].

Long-term clinical outcomes

In the Arterial Revascularization Trial (ART), no difference was found in 10-year survival and event free survival among patients randomized to single vs bilateral ITA to the 2 most important left-sided targets [60]. There was a relatively high crossover rate from bilateral to single ITA and the RA was used in ∼20% of the patients, potentially diluting the treatment effect. In an observational comparison, patients who received multiple arterial grafting (including the RA) had better survival and event free survival compared to patients who received a single ITA.

In an observational analysis of 7223 patients comparing long-term (>15 years) survival in 490 2:1 propensity-matched pairs of RITA-right coronary artery (RCA) versus SVG-RCA, time-segmented cox regression showed that during the first 9 years of follow-up the 2 strategies were associated with a similar risk of death (HR 1.13, 95% CI 0.67–1.90; $P = 0.65$) [61]. However, beyond 9 years, RITA-RCA was associated with a significantly lower risk of death (HR 0.43, 95% CI 0.22–0.84; $P = 0.01$). A NMA of 31 adjusted observational studies and 4 RCTs including 149 902 patients (SVG 112 018; RITA 21 683) found that use of the RITA was associated with lower long-term mortality (IRR 0.80, 95% CI 0.73–0.86) at 8.5 years of follow-up when directly compared with the SVG [62]. This was confirmed in the NMA, showing that use of the SVG was associated with higher late mortality (IRR 1.26, 95% CI 1.17–1.35), operative mortality (OR 1.45, 95% CI 1.14–1.84), and perioperative MI (OR 1.30, 95% CI 1.06–1.61) compared with the RITA [62]. There was no difference in the risk of perioperative stroke (OR 1.24, 95% CI 0.93–1.64), while the risk of deep sternal wound infection (DSWI) (OR 0.71, 95% CI 0.55–0.91) was lower with SVG compared with the RITA. However, when limiting the analysis to studies in which the skeletonized harvesting technique for the ITA was used, no difference in DSWI between RITA and SVG was found in pairwise comparison [62].

In summary, although long-term data do not currently show a consistent difference in terms of graft patency, adjusted observational data suggest superior long-term survival with use of the RITA compared with the SVG, and support use of the RITA over the SVG, particularly in patients with long life-expectancy. A volume to outcome effect for the use of bilateral internal thoracic artery (BITA) has been suggested in observational studies [63].

Patient selection

Selective use of BITA grafting is essential for safe and effective application. Because BITA harvesting is associated with increased sternal wound complications, alternative conduit options to BITA are recommended in patients at increased risk for such complications. In addition, patients with a limited life expectancy or those with severe comorbidities may not benefit from longevity associated with multiarterial grafting [64, 65]. Three common patient groups where a thoughtful application of BITA grafting is particularly pertinent are discussed below:

Patients with diabetes. A 2013 meta-analysis of 1 RCT and 10 observational studies of patients with diabetes found that DSWI occurred in 3.1% and 1.6% for the BITA and single internal thoracic artery cohorts, respectively (relative risk 1.71, 95% CI 1.37–2.14) [66]. Likewise, Dai *et al.* [67] reported higher DSWI in diabetic patients in another meta-analysis (relative risk 0.65, 95% CI 0.52–0.81). A third meta-analysis found a higher rate of DSWI regardless of how the ITAs were harvested [68].

Recent retrospective data have not always supported these findings, failing to demonstrate a higher incidence of DSWI even in diabetic patients [69–72]. While the preponderance of evidence suggests higher DSWI risk in patients with diabetes, BITA has been used successfully in diabetic patients with equivalent safety results by centres experienced with the technique [66, 67].

Low ejection fraction. Low ejection fraction is strongly associated with increased perioperative mortality [73]. The priority in patients with ischaemic cardiomyopathy is to mitigate the upfront risk of surgery [74]. Immediate flow in an arterial graft may not be as high as that in a vein graft with the potential for clinically significant early coronary hypoperfusion [75, 76]. In addition, multiple arterial grafting usually adds to the complexity and duration of the operation which may not be well tolerated in patients with severe ventricular dysfunction.

Retrospective analyses suggest that the operative safety of using BITA is equivalent to single internal thoracic artery, although whether BITA improves long-term survival in this patient population is not clear with mixed results derived from observational studies [77–80].

Although BITA grafting is not routinely recommended for patients with severe ventricular dysfunction, its use may be considered in select scenarios guided by the patient's anticipated survival and surgeon experience and judgement [74].

Advanced age. An age-dependent benefit of BITA grafting was seen in a *post hoc* analysis of the ART, with a cut-off at 65 years [81].

A meta-analysis of retrospective studies by Deo *et al.* [82] reported significantly higher DSWI in elderly patients associated with use of BITA (OR 1.86, 95% CI 1.3–2.5; $P < 0.01$) with no heterogeneity. Safety outcomes were equivalent, although long-term survival was not quantitatively analysed and reported as mixed. Pevni *et al.* [83] reported similar safety and survival outcomes for BITA in octogenarians.

There is insufficient data on a specific age cut-off for use of BITA; however, observational studies including 2 large state registries suggest that the survival benefit associated with multiarterial grafting may be lost in patients over the age of 70 years [64].

Target vessel selection

In addition to demographic factors, morphology and extent of cardiac disease may influence the outcome for BITA use. Bypassing with BITA multiple non-LAD target vessels that perfuse a large myocardial mass has been associated with improve long-term survival [84]. Additionally, a recent study suggests larger target vessels may be better suited for BITA use with a reduced rate of graft occlusion (OR 0.18, 95% CI 0.05–0.62; $P = 0.007$) and a cut-off of 1.93 mm [85]. Target vessel size, however, was not a factor in a previous analysis [86].

Whether to use BITA in target vessels with moderate stenosis has long been an issue of debate. The impact of moderate proximal stenosis varies, with some studies suggesting a mild effect [87, 88] to some suggesting significantly reduced patency. Composite grafts may fare particularly poorly compared to free grafts in bypassing these targets [89]. A prospective RCT associated an fractional flow reserve of ≤ 0.78 with improved RITA patency [17].

The decision to use an *in situ* RITA or a free RITA depends on a number of factors, including coronary anatomy, a diseased ascending aorta, or high-risk for a redo sternotomy [90]. In limited data thus far, long-term RITA patency appears independent of its inflow configuration [86, 90]. Clinical results have mostly been comparable between the *in situ* and composite configurations, although composite grafts tend to offer more complete revascularization at the potential risk of imbalanced flow [91].

RITA vs LITA to the LAD

The paper by Loop *et al.* [2] that established the use of the ITA to the LAD as the gold-standard did not differentiate between LITA and RITA, however both were used in an *in situ* configuration. One small RCT [92] and a few retrospective analyses, mostly from single centres, have compared BITA configurations where an *in situ* RITA is anastomosed to the LAD vs the standard *in situ* LITA to LAD. The evidence suggests that RITA to LAD is similar in terms of graft patency [92–95], perioperative, operative [92, 93, 95–97] or longer-term clinical outcomes [96–99].

Patency. A randomized study by Deininger with 100 patients reported 100% patency after 6 months for both RITA-LAD and LITA-LAD [92]. Ji *et al.* [94] found no significant difference in rate of graft failure at mean follow-up of 36.6 ± 12.1 months.

A recent study by Ogawa *et al.* [95] reported that using the RITA for a vessel other than the LAD led to worse patency (HR 2.05, 95% CI 1.08–3.88; $P = 0.029$). Tatoulis *et al.* [93] reported similar overall patency in the RITA and LITA with a mean of 100 months of follow-up in over 2000 grafts (RITA 94.6% vs 96.9%; $P = 0.74$), although this still represented a small portion of the total population. These findings were confirmed in a study by Bakaeen *et al.* [90] demonstrating that RITAs grafted to the LAD had patency similar to LITA to LAD.

The patency data are at higher risk of bias and generally come from clinically driven angiograms and many of the studies were not principally designed to test the patency of LITA versus RITA to the LAD. Another caveat is that use of pedicled ITAs was not well-represented in this data, and that many of the patients were operated on off-pump. Thus, the patency data should be interpreted with caution.

Long-term clinical outcomes. Deininger *et al.* [92] reported no adverse operative outcomes in either for both RITA-LAD and LITA-LAD groups, although it was clearly underpowered to find any differences for these rarer endpoints. Observational data, both matched and unmatched, have yet to find a significant difference in either operative or longer-term major adverse cardiovascular events (MACE) outcomes, individually or as a composite endpoint [92]. Raja *et al.* [98] reported a significant increase in perioperative mortality for LITA to LAD patients, but this unusual finding has not been reproduced in subsequent larger studies.

Ogawa *et al.* [95] reported a significant benefit to using the RITA for the LAD during their 6 years of follow-up in the composite outcome of death, MI, and revascularization (27.8% vs 41.5%; $P = 0.029$). Raja *et al.* [98] combined death and revascularization and found no significant difference between the groups (HR 0.81, 95% CI 0.64–1.14). Jabagi *et al.* [96] found no difference in 10-year reintervention rates.

The matched study by Ji *et al.* [94] combined mortality, MI and stroke and found no significant difference between groups with a mean follow-up of over 3 years.

The matched cohort studies by Ogawa *et al.* [95] and Raja *et al.* [98] both explored mortality with at least 5 years of follow-up in nearly 1500 patients and found no significant difference in late death with up to 15 years after surgery. The multivariable analyses by Ben-Gal *et al.* in 1990 patients and Mohammadi *et al.* in 1977 patients, as well as the entropy-balanced analysis by Jabagi *et al.* of 2050 patients likewise found no significant difference in long-term mortality between graft configurations [96, 97, 99].

Technical considerations: RITA to LAD as part of a BITA revascularization strategy. The strategy and use of the *in situ* RITA to revascularize the LAD territory (and the LITA to bypass the circumflex territory) requires several important technical and clinical considerations:

Limited length. The RITA needs to be harvested for its maximal length especially proximally to reach coronary targets without tension. The very distal part of the ITA however has a small caliber, is very muscular and prone to spasm, and may be associated with inferior patency when used for grafting.

This limitation could potentially be mitigated by the use of the RITA as a Y or T graft to the lateral wall with a proximal anastomosis of the RITA to an *in situ* LITA to the LAD.

Potential injury at time of redo sternotomy. An *in situ* RITA crossing the midline either anteriorly or when the RITA is tunnelled through the transverse sinus posteriorly is more prone to injury at the time of redo sternotomy [100, 101]. Such injury could have potential devastating consequences. Specific location and proximity of crossing grafts to the sternum or cross-clamp must be carefully defined by preoperative gated computed tomography angiography and or angiography. Even with such careful and detailed preoperative assessments, because of the variable and unpredictable presence of adhesions, aortopathy and significant residual native coronary artery disease, such injuries could have potentially very significant adverse consequences [100].

Skeletonized ITA harvesting

Evidence on skeletonized ITA harvesting has been mixed and generally highly dependent on retrospective and anecdotal experience. Randomized control data has documented that carefully harvested skeletonized ITA grafts can maintain structural integrity [102, 103], physiological response to vasoactive stimulation [104, 105] and acute graft flow that is at least comparable if not greater than that achieved with a pedicled approach [106–108]. Postanastomotic flow appears to be comparable or possibly increased [109, 110]. Moreover, even though acute sternal microcirculation is clearly impaired with either approach [111, 112], sternal perfusion has been demonstrated to be better preserved over time with skeletonization [113–115]. Although this provides a rational substrate for fewer sternal wound complications, the data regarding reduced sternal wound infection, although abundant, is generally based on retrospective data without uniform definition of sternal infection, with or without controls and with minimal if any statistical adjustment [116–119]. Of note, *post hoc* analysis of the ITA harvesting technique from the ART revealed that pedicled BITA but not skeletonized single internal thoracic artery or BITA was associated with a significantly increased risk of any sternal wound complication [120]. Careful analysis of the STS Adult Cardiac Surgery Database, which reflects over 95% of cardiac operations performed in the USA [121], revealed that skeletonized ITA harvesting, although less common than the pedicled approach, was associated with a significantly lower risk of DSWI (adjusted OR 0.66, 95% CI 0.44–1.00; $P = 0.05$) and an equivalent risk of operative mortality [122]. However, recent meta-analysis showed that the skeletonized approach did not eliminate the elevated risk of sternal infection in bilateral internal mammary artery grafting [123].

Graft patency studies are generally retrospective, based on clinical indication and vary greatly in the length of follow-up, but have historically demonstrated comparable graft patency between the 2 approaches [124, 125]. Some studies of late mortality favoured the skeletonized approach [126]. However, 2 recent *post hoc* analyses of clinical trial data raise considerable concern regarding graft patency and clinical outcome in the contemporary practice of skeletonized ITA grafting. Data from the COMPASS trial which assessed the role of rivaroxaban plus/minus aspirin in patients with cardiovascular disease was able to study the 1-year graft patency (by computed tomography angiography) of 1002/1448 patients in the CABG arm and found graft occlusion in 33/344 (9.6%) of ITA grafts in the skeletonized group compared with 30/764 (3.9%) in the pedicled group (adjusted OR 2.41, 95% CI 1.39–4.20; $P = 0.002$). Perhaps of greater concern, at the end of the 2.5-year trial, the skeletonized graft patients had a higher risk of MACE including cardiovascular death, MI, stroke or revascularization (adjusted HR 3.19, 95% CI 1.53–6.67; $P = 0.002$), driven by revascularization and stroke [127]. Patients were not randomized by surgical technique and the skeletonized group had a higher incidence of hypertension, elevated cholesterol, and medication profile. Overall, RITA occlusion was 18/84 (21.4%), reflecting potential variability in surgical technique. *Post hoc* analysis of the ART trial patients revealed similar mortality but higher MACE in the skeletonized versus the pedicled ITA patients at 10 years of follow-up (HR 1.25, 95% CI 1.06–1.47; $P = 0.01$) driven by a higher need for repeat revascularization (HR 1.42, 95% CI 1.11–1.82; $P = 0.01$). Interestingly, when limiting analysis to

surgeons enrolling 51 patients or more, the difference disappeared [128].

As with any surgical procedure, ITA skeletonization is subject to tremendous variability in surgical technique and experience: use of unipolar versus bipolar cautery versus harmonic scalpel, mobilization of the isolated artery versus use of surrounding tissue, clips versus cautery for branches, speed and experience of harvest, use of sequential and Y-grafts, *in situ* versus free-graft, off-pump versus on-pump application, may all play a role in surgical results. To date, RCTs have been small and limited to assessment of graft flow and histology and not powered for clinical outcomes. Discrepancy in clinical results may reflect the fact that earlier studies arose from centres specializing in the technique which may not be uniformly translatable to a more recent broadly applied experience. It appears as it is generally utilized, the skeletonized approach to ITA harvesting may be associated with a decreased risk of DSWI, comparable graft flow, but variable clinical results that are largely operator dependent. Therefore, use is best reserved for patients with increased risk of DSWI, such as diabetics or those undergoing BITA grafting, and for surgeons who have considerable experience with atraumatic harvest and good clinical outcomes.

Key messages

- Patency data are mixed, and there is no clear evidence of better patency for the RITA compared to SVG.
- Observational evidence shows that patients who received RITA rather than SVG for CABG have longer survival and better outcomes after surgery, but the only RCT was neutral.
- BITA harvesting may be associated with higher risk of DSWI and should be avoided in high-risk patients.
- The RITA should be used to graft target vessels with good run-off that perfuse a large myocardial mass.
- The evidence on skeletonization of the ITA is limited and suggests a decrease in sternal complications, but no clear conclusions can be drawn on the impact of skeletonization on graft patency and cardiovascular outcomes.

ENDOSCOPIC VEIN HARVESTING

A systematic review of studies comparing open vein graft harvesting (OVH) and EVH yielded 5 relevant meta-analyses and 1 RCT not included in any of the meta-analyses [129–134].

The 2016 International Society for Minimally Invasive Cardiothoracic Surgery Systematic Review and Consensus Conference Statement [131] specifically examining patient-centred outcomes and resource utilization found that the risk of wound-related complications (i.e. abscess, necrosis, dehiscence, drainage, seromas, lymphocele, oedema and haematoma) was significantly reduced with EVH (OR 0.29, 95% CI 0.22–0.37, 29 studies, 11 919 patients, $P < 0.00001$), as was pain during the postoperative period (OR 0.19, 95% CI 0.11–0.34, 7 studies, 834 patients, $P < 0.00001$). In addition, EVH was associated with a reduction in total hospital length of stay (mean difference = -0.73 -days, 95% CI -1.18 to -0.28, 18 studies, 14 983 patients, $P < 0.00001$), and a reduced need for outpatient wound management resources.

The Randomized Endovein Graft Prospective (REGROUP) trial [134] did not find a significant difference between OVH and EVH in the risk of the primary outcome of a composite of MACE including death from any cause, nonfatal MI, and repeat revascularization (OVH 15.5% vs EVH 13.9%, HR 1.12, 95% CI 0.83–1.51; $P = 0.47$) over a median follow-up of 2.8 years that was confirmed over an extended median follow-up of 4.7 years (OVH 23.5% vs EVH 21.9%, HR 0.92, 95% CI 0.72–1.18; $P = 0.52$) [135]. However, the trial did not include angiographic follow-up, and mandated minimum harvester experience for both techniques which has been shown to affect quality of the conduit, particularly for EVH [136].

A meta-analysis by Sastry *et al.* [129] that included 4 studies (2 randomized, 2 non-randomized) evaluating graft patency in 4700 patients with up to 18 months of angiographic follow-up found a higher rate of vein graft failure with EVH (OR 1.39, 95% CI 1.11–1.75; $P = 0.004$). When only the 2 RCTs [137, 138] with angiographic follow-up of 3 and 6 months, respectively, were included in the analysis this finding no longer reached statistical significance (OR 1.21, 95% CI 0.76–1.90; $P = 0.42$). The meta-analysis by Deppe *et al.* [130] of 5 studies with angiographic follow-up of 6504 grafts reported a significantly higher risk of graft failure with EVH (OR 1.38, 95% CI, 1.01–1.88; $P < 0.0001$). Similarly, Kodia *et al.* [132] reported superior SVG patency with OVH at a mean follow-up of 2.6 years (OVH 82.3% vs EVH 75.1%; OR 0.61, 95% CI 0.43–0.87; $P = 0.01$). Both meta-analyses were driven by the non-randomized *post hoc* analyses of the Project of *Ex vivo* Vein Graft Engineering via Transfection (PREVENT-IV) [139] and the Randomized On/Off Bypass (ROOBY) [140] trials. The latter study also reported a higher 30-day mortality rate (OVH 3.4% vs EVH 2.1%, OR 0.59, 95% CI 0.37–0.94; $P = 0.03$). Li *et al.* [133] also reported lower patency with EVH at 1–5 years (OR 0.80, 95% CI 0.70–0.91, 5 studies, 5235 patients; $P = 0.0005$).

Thus, the current evidence for SVG patency beyond 1-year of follow-up, which is mostly observational, suggests that EVH is associated with reduced patency in the longer term. An adequately powered RCT of EVH vs OVH with angiographic follow-up may address this gap in the evidence. Randomized data pointing to equipoise for EVH and OVH in terms of MACE underscores the highly complex and variable association of graft patency with clinical outcomes, particularly for SVG typically grafted to non-LAD territories.

Key messages

- EVH reduces the risk of leg wound complications.
- Patency data suggest that EVH is associated with reduced patency in the long term, but a large RCT found no difference between EVH and OVH in terms of MACE.
- More evidence on this important topic is needed.

NO TOUCH SAPHENOUS VEIN GRAFT

Given that the most commonly used graft continues to be the SVG and that there exist patient specific factors affecting graft patency and wound complications with the use of additional

arterial grafts, there is a compelling rationale for improving outcomes using SVGs.

The no touch saphenous vein graft (NT SVG) is a Class IIA, LOE B recommendation in the 2018 European Revascularization Guidelines [141] based on 2 small graft patency RCTs [142, 143]. The NT SVG harvesting method was designed to reduce vessel injury during surgical preparation. The key features are atraumatic harvesting with inclusion of a pedicle of adjacent fatty tissue to minimize graft spasm and avoid high-pressure dilation during vein preparation. A longitudinal single-centre angiographic RCT of 104 patients by de Souza *et al.* comparing NT and conventional saphenous vein grafts (CON SVGs) revealed significantly better patency of the NT veins at 8.5 years (91% vs 77%; $P = 0.01$) which was maintained at 16 years (83% vs 64%; $P = 0.03$) [142]. In an intravascular ultrasound substudy of the same patient population, there were significant differences which favoured the NT SVGs according to multiple graft imaging endpoints 8.5 years postoperatively [144]. Two additional RCTs using angiographic patency have been completed—one multicentre trial of 250 patients [145] and one single-centre trial of 60 patients [146]. Aggregated results from the 3 RCTs (525 SVGs) revealed a significant reduction of graft stenosis or occlusion at 1 year in the NT SVGs (OR 0.47, 95% CI 0.26–0.84; $P = 0.01$) and a trend for complete occlusion (OR 0.57, 95% CI 0.30–1.06; $P = 0.07$) with no evidence of heterogeneity between the studies [145]. De Sousa also compared the NT SVG with a RA in an angiographic trial using a within patient randomization in 108 patients. At 8.5 years, patency was similar between the 2 conduits (NT SVG 86%; RA 79%, $P = 0.22$) but NT was superior when analysed per distal anastomosis (NT SVG 91%; RA 81%, $P < 0.05$) [143]. A comprehensive NMA of 14 angiographic RCTs involving 3651 grafts at a mean follow-up of 5.1 years, confirmed that graft occlusion was reduced in NT compared to CON SVGs (IRR 0.55, 95% CI 0.39–0.78); the RA and NT SVG ranked as the best conduits (rank scores 0.87 and 0.85 respectively) [6]. An additional NMA of 11 studies by Yokoyama *et al.* [147] was consistent with this result, reporting an IRR of 0.32 (95% CI 0.17–0.60) with at least 3 years of follow-up in favour of NT SVGs over CON SVGs. Kim *et al.* [148] reported better 1 year graft SVG patency of LITA-SVG composite grafts with NT SVGs compared to SVGs without a pedicle (97.3% vs 92.6%; $P = 0.05$) in a propensity score-matched study of 196 patients.

In a 2655-patient RCT from China graft failure was substantially reduced for the NT grafts compared with CON SVG, both at 3 months (OR, 0.57, 95% CI 0.41–0.80; $P < 0.001$) and 12 months (OR 0.56, 95% CI 0.41–0.76; $P < 0.001$) [149].

SWEDEGRAFT is an ongoing 900-patient registry-based RCT comparing NT and CON SVGs; the primary endpoint is the proportion of patients with SVG graft failure according to study CT angiography, SVG graft failure according to clinically driven angiography, or death over 2 years of follow-up [150].

At this point, there is no convincing data that clinical outcomes are favourably affected using NT SVGs. The previously mentioned multicentre RCT by Deb and associates reported that major cardiac and cerebrovascular events were not statistically different at 1 year (HR 1.19, 95% CI 0.64–2.19) [145]. A propensity-matched study of 2698 patients using the SWEDEHEART registry reported on mortality and repeat intervention at a mean of 6.6 years follow-up [151]. There was no difference in mortality (HR 0.97, 95% CI 0.80–1.19) or repeat revascularization (HR 0.91, 95% CI 0.71–1.17) although repeat angiography was reduced in the NT patients (HR 0.76, 95% CI 0.63–0.93) [151].

Two studies have reported on leg wound healing using standardized questionnaires serially postoperatively. The PATENT SVG study ($n = 17$) used a within patient randomization [152]. Leg assessment scores were worse in the NT legs at 3 months ($P < 0.001$) but similar and with minimal impairment at 1 year [153]. In the trial by Deb *et al.* [145], the cumulative incidence of leg wound infection over 1 year was greater with NT SVG harvesting (25.4% vs 11.8%; $P < 0.01$), primarily because of differences at 1 and 3 months. Adverse leg outcomes using the standardized questionnaire were worse following NT SVG harvesting at 1 and 3 months but similar and with minimal impairment at 1 year. In the original trial by de Souza, leg wound complications were 11.1% with NT harvesting versus 4.3% in the controls [153]. EVH compared to OVH is associated improved wound healing [129]. Given the increased incidence of adverse harvest site outcomes using NT SVGs, endoscopic approaches have been considered. There are reports of small case series of minimally invasive NT SVG harvesting combining both techniques [135].

Key messages

- Randomized data show that the patency rate of NT SVG is significantly better than that of the traditionally harvested SVG.
- There is no clear evidence of better clinical outcomes using the NT SVG compared to the CON SVG.
- The use of the NT SVG is associated with a significantly higher risk of harvesting site complications.

GASTROEPIPLOIC ARTERY

The right gastroepiploic artery (RGEA) conduit has most commonly been used as an *in situ* arterial bypass graft; however, it can also be used as a composite graft based on the ITA, or alternately as a free graft if a preoperative abdominal aortogram or computed tomography shows significant narrowing of the coeliac axis or if the RGEA had low free flow [154, 155].

Long-term patency

Available data on early and long-term outcomes are mostly from reports of *in situ* RGEA grafts anastomosed to the RCA [156–162]. The reported early postoperative angiographic patency rate ranges as high as 97.1–99.6% [157–159, 162]. However, patency rate varies between 81.4–98.7% at 1 year [156–159, 162], 91.1–96% at 3 years [156, 159, 161], 83.4–94.7% at 5 years [156, 157, 159, 161, 162] and 66.5–90.2% [157, 159–162] at 8–10 years. This is likely because the patency of RGEA graft is influenced by target vessel stenosis and graft harvesting technique.

Long-term clinical outcomes

Few studies have directly compared use of *in situ* RGEA vs SVG, and the data that exists generally tests its use as the third conduit to supplement BITA.

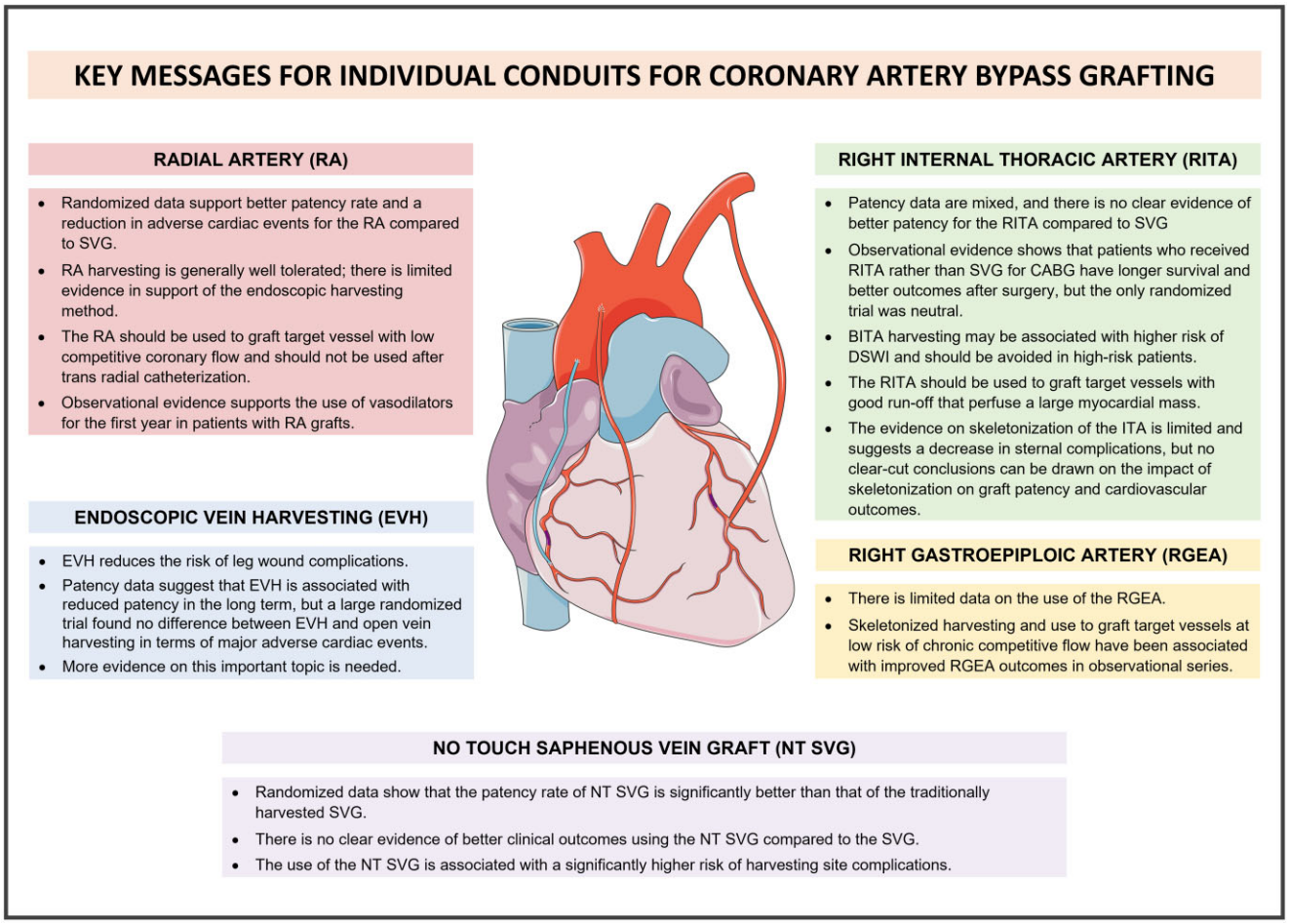


Figure 1: Visual summary of key messages. Parts of the figure were drawn by using pictures from Servier Medical Art (smart.servier.com). Servier Medical Art by Servier is licenced under a Creative Commons Attribution 3.0 Unported Licence (https://creativecommons.org/licenses/by/3.0/).

A meta-analysis by Di Mauro *et al.* [163] compared 2548 patients from 6 studies receiving either *in situ* RGEA ($n = 1023$) or SVG ($n = 1525$) to supplement BITA. Overall, long-term survival was not different between the 2 conduits, albeit with a high degree of heterogeneity. When only propensity-matched studies were included, *in situ* GEA had a long-term survival advantage over SVG (HR 0.47, 95% CI 0.31–0.71, $n = 1051$; $P < 0.001$) and the heterogeneity was reduced.

One propensity-matched study compared long-term clinical outcomes of RGEA composite grafts with those of RITA composite grafts and found no statistically significant survival difference at 15 years (52.9% vs 49.4%; $P = 0.470$) [162].

Suzuki *et al.* [164] reported better freedom from MACE at 7 years for *in situ* RGEA over SVG, although this has not been replicated by other matched cohort studies whether an *in situ* or composite graft is used [160, 162].

Skeletonized/pedicle harvesting

Although RGEA is contractile and prone to vasospasm, skeletonization using the harmonic scalpel can reduce spasm by removing the periarterial nerve plexus, as well as extend the graft length and enable anastomosis with a larger diameter vessel [165, 166]. Suzuki *et al.* [159] reported 8 years patency of 90.2% and Akita *et al.* [161] reported 10 years patency of 89.8%, when *in situ* RGEA was harvested in skeletonized or semi-skeletonized fashion and used as *in situ* graft, anastomosed to distal RCA with more than 90% stenosis or minimal lumen diameter (MLD) of <1 mm. These results were better than previously reported patency of *in situ* pedicled GEA, although direct comparisons are lacking [157].

Patient and target vessel selection

Contraindications for *in situ* GEA conduits include obese or very elderly patients, and those in whom future abdominal surgery may be needed. Although rerouting of the patent GEA graft using SVG in case of abdominal surgery is possible, it requires meticulous surgical management [167].

In situ RGEA flow can be compromised by native flow competition when anastomosed to target coronary artery with moderate stenosis [160, 168]. MLD of native RCA seems a more reliable indicator rather than angiographic stenosis, especially for the RCA. On the basis of systematic 3-year angiographic data, Glineur *et al.* [169] recommend that *in situ* RGEA should be used preferentially to graft the RCA system only when the MLD of target RCA is below 1.1 mm. Akita *et al.* [161] reported a 10-year patency rate of only 39.3% for *in situ* RGEA when it was anastomosed to RCA with MLD >1 mm, but a satisfactory patency of 89.8% when MLD was <1 mm. A visual summary of all the key messages is displayed in Figure 1.

Key messages

- There is limited data on the use of the RGEA.
- Skeletonized harvesting and use to graft target vessels at low risk of chronic competitive flow have been associated with improved RGEA outcomes in observational series.

Funding

None to declare.

Conflict of interest: none declared.

DATA AVAILABILITY

All relevant data are within the manuscript and its supporting information files.

Author contributions:

Mario Gaudino: Conceptualization; Investigation; Methodology; Validation; Writing—original draft; Writing—review & editing. **Faisal G. Bakaeen:** Conceptualization; Writing—original draft. **Sigrid Sandner:** Conceptualization; Writing—original draft. **Gabriel S. Aldea:** Conceptualization; Writing—original draft. **Hirokuni Arai:** Conceptualization; Writing—original draft. **Joanna Chikwe:** Conceptualization; Writing—original draft. **Scott Firestone:** Data curation; Project administration. **Stephen E. Fremes:** Conceptualization; Writing—original draft. **Walter J. Gomes:** Conceptualization; Writing—original draft. **Ki Bong-Kim:** Conceptualization; Writing—original draft. **Kalie Kisson:** Data curation; Project administration. **Paul Kurlansky:** Conceptualization; Writing—original draft. **Jennifer Lawton:** Conceptualization; Writing—original draft. **Daniel Navia:** Conceptualization; Writing—original draft. **John D. Puskas:** Conceptualization; Writing—original draft. **Marc Ruel:** Conceptualization; Writing—original draft. **Joseph F. Sabik:** Conceptualization; Writing—original draft. **Thomas A. Schwann:** Conceptualization; Writing—original draft. **David P. Taggart:** Conceptualization; Writing—original draft. **James Tatoulis:** Conceptualization; Writing—original draft. **Moritz Wyler von Ballmoos:** Conceptualization; Formal analysis; Investigation; Methodology; Writing—original draft; Writing—review & editing.

Reviewer information

European Journal of Cardio-Thoracic Surgery thanks Piroze Davierwala, Dawn Hui, Rafael Sadaba and the other, anonymous reviewer(s) for their contribution to the peer review process of this article.

REFERENCES

[1] ElBardissi AW, Aranki SF, Sheng S, O'Brien SM, Greenberg CC, Gammie JS. Trends in isolated coronary artery bypass grafting: an analysis of the Society of Thoracic Surgeons adult cardiac surgery database. J Thorac Cardiovasc Surg 2012;143:273–81.

[2] Loop FD, Lytle BW, Cosgrove DM, Stewart RW, Goormastic M, Williams GW *et al.* Influence of the internal-mammary-artery graft on 10-year survival and other cardiac events. N Engl J Med 1986;314:1–6.

[3] Cameron A, Davis KB, Green G, Schaff HV. Coronary bypass surgery with internal-thoracic-artery grafts effects on survival over a 15-year period. N Engl J Med 1996;334:216–9.

[4] Loop F. Internal-thoracic-artery grafts—biologically better coronary arteries. N Engl J Med 1996;334:263–5.

[5] Cao C, Manganas C, Horton M, Bannon P, Munkholm-Larsen S, Ang SC *et al.* Angiographic outcomes of radial artery versus saphenous vein in coronary artery bypass graft surgery: a meta-analysis of randomized controlled trials. J Thorac Cardiovasc Surg 2013;146:255–61.

[6] Gaudino M, Hameed I, Robinson NB, Ruan Y, Rahouma M, Naik A *et al.* Angiographic patency of coronary artery bypass conduits: a network meta-analysis of randomized trials. J Am Heart Assoc 2021;10:e019206.

[7] Gaudino M, Benedetto U, Fremes S, Biondi-Zoccai G, Sedrakyan A, Puskas JD *et al.*; RADIAL Investigators. Radial-artery or saphenous-vein grafts in coronary-artery bypass surgery. N Engl J Med 2018;378:2069–77.

[8] Benedetto U, Raja SG, Albanese A, Amrani M, Biondi-Zoccai G, Frati G. Searching for the second best graft for coronary artery bypass surgery: a network meta-analysis of randomized controlled trials. Eur J Cardiothorac Surg 2015;47:59–65; discussion 65.

[9] Gaudino M, Rahouma M, Abouarab A, Leonard J, Kamel M, Di Franco A *et al.* Radial artery versus saphenous vein as the second conduit for coronary artery bypass surgery: a meta-analysis. J Thorac Cardiovasc Surg 2019;157:1819–25.e10.

[10] Gaudino M, Benedetto U, Fremes S, Ballman K, Biondi-Zoccai G, Sedrakyan A *et al.*; RADIAL Investigators. Association of radial artery graft vs saphenous vein graft with long-term cardiovascular outcomes among patients undergoing coronary artery bypass grafting: a systematic review and meta-analysis. JAMA 2020;324:179–87.

[11] Goldman S, Sethi GK, Holman W, Thai H, McFalls E, Ward HB *et al.* Radial artery grafts vs saphenous vein grafts in coronary artery bypass surgery a randomized trial. JAMA 2011;305:167–74.

[12] Goldman S, McCarren M, Sethi GK, Holman W, Bakaeen FG, Wagner TH *et al.*; CSP #474 Investigators. Long-term mortality follow-up of radial artery versus saphenous vein in coronary artery bypass grafting: a multicenter, randomized trial. Circulation 2022;146:1323–5.

[13] Buxton BF, Hayward PA, Raman J, Moten SC, Rosalion A, Gordon I *et al.*; RAPCO Investigators. Long-term results of the RAPCO trials. Circulation 2020;142:1330–8.

[14] Jarvis MA, Jarvis CL, Jones PR, Spyt TJ. Reliability of Allen's test in selection of patients for radial artery harvest. Ann Thorac Surg 2000;70:1362–5.

[15] Holman WL, Davies JE, Lin JY, Wang Y, Goldman S, Bakaeen FG *et al.*; VA CSP 474 Investigators. Consequences of radial artery harvest: results of a prospective, randomized, multicenter trial. JAMA Surg 2013;148:1020–3.

[16] Moon MR, Barner HB, Bailey MS, Lawton JS, Moazami N, Pasque MK *et al.* Long-term neurologic hand complications after radial artery harvesting using conventional cold and harmonic scalpel techniques. Ann Thorac Surg 2004;78:535–8; discussion 538.

[17] Glineur D, Grau JB, Etienne PY, Benedetto U, Fortier JH, Papadatos S *et al.* Impact of preoperative fractional flow reserve on arterial bypass graft anastomotic function: the IMPAG trial. Eur Heart J 2019;40:2421–8.

[18] Gatti G, Taffarello P, De Groodt J, Benussi B. A non-conventional proximal inflow for the radial artery coronary graft. Interact CardioVasc Thorac Surg 2020;31:179–81.

[19] Karagoz HY, Kurtoglu M, Bakkaloglu B, Sonmez B, Cetintas T, Bayazit K. Coronary artery bypass grafting in the awake patient: three years' experience in 137 patients. J Thorac Cardiovasc Surg 2003;125:1401–4.

[20] Yoon SK, Song H, Lim JY. Effect of the proximal anastomosis configuration of the radial artery in patients undergoing coronary artery bypass grafting. J Chest Surg 2021;54:117–26.

[21] Tinica G, Chistol RO, Bulgaru Iliescu D, Furnica C. Long-term graft patency after coronary artery bypass grafting: effects of surgical technique. Exp Ther Med 2019;17:359–67.

[22] Hosono M, Murakami T, Hirai H, Sasaki Y, Suehiro S, Shibata T. The risk factor analysis for the late graft failure of radial artery graft in coronary artery bypass grafting. Ann Thorac Cardiovasc Surg 2019;25:32–8.

[23] Kim DJ, Lee SH, Joo HC, Yoo KJ, Youn YN. Effect of the proximal anastomosis site on mid-term radial artery patency in off-pump coronary artery bypass. Eur J Cardiothorac Surg 2018;54:475–82.

[24] Watson RA, Hamza M, Tsakok TM, Tsakok MT. Radial artery for coronary artery bypass grafting: does proximal anastomosis to the aorta or left internal mammary artery achieve better patency? Interact CardioVasc Thorac Surg 2013;17:1020–4.

[25] Nakajima H, Kobayashi J, Toda K, Fujita T, Shimahara Y, Kasahara Y *et al.* Angiographic evaluation of flow distribution in sequential and composite arterial grafts for three vessel disease. Eur J Cardiothorac Surg 2012; 41:763–9.
[26] Gaudino M, Alessandrini F, Pragliola C, Cellini C, Glieca F, Luciani N *et al.* Effect of target artery location and severity of stenosis on mid-term patency of aorta-anastomosed vs. internal thoracic artery-anastomosed radial artery grafts. Eur J Cardiothorac Surg 2004;25:424–8.
[27] Deb S, Cohen EA, Singh SK, Une D, Laupacis A, Fremes SE; RAPS Investigators. Radial artery and saphenous vein patency more than 5 years after coronary artery bypass surgery: results from RAPS (Radial Artery Patency Study). J Am Coll Cardiol 2012;60:28–35.
[28] Qiao E, Wang Y, Yu J, Wang X, Luo X, Wang W. Short-term assessment of radial artery grafts with multidetector computed tomography. J Cardiothorac Surg 2021;16:93.
[29] Royse AG, Brennan AP, Pawanis Z, Canty D, Royse CF. Patency when grafted to coronary stenosis more than 50% in LIMA-RA-Y grafts. Heart Lung Circ 2020;29:1101–7.
[30] Jawitz OK, Cox ML, Ranney D, Williams JB, Mulder H, Gaudino MFL *et al.* Outcomes following revascularization with radial artery bypass grafts: insights from the PREVENT-IV trial. Am Heart J 2020;228:91–7.
[31] Tamim M, Alexiou C, Al-Hassan D, Al-Faraidy K. Prospective randomized trial of endoscopic vs open radial artery harvest for CABG: clinical outcome, patient satisfaction, and midterm RA graft patency. J Card Surg 2020;35:2147–54.
[32] Gaudino MF, Lorusso R, Ohmes LB, Narula N, McIntire P, Gargiulo A *et al.* Open radial artery harvesting better preserves endothelial function compared to the endoscopic approach. Interact CardioVasc Thorac Surg 2019;29:561–7.
[33] Kiaii BB, Swinamer SA, Fox SA, Stitt L, Quantz MA, Novick RJ. A prospective randomized study of endoscopic versus conventional harvesting of the radial artery. Innovations (Phila) 2017;12:231–8.
[34] Lei JJH, Ravendren A, Snosi M, Harky A. In patients undergoing coronary artery bypass grafting, is endoscopic harvesting superior to open radial artery harvesting? Interact CardioVasc Thorac Surg 2021;32:447–51.
[35] Huang TY, Huang TS, Cheng YT, Wang YC, Chen TP, Yin SY *et al.* Radial artery harvesting in coronary artery bypass grafting surgery-endoscopic or open method? A meta-analysis. PLoS One 2020;15:e0236499.
[36] Kamiya H, Ushijima T, Kanamori T, Ikeda C, Nakagaki C, Ueyama K *et al.* Use of the radial artery graft after transradial catheterization: is it suitable as a bypass conduit? Ann Thorac Surg 2003;76:1505–9.
[37] Antonopoulos AS, Latsios G, Oikonomou E, Aznaouridis K, Papanikolaou A, Syrseloudis D *et al.* Long-term endothelial dysfunction after transradial catheterization: a meta-analytic approach. J Card Surg 2017;32: 464–73.
[38] Dharma S, Kedev S, Patel T, Kiemeneij F, Gilchrist IC. A novel approach to reduce radial artery occlusion after transradial catheterization: post-procedural/prehemostasis intra-arterial nitroglycerin. Catheter Cardiovasc Interv 2015;85:818–25.
[39] Mounsey CA, Mawhinney JA, Werner RS, Taggart DP. Does previous transradial catheterization preclude use of the radial artery as a conduit in coronary artery bypass surgery? Circulation 2016;134:681–8.
[40] Rashid M, Kwok CS, Pancholy S, Chugh S, Kedev SA, Bernat I *et al.* Radial artery occlusion after transradial interventions: a systematic review and meta-analysis. J Am Heart Assoc 2016;5:e002686.
[41] Wakeyama T, Ogawa H, Iida H, Takaki A, Iwami T, Mochizuki M *et al.* Intima-media thickening of the radial artery after transradial intervention. An intravascular ultrasound study. J Am Coll Cardiol 2003;41: 1109–14.
[42] Yonetsu T, Kakuta T, Lee T, Takayama K, Kakita K, Iwamoto T *et al.* Assessment of acute injuries and chronic intimal thickening of the radial artery after transradial coronary intervention by optical coherence tomography. Eur Heart J 2010;31:1608–15.
[43] Di Vito L, Burzotta F, Trani C, Pirozzolo G, Porto I, Niccoli G *et al.* Radial artery complications occurring after transradial coronary procedures using long hydrophilic-coated introducer sheath: a frequency domain-optical coherence tomography study. Int J Cardiovasc Imaging 2014;30: 21–9.
[44] Gaudino M, Leone A, Lupascu A, Toesca A, Mazza A, Ponziani FR *et al.* Morphological and functional consequences of transradial coronary angiography on the radial artery: implications for its use as a bypass conduit. Eur J Cardiothorac Surg 2015;48:370–4.
[45] Staniloae CS, Mody KP, Sanghvi K, Mindrescu C, Coppola JT, Antonescu CR *et al.* Histopathologic changes of the radial artery wall secondary to transradial catheterization. Vasc Health Risk Manag 2009;5:527–32.
[46] Buturak A, Tekturk BM, Degirmencioglu A, Ulus S, Surgit O, Ariturk C *et al.* Transradial catheterization may decrease the radial artery luminal diameter and impair the vasodilatation response in the access site at late term: an observational study. Heart Vessels 2016;31:482–9.
[47] Madssen E, Haere P, Wiseth R. Radial artery diameter and vasodilatory properties after transradial coronary angiography. Ann Thorac Surg 2006;82:1698–702.
[48] Yan Z, Zhou Y, Zhao Y, Zhou Z, Yang S, Wang Z. Impact of transradial coronary procedures on radial artery function. Angiology 2014;65: 104–7.
[49] Dawson EA, Rathore S, Cable NT, Wright DJ, Morris JL, Green DJ. Impact of introducer sheath coating on endothelial function in humans after transradial coronary procedures. Circ Cardiovasc Interv 2010;3:148–56.
[50] Burstein JM, Gidrewicz D, Hutchison SJ, Holmes K, Jolly S, Cantor WJ. Impact of radial artery cannulation for coronary angiography and angioplasty on radial artery function. Am J Cardiol 2007;99:457–9.
[51] Lim LM, Galvin SD, Javid M, Matalanis G. Should the radial artery be used as a bypass graft following radial access coronary angiography. Interact CardioVasc Thorac Surg 2014;18:219–24.
[52] Ruzieh M, Moza A, Siddegowda Bangalore B, Schwann T, Tinkel JL. Effect of transradial catheterisation on patency rates of radial arteries used as a conduit for coronary bypass. Heart Lung Circ 2017;26:296–300.
[53] Gaudino M, Fremes S, Schwann TA, Tatoulis J, Wingo M, Tranbaugh RF. Technical aspects of the use of the radial artery in coronary artery bypass surgery. Ann Thorac Surg 2019;108:613–22.
[54] Moscarelli M, Gaudino M. Calcium-channel blockers in patients with radial artery grafts. When enough is enough. J Card Surg 2021;36:1827–31.
[55] Cable DG, Caccitolo JA, Pearson PJ, O'Brien T, Mullany CJ, Daly RC *et al.* New approaches to prevention and treatment of radial artery graft vasospasm. Circulation 1998;98:II15-21; discussion II21-2.
[56] He GW, Yang CQ. Comparative study on calcium channel antagonists in the human radial artery: clinical implications. J Thorac Cardiovasc Surg 2000;119:94–100.
[57] Tatoulis J, Buxton BF, Fuller JA, Meswani M, Theodore S, Powar N *et al.* Long-term patency of 1108 radial arterial-coronary angiograms over 10 years. Ann Thorac Surg 2009;88:23–9; discussion 29–30.
[58] Gaudino M, Benedetto U, Fremes SE, Hare DL, Hayward P, Moat N *et al.*; RADIAL Investigators. Effect of calcium-channel blocker therapy on radial artery grafts after coronary bypass surgery. J Am Coll Cardiol 2019; 73:2299–306.
[59] Gaudino M, Burzotta F, Bakaeen F, Bertrand O, Crea F, Di Franco A *et al.*; Arterial Grafting International Consortium Alliance. The radial artery for percutaneous coronary procedures or surgery? J Am Coll Cardiol 2018; 71:1167–75.
[60] Taggart DP, Benedetto U, Gerry S, Altman DG, Gray AM, Lees B *et al.*; Arterial Revascularization Trial Investigators. Bilateral versus single internal-thoracic-artery grafts at 10 years. N Engl J Med 2019;380: 437–46.
[61] Benedetto U, Caputo M, Gaudino M, Mariscalco G, Bryan A, Angelini GD. Is the right internal thoracic artery superior to saphenous vein for grafting the right coronary artery? A propensity score-based analysis. J Thorac Cardiovasc Surg 2017;154:1269–75.e5.
[62] Gaudino M, Lorusso R, Rahouma M, Abouarab A, Tam DY, Spadaccio C *et al.* Radial artery versus right internal thoracic artery versus saphenous vein as the second conduit for coronary artery bypass surgery: a network meta-analysis of clinical outcomes. J Am Heart Assoc 2019;8:e010839.
[63] Gaudino M, Bf U, Benedetto M, Rahouma D, Franco A, Tam DY *et al.* Use rate and outcome in bilateral internal thoracic artery grafting: insights from a systematic review and meta-analysis. J Am Heart Assoc 2018;7:e009361.
[64] Chikwe J, Sun E, Hannan EL, Itagaki S, Lee T, Adams DH *et al.* Outcomes of second arterial conduits in patients undergoing multivessel coronary artery bypass graft surgery. J Am Coll Cardiol 2019; 74:2238–48.
[65] Samadashvili Z, Sundt TM 3rd, Wechsler A, Chikwe J, Adams DH, Smith CR *et al.* Multiple versus single arterial coronary bypass graft surgery for multivessel disease. J Am Coll Cardiol 2019;74:1275–85.
[66] Deo SV, Shah IK, Dunlay SM, Erwin PJ, Locker C, Altarabsheh SE *et al.* Bilateral internal thoracic artery harvest and deep sternal wound infection in diabetic patients. Ann Thorac Surg 2013;95:862–9.
[67] Dai C, Lu Z, Zhu H, Xue S, Lian F. Bilateral internal mammary artery grafting and risk of sternal wound infection: evidence from observational studies. Ann Thorac Surg 2013;95:1938–45.
[68] Urso S, Nogales E, González JM, Sadaba R, Tena MÁ, Bellot R *et al.* Bilateral internal thoracic artery versus single internal thoracic artery: a

meta-analysis of propensity score-matched observational studies. Interact CardioVasc Thorac Surg 2019;29:163–72.
[69] Dorman MJ, Kurlansky PA, Traad EA, Galbut DL, Zucker M, Ebra G. Bilateral internal mammary artery grafting enhances survival in diabetic patients: a 30-year follow-up of propensity score-matched cohorts. Circulation 2012;126:2935–42.
[70] Puskas JD, Sadiq A, Vassiliades TA, Kilgo PD, Lattouf OM. Bilateral internal thoracic artery grafting is associated with significantly improved long-term survival, even among diabetic patients. Ann Thorac Surg 2012;94: 710–5; discussion 715–6.
[71] Pevni D, Medalion B, Mohr R, Ben-Gal Y, Laub A, Nevo A *et al.* Should bilateral internal thoracic artery grafting be used in patients with diabetes mellitus? Ann Thorac Surg 2017;103:551–8.
[72] Raza S, Blackstone EH, Houghtaling PL, Koprivanac M, Ravichandren K, Javadikasgari H *et al.* Similar outcomes in diabetes patients after coronary artery bypass grafting with single internal thoracic artery plus radial artery grafting and bilateral internal thoracic artery grafting. Ann Thorac Surg 2017;104:1923–32.
[73] Shahian DM, O'Brien SM, Filardo G, Ferraris VA, Haan CK, Rich JB *et al.*; Society of Thoracic Surgeons Quality Measurement Task Force. The Society of Thoracic Surgeons 2008 cardiac surgery risk models: part 1–coronary artery bypass grafting surgery. Ann Thorac Surg 2009;88:S2–22.
[74] Bakaeen FG, Gaudino M, Whitman G, Doenst T, Ruel M, Taggart DP *et al.*; Invited Experts. 2021: the American Association for Thoracic Surgery Expert Consensus Document: coronary artery bypass grafting in patients with ischemic cardiomyopathy and heart failure. J Thorac Cardiovasc Surg 2021;162:829–50.e1.
[75] Jones EL, Lattouf OM, Weintraub WS. Catastrophic consequences of internal mammary artery hypoperfusion. J Thorac Cardiovasc Surg 1989; 98:902–7.
[76] Navia D, Cosgrove DM 3rd, Lytle BW, Taylor PC, McCarthy PM, Stewart RW *et al.* Is the internal thoracic artery the conduit of choice to replace a stenotic vein graft? Ann Thorac Surg 1994;57:40–4.
[77] Lytle BW, Blackstone EH, Sabik JF, Houghtaling P, Loop FD, Cosgrove DM. The effect of bilateral internal thoracic artery grafting on survival during 20 postoperative years. Ann Thorac Surg 2004;78:2005–12; discussion 2012–4.
[78] Galbut DL, Kurlansky PA, Traad EA, Dorman MJ, Zucker M, Ebra G. Bilateral internal thoracic artery grafting improves long-term survival in patients with reduced ejection fraction: a propensity-matched study with 30-year follow-up. J Thorac Cardiovasc Surg 2012;143:844–53.e4.
[79] Farkash A, Pevni D, Mohr R, Kramer A, Ziv-Baran T, Paz Y *et al.* Single versus bilateral internal thoracic artery grafting in patients with low ejection fraction. Medicine (Baltimore) 2020;99:e22842.
[80] Mohammadi S, Kalavrouziotis D, Cresce G, Dagenais F, Dumont E, Charbonneau E *et al.* Bilateral internal thoracic artery use in patients with low ejection fraction: is there any additional long-term benefit? Eur J Cardiothorac Surg 2014;46:425–31; discussion 431.
[81] Gaudino M, Di Franco A, Flather M, Gerry S, Bagiella E, Gray A *et al.* Association of age with 10-year outcomes after coronary surgery in the arterial revascularization trial. J Am Coll Cardiol 2021;77: 18–26.
[82] Deo SV, Altarabsheh SE, Shah IK, Cho YH, McGraw M, Sarayyepoglu B *et al.* Are two really always better than one? Results, concerns and controversies in the use of bilateral internal thoracic arteries for coronary artery bypass grafting in the elderly: a systematic review and meta-analysis. Int J Surg 2015;16:163–70.
[83] Pevni D, Ziv-Baran T, Kramer A, Farkash A, Ben-Gal Y. Is the use of BITA vs SITA grafting safe and beneficial in octogenarians? Ann Thorac Surg 2021;111:1998–2003.
[84] Bakaeen FG, Ravichandren K, Blackstone EH, Houghtaling PL, Soltesz EG, Johnston DR *et al.* Coronary artery target selection and survival after bilateral internal thoracic artery grafting. J Am Coll Cardiol 2020;75: 258–68.
[85] Limanto DH, Chang HW, Kim DJ, Kim JS, Park KH, Lim C. Coronary artery size as a predictor of Y-graft patency following coronary artery bypass surgery. Medicine (Baltimore) 2021;100:e24063.
[86] Glineur D, Hanet C, D'Hoore W, Poncelet A, De Kerchove L, Etienne PY *et al.* Causes of non-functioning right internal mammary used in a Y-graft configuration: insight from a 6-month systematic angiographic trial. Eur J Cardiothorac Surg 2009;36:129–35; discussion 135–6.
[87] Sabik JF 3rd, Lytle BW, Blackstone EH, Khan M, Houghtaling PL, Cosgrove DM. Does competitive flow reduce internal thoracic artery graft patency? Ann Thorac Surg 2003;76:1490–6; discussion 1497.
[88] Raza S, Blackstone EH, Houghtaling PL, Olivares G, Ravichandren K, Koprivanac M *et al.* Natural history of moderate coronary artery stenosis after surgical revascularization. Ann Thorac Surg 2018;105:815–21.
[89] Manabe S, Fukui T, Shimokawa T, Tabata M, Katayama Y, Morita S *et al.* Increased graft occlusion or string sign in composite arterial grafting for mildly stenosed target vessels. Ann Thorac Surg 2010;89:683–7.
[90] Bakaeen FG, Ghandour H, Ravichandren K, Zhen-Yu Tong M, Soltesz EG, Johnston DR *et al.* Right internal thoracic artery patency is affected more by target choice than conduit configuration. Ann Thorac Surg 2022;114: 458–66.
[91] Yanagawa B, Verma S, Jüni P, Tam DY, Mazine A, Puskas JD *et al.* A systematic review and meta-analysis of in situ versus composite bilateral internal thoracic artery grafting. J Thorac Cardiovasc Surg 2017;153: 1108–16.e16.
[92] Deininger MO, Moreira LFP, Dallan LAO, Oliveira O, Magalhaes DMS, Coelho J *et al.* Comparative analysis of the patency of the internal thoracic artery in the CABG of left anterior descending artery: 6-month postoperative coronary CT angiography evaluation. Rev Bras Cir Cardiovasc 2014;29:192–201.
[93] Tatoulis J, Buxton BF, Fuller JA. The right internal thoracic artery: the forgotten conduit–5,766 patients and 991 angiograms. Ann Thorac Surg 2011;92:9–7.
[94] Ji Q, Xia L, Shi Y, Ma R, Shen J, Lai H *et al.* Mid-term graft patency of right versus left internal mammary artery as arterial conduit usage for left anterior descending artery revascularisation: insights from a single-centre study of propensity-matched data. Int J Surg 2017;48:99–104.
[95] Ogawa S, Tsunekawa T, Hosoba S, Goto Y, Kato T, Kitamura H *et al.* Bilateral internal thoracic artery grafting: propensity analysis of the left internal thoracic artery versus the right internal thoracic artery as a bypass graft to the left anterior descending artery. Eur J Cardiothorac Surg 2020;57:701–8.
[96] Jabagi H, Tran D, Glineur D, Rubens FD. Optimal configuration for bypass of the left anterior descending artery during bilateral internal thoracic artery grafting. Ann Thorac Surg 2020;110:1917–25.
[97] Ben-Gal Y, Gordon A, Ziv-Baran T, Farkash A, Mohr R, Kramer A *et al.* Late outcomes of in situ versus composite bilateral internal thoracic artery revascularization. Ann Thorac Surg 2021;112:1441–6.
[98] Raja SG, Benedetto U, Husain M, Soliman R, De Robertis F, Amrani M; Harefield Cardiac Outcomes Research Group. Does grafting of the left anterior descending artery with the in situ right internal thoracic artery have an impact on late outcomes in the context of bilateral internal thoracic artery usage? J Thorac Cardiovasc Surg 2014;148:1275–81.
[99] Mohammadi S, Dagenais F, Voisine P, Dumont E, Baillot R, Doyle D *et al.* Lessons learned from the use of 1,977 in-situ bilateral internal mammary arteries: a retrospective study. J Cardiothorac Surg 2014;9:158.
[100] Joyce FS, McCarthy PM, Taylor PC, Cosgrove DM 3rd, Lytle BW. Cardiac reoperation in patients with bilateral internal thoracic artery grafts. Ann Thorac Surg 1994;58:80–5.
[101] Bakaeen FG, Ghandour H, Ravichandren K, Pettersson GSB, Weiss AJ, Tong MZ *et al.* Risks and outcomes of reoperative cardiac surgery in patients with patent bilateral internal thoracic artery grafts. Ann Thorac Surg 2022;114:736–43.
[102] Gaudino M, Toesca A, Nori SL, Glieca F, Possati G. Effect of skeletonization of the internal thoracic artery on vessel wall integrity. Ann Thorac Surg 1999;68:1623–7.
[103] Yoshikai M, Ito T, Kamohara K, Yunoki J. Endothelial integrity of ultrasonically skeletonized internal thoracic artery: morphological analysis with scanning electron microscopy. Eur J Cardiothorac Surg 2004;25: 208–11.
[104] Gaudino M, Toesca A, Glieca F, Girola F, Luciani N, Possati G. Skeletonization does not influence internal thoracic artery innervation. Ann Thorac Surg 2004;77:1257–61.
[105] Deja MA, Woś S, Gołba KS, Zurek P, Domaradzki W, Bachowski R *et al.* Intraoperative and laboratory evaluation of skeletonized versus pedicled internal thoracic artery. Ann Thorac Surg 1999;68:2164–8.
[106] Sá MP, Cavalcanti PE, Santos HJ, Soares AF, Miranda RG, Araújo ML *et al.* Flow capacity of skeletonized versus pedicled internal thoracic artery in coronary artery bypass graft surgery: systematic review, meta-analysis and meta-regression. Eur J Cardiothorac Surg 2015;48:25–31.
[107] Chaudhri MS, Shah MU, Asghar MI, Siddiqi R, Janjua AM, Iqbal A. Skeletonization of left internal mammary artery in coronary artery bypass grafting. J Coll Physicians Surg Pak 2016;26:736–9.
[108] Satdhabudha O, Noppawinyoowong N. A randomized comparison of flow characteristics of semiskeletonized and pedicled internal thoracic

artery preparations in coronary artery bypass. J Cardiothorac Surg 2017; 12:28.
[109] Silva M, Rong LQ, Naik A, Rahouma M, Hameed I, Robinson B *et al.* Intraoperative graft flow profiles in coronary artery bypass surgery: a meta-analysis. J Card Surg 2020;35:279–85.
[110] Kusu-Orkar TE, Kermali M, Masharani K, Noshirwani A, MacCarthy-Ofosu B, Oguamanam N *et al.* Skeletonized or pedicled harvesting of left internal mammary artery: a systematic review and meta-analysis. Semin Thorac Cardiovasc Surg 2021;33:10–8.
[111] Kamiya H, Akhyari P, Martens A, Karck M, Haverich A, Lichtenberg A. Sternal microcirculation after skeletonized versus pedicled harvesting of the internal thoracic artery: a randomized study. J Thorac Cardiovasc Surg 2008;135:32–7.
[112] Nishi H, Mitsuno M, Tanaka H, Ryomoto M, Fukui S, Miyamoto Y. Decreasing sternum microcirculation after harvesting the internal thoracic artery. Eur J Cardiothorac Surg 2011;40:240–4.
[113] Lorberboym M, Medalion B, Bder O, Lockman J, Cohen N, Schachner A *et al.* 99mTc-MDP bone SPECT for the evaluation of sternal ischaemia following internal mammary artery dissection. Nucl Med Commun 2002;23:47–52.
[114] Cohen AJ, Lockman J, Lorberboym M, Bder O, Cohen N, Medalion B *et al.* Assessment of sternal vascularity with single photon emission computed tomography after harvesting of the internal thoracic artery. J Thorac Cardiovasc Surg 1999;118:496–502.
[115] Boodhwani M, Lam BK, Nathan HJ, Mesana TG, Ruel M, Zeng W *et al.* Skeletonized internal thoracic artery harvest reduces pain and dysesthesia and improves sternal perfusion after coronary artery bypass surgery: a randomized, double-blind, within-patient comparison. Circulation 2006;114:766–73.
[116] Toumpoulis IK, Theakos N, Dunning J. Does bilateral internal thoracic artery harvest increase the risk of mediastinitis? Interact CardioVasc Thorac Surg 2007;6:787–91.
[117] Saso S, James D, Vecht JA, Kidher E, Kokotsakis J, Malinovski V *et al.* Effect of skeletonization of the internal thoracic artery for coronary revascularization on the incidence of sternal wound infection. Ann Thorac Surg 2010;89:661–70.
[118] Sá MP, Cavalcanti PE, de Andrade Costa Santos HJ, Soares AF, Albuquerque Miranda RG, Araújo ML *et al.* Skeletonized versus pedicled bilateral internal mammary artery grafting: outcomes and concerns analyzed through a meta-analytical approach. Int J Surg 2015;16:146–52.
[119] Fouquet O, Tariel F, Desulauze P, Mével G. Does a skeletonized internal thoracic artery give fewer postoperative complications than a pedicled artery for patients undergoing coronary artery bypass grafting? Interact CardioVasc Thorac Surg 2015;20:663–8.
[120] Benedetto U, Altman DG, Gerry S, Gray A, Lees B, Pawlaczyk R *et al.*; Arterial Revascularization Trial investigators. Pedicled and skeletonized single and bilateral internal thoracic artery grafts and the incidence of sternal wound complications: insights from the Arterial Revascularization Trial. J Thorac Cardiovasc Surg 2016;152:270–6.
[121] Jacobs JP, Shahian DM, Grau-Sepulveda M, O'Brien SM, Pruitt EY, Bloom JP *et al.* Current penetration, completeness, and representativeness of the Society of Thoracic Surgeons Adult Cardiac Surgery Database. Ann Thorac Surg 2022;113:1461–8.
[122] Schwann TA, Gaudino MFL, Engelman DT, Sedrakyan A, Li D, Tranbaugh RF *et al.* Effect of skeletonization of bilateral internal thoracic arteries on deep sternal wound infections. Ann Thorac Surg 2021;111:600–6.
[123] Oswald I, Boening A, Pons-Kuehnemann J, Grieshaber P. Wound infection after CABG using internal mammary artery grafts: a meta-analysis. Thorac Cardiovasc Surg 2021;69:639–48.
[124] Sá MP, Ferraz PE, Escobar RR, Nunes EO, Lustosa P, Vasconcelos FP *et al.* Patency of skeletonized versus pedicled internal thoracic artery in coronary bypass graft surgery: a systematic review, meta-analysis and meta-regression. Int J Surg 2014;12:666–72.
[125] Sun X, Huang J, Wang W, Lu S, Zhu K, Li J *et al.* Off-pump skeletonized versus pedicled left internal mammary artery grafting: mid-term results. J Card Surg 2015;30:494–9.
[126] Hu X, Zhao Q. Skeletonized internal thoracic artery harvest improves prognosis in high-risk population after coronary artery bypass surgery for good quality grafts. Ann Thorac Surg 2011;92:48–58.
[127] Lamy A, Browne A, Sheth T, Zheng Z, Dagenais F, Noiseux N *et al.*; COMPASS Investigators. Skeletonized vs pedicled internal mammary artery graft harvesting in coronary artery bypass surgery: a post hoc analysis from the COMPASS trial. JAMA Cardiol 2021;6:1042–8.
[128] Gaudino M, Audisio K, Rahouma M, Chadow D, Cancelli G, Soletti GJ *et al.*; ART Investigators. Comparison of long-term clinical outcomes of skeletonized vs pedicled internal thoracic artery harvesting techniques in the arterial revascularization trial. JAMA Cardiol 2021;6:1380–6.
[129] Sastry P, Rivinius R, Harvey R, Parker RA, Rahm AK, Thomas D *et al.* The influence of endoscopic vein harvesting on outcomes after coronary bypass grafting: a meta-analysis of 267,525 patients. Eur J Cardiothorac Surg 2013;44:980–9.
[130] Deppe AC, Liakopoulos OJ, Choi YH, Slottosch I, Kuhn EW, Scherner M *et al.* Endoscopic vein harvesting for coronary artery bypass grafting: a systematic review with meta-analysis of 27,789 patients. J Surg Res 2013; 180:114–24.
[131] Ferdinand FD, MacDonald JK, Balkhy HH, Bisleri G, Hwang HY, Northrup P *et al.* Endoscopic conduit harvest in coronary artery bypass grafting surgery: an ISMICS systematic review and consensus conference statements. Innovations (Phila) 2017;12:301–19.
[132] Kodia K, Patel S, Weber MP, Luc JGY, Choi JH, Maynes EJ *et al.* Graft patency after open versus endoscopic saphenous vein harvest in coronary artery bypass grafting surgery: a systematic review and meta-analysis. Ann Cardiothorac Surg 2018;7:586–97.
[133] Li G, Zhang Y, Wu Z, Liu Z, Zheng J. Mid-term and long-term outcomes of endoscopic versus open vein harvesting for coronary artery bypass: a systematic review and meta-analysis. Int J Surg 2019;72:167–73.
[134] Zenati MA, Bhatt DL, Bakaeen FG, Stock EM, Biswas K, Gaziano JM *et al.*; REGROUP Trial Investigators. Randomized trial of endoscopic or open vein-graft harvesting for coronary-artery bypass. N Engl J Med 2019;380:132–41.
[135] Zenati MA, Bhatt DL, Stock EM, Hattler B, Wagner TH, Bakaeen FG *et al.* Intermediate-term outcomes of endoscopic or open vein harvesting for coronary artery bypass grafting: the REGROUP randomized clinical trial. JAMA Netw Open 2021;4:e211439.
[136] Desai P, Kiani S, Thiruvanthan N, Henkin S, Kurian D, Ziu P *et al.* Impact of the learning curve for endoscopic vein harvest on conduit quality and early graft patency. Ann Thorac Surg 2011;91:1385–91; discussion 1391–2.
[137] Perrault LP, Jeanmart H, Bilodeau L, Lesperance J, Tanguay JF, Bouchard D *et al.* Early quantitative coronary angiography of saphenous vein grafts for coronary artery bypass grafting harvested by means of open versus endoscopic saphenectomy: a prospective randomized trial. J Thorac Cardiovasc Surg 2004;127:1402–7.
[138] Yun KL, Wu Y, Aharonian V, Mansukhani P, Pfeffer TA, Sintek CF *et al.* Randomized trial of endoscopic versus open vein harvest for coronary artery bypass grafting: six-month patency rates. J Thorac Cardiovasc Surg 2005;129:496–503.
[139] Lopes RD, Hafley GE, Allen KB, Ferguson TB, Peterson ED, Harrington RA *et al.* Endoscopic versus open vein-graft harvesting in coronary-artery bypass surgery. N Engl J Med 2009;361:235–44.
[140] Zenati MA, Shroyer AL, Collins JF, Hattler B, Ota T, Almassi GH *et al.* Impact of endoscopic versus open saphenous vein harvest technique on late coronary artery bypass grafting patient outcomes in the ROOBY (Randomized On/Off Bypass) trial. J Thorac Cardiovasc Surg 2011;141: 338–44.
[141] Neumann FJ, Sousa-Uva M, Ahlsson A, Alfonso F, Banning AP, Benedetto U *et al.*; ESC Scientific Document Group. 2018 ESC/EACTS Guidelines on myocardial revascularization. Eur Heart J 2019;40:87–165.
[142] Samano N, Geijer H, Liden M, Fremes S, Bodin L, Souza D. The no-touch saphenous vein for coronary artery bypass grafting maintains a patency, after 16 years, comparable to the left internal thoracic artery: a randomized trial. J Thorac Cardiovasc Surg 2015;150:880–8.
[143] Dreifaldt M, Mannion JD, Geijer H, Liden M, Bodin L, Souza D. The no-touch saphenous vein is an excellent alternative conduit to the radial artery 8 years after coronary artery bypass grafting: a randomized trial. J Thorac Cardiovasc Surg 2021;161:624–30.
[144] Johansson BL, Souza DSR, Bodin L, Filbey D, Loesch A, Geijer H *et al.* Slower progression of atherosclerosis in vein grafts harvested with 'no touch' technique compared with conventional harvesting technique in coronary artery bypass grafting: an angiographic and intravascular ultrasound study. Eur J Cardiothorac Surg 2010;38:414–9.
[145] Deb S, Singh SK, de Souza D, Chu MWA, Whitlock R, Meyer SR *et al.*; SUPERIOR SVG Study Investigators. SUPERIOR SVG: no touch saphenous harvesting to improve patency following coronary bypass grafting (a multi-Centre randomized control trial, NCT01047449). J Cardiothorac Surg 2019;14:85.
[146] Pettersen Ø, Haram PM, Winnerkvist A, Karevold A, Wahba A, Stenvik M *et al.* Pedicled vein grafts in coronary surgery: perioperative data from a randomized trial. Ann Thorac Surg 2017;104:1313–7.

[147] Yokoyama Y, Takagi H, Kuno T. Graft patency of a second conduit for coronary artery bypass surgery: a network meta-analysis of randomized controlled trials. Semin Thorac Cardiovasc Surg 2022;34:102–9.
[148] Kim YH, Oh HC, Choi JW, Hwang HY, Kim K-B. No-touch saphenous vein harvesting may improve further the patency of saphenous vein composite grafts: early outcomes and 1-year angiographic results. Ann Thorac Surg 2017;103:1489–97.
[149] Wang X, Tian M, Zheng Z, Gao H, Wang Y, Wang L *et al.* Rationale and design of a multicenter randomized trial to compare the graft patency between no-touch vein harvesting technique and conventional approach in coronary artery bypass graft surgery. Am Heart J 2019;210: 75–80.
[150] Ragnarsson S, Janiec M, Modrau IS, Dreifaldt M, Ericsson A, Holmgren A *et al.* No-touch saphenous vein grafts in coronary artery surgery (SWEDEGRAFT): rationale and design of a multicenter, prospective, registry-based randomized clinical trial. Am Heart J 2020;224:17–24.
[151] Janiec M, Friberg O, Thelin S. Long-term clinical outcomes after coronary artery bypass grafting with pedicled saphenous vein grafts. J Cardiothorac Surg 2018;13:122.
[152] Verma S, Lovren F, Pan Y, Yanagawa B, Deb S, Karkhanis R *et al.* Pedicled no-touch saphenous vein graft harvest limits vascular smooth muscle cell activation: the PATENT saphenous vein graft study. Eur J Cardiothorac Surg 2014;45:717–25.
[153] Souza DSR, Dashwood MR, Tsui JCS, Filbey D, Bodin L, Johansson B *et al.* Improved patency in vein grafts harvested with surrounding tissue: results of a randomized study using three harvesting techniques. Ann Thorac Surg 2002;73:1189–95.
[154] Mills NL, Hockmuth DR, Everson CT, Robart CC. Right gastroepiploic artery used for coronary artery bypass grafting. Evaluation of flow characteristics and size. J Thorac Cardiovasc Surg 1993;106:579–86.
[155] Kim KB, Cho KR, Choi JS, Lee HJ. Right gastroepiploic artery for revascularization of the right coronary territory in off-pump total arterial revascularization: strategies to improve patency. Ann Thorac Surg 2006;81: 2135–41.
[156] Hirose H, Amano A, Takanashi S, Takahashi A. Coronary artery bypass grafting using the gastroepiploic artery in 1,000 patients. Ann Thorac Surg 2002;73:1371–9.
[157] Suma H, Tanabe H, Takahashi A, Horii T, Isomura T, Hirose H *et al.* Twenty years experience with the gastroepiploic artery graft for CABG. Circulation 2007;116:I188–91.
[158] Fukui T, Tabata M, Manabe S, Shimokawa T, Takanashi S. Graft selection and one-year patency rates in patients undergoing coronary artery bypass grafting. Ann Thorac Surg 2010;89:1901–5.
[159] Suzuki T, Asai T, Nota H, Kuroyanagi S, Kinoshita T, Takashima N *et al.* Early and long-term patency of in situ skeletonized gastroepiploic artery after off-pump coronary artery bypass graft surgery. Ann Thorac Surg 2013;96:90–5.
[160] Jeong DS, Kim YH, Lee YT, Chung SR, Sung K, Kim WS *et al.* Revascularization for the right coronary artery territory in off-pump coronary artery bypass surgery. Ann Thorac Surg 2013;96:778–85; discussion 785.
[161] Akita S, Tajima K, Kato W, Tanaka K, Goto Y, Yamamoto R *et al.* The long-term patency of a gastroepiploic artery bypass graft deployed in a semiskeletonized fashion: predictors of patency. Interact CardioVasc Thorac Surg 2019;28:868–75.
[162] Kim MS, Hwang HY, Cho KR, Kim KB. Right gastroepiploic artery versus right internal thoracic artery composite grafts: 10-year patency and long-term outcomes. J Thorac Cardiovasc Surg 2022;163:1333–43.
[163] Di Mauro M, Lorusso R, Di Franco A, Foschi M, Rahouma M, Soletti G *et al.* What is the best graft to supplement the bilateral internal thoracic artery to the left coronary system? A meta-analysis. Eur J Cardiothorac Surg 2019;56:21–9.
[164] Suzuki T, Asai T, Matsubayashi K, Kambara A, Kinoshita T, Takashima N *et al.* In off-pump surgery, skeletonized gastroepiploic artery is superior to saphenous vein in patients with bilateral internal thoracic arterial grafts. Ann Thorac Surg 2011;91:1159–64.
[165] Yokoyama Y, Matsushita S, Iesaki T, Yamamoto T, Inaba H, Okada T *et al.* Denervation of gastroepiploic artery graft can reduce vasospasm. J Thorac Cardiovasc Surg 2014;147:951–5.
[166] Asai T, Tabata S. Skeletonization of the right gastroepiploic artery using an ultrasonic scalpel. Ann Thorac Surg 2002;74:1715–7.
[167] Sakai K, Mizuno T, Watanabe T, Nagaoka E, Oi K, Yashima M *et al.* Management of right gastroepiploic arterial coronary grafts in subsequent abdominal surgeries. Ann Thorac Surg 2018;106:52–7.
[168] Shimizu T, Suesada H, Cho M, Ito S, Ikeda K, Ishimaru S. Flow capacity of gastroepiploic artery versus vein grafts for intermediate coronary artery stenosis. Ann Thorac Surg 2005;80:124–30.
[169] Glineur D, D'Hoore W, de Kerchove L, Noirhomme P, Price J, Hanet C *et al.* Angiographic predictors of 3-year patency of bypass grafts implanted on the right coronary artery system: a prospective randomized comparison of gastroepiploic artery, saphenous vein, and right internal thoracic artery grafts. J Thorac Cardiovasc Surg 2011;142:980–8.