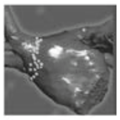

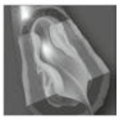

Anaortic, off-pump coronary artery surgery: should it be the standard-of-care?

Recent trials have shown that coronary artery bypass grafting remains the standard-of-care for multivessel coronary artery disease. However, the main criticism of surgery in these trials has been the higher rate of stroke. Off-pump coronary artery bypass grafting (OPCAB) has been suggested as a technique to reduce the rate of stroke. However, large randomized trials comparing coronary artery bypass grafting with OPCAB have failed to show any neurological benefit, most probably because surgeons in these trials fail to avoid manipulation of the ascending aorta. Herein, the authors review a technique of OPCAB surgery where manipulation of the ascending aorta is completely avoided – 'anaortic OPCAB' – facilitated by the use of composite and *in situ* grafts using bilateral internal mammary arteries.

KEYWORDS: coronary artery bypass grafting ▪ coronary artery disease ▪ off-pump coronary artery bypass grafting ▪ stroke

Michael P Vallely*[1,2,3] & J James B Edelman[1,2,3]

[1]*Cardiothoracic Surgical Unit, Royal Prince Alfred Hospital, Sydney, Australia*
[2]*The Baird Institute, Sydney, Australia*
[3]*University of Sydney, Sydney, Australia*
**Author for correspondence: michael.vallely@bigpond.com*

The recently published ASCERT [1], SYNTAX [2] and FREEDOM [3] trials have demonstrated a clear benefit for coronary artery bypass grafting (CABG) over percutaneous coronary intervention (PCI) in the treatment of multivessel coronary disease that increases over time [4]. The main criticism of CABG in the SYNTAX trial was the higher 30-day stroke rate when compared with PCI (2.2 vs 0.6%). However, the stroke rate converges over time [2]. Macro- and micro-embolisation (e.g., atheroma, platelet, air, fat and calcium, among others) are the cause of most brain and distal organ injuries after cardiac surgery [5], along with hypoperfusion and a systemic inflammatory response. Avoiding cardiopulmonary bypass (CPB) with 'off-pump' CABG (OPCAB) has been put forward as a solution to this problem. The term 'OPCAB' describes a heterogeneous group of techniques, the common factor of which is the avoidance of CPB.

The confusion surrounding OPCAB and on-pump CABG surgery, and the evidence for and against each technique, has not been helped by the large randomized trials comparing CABG with OPCAB (i.e., the ROOBY and CORONARY trials) [6,7]. These trials failed to show a neurological benefit for OPCAB over CABG. Surgeons performing OPCAB in the ROOBY and CORONARY trials did not avoid manipulation of the ascending aorta; most often, a partial occlusion clamp or a 'heart-string' device was used to place vein grafts on the aorta [6,7]. The ROOBY and CORONARY trials suggest that simply avoiding CPB alone is not enough to reduce the rate of stroke. The results contrast with the very low stroke rate observed in other studies, where aortic manipulation is completely avoided during OPCAB [8]. The ROOBY trial also demonstrated that surgeons must be experienced in the OPCAB technique to obtain good results [9–11].

Increasingly, there are surgeons around the world pursuing an 'aortic no-touch' or 'anaortic' OPCAB technique, often using all-arterial grafts. Anaortic CABG refers to OPCAB without any manipulation of the ascending aorta whatsoever. Elimination of aortic manipulation by not cannulating the aorta for CPB, not cross-clamping for cardioplegic arrest and not placing a partial occlusion or side-biting clamp for fashioning aorto–coronary grafts can virtually eliminate emboli from the equation. This is even more important in the subgroup of high-risk patients who are elderly, or have peripheral vascular disease, diabetes, renal impairment or chronic airway disease [12].

The aim of this article is not to provide a review comparing OPCAB with CABG; the vast majority of OPCAB series and randomized trials are comparisons of CABG with CPB and aortic cross-clamping versus OPCAB with an aortic side-biting clamp. The aim of this article is to discuss the concept of anaortic OPCAB and the significant reduction in morbidity it can provide.

Stroke & cardiac surgery

Stroke is the most devastating nonlethal complication after cardiac surgery for patients, their families and the surgeon. The cause of

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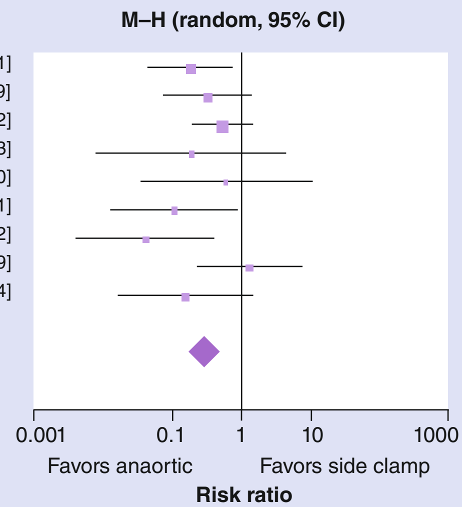
stroke during and immediately after cardiac surgery includes emboli (e.g., atheroma, platelet aggregates, air, calcium and plastics from the CPB circuit, among other causes), hypoperfusion, small-vessel cerebrovascular disease and intracranial hemorrhage. Sometimes the cause of stroke is multifactorial; however, embolic stroke remains to be the most common cause after cardiac surgery [13].

Eliminating emboli from coronary artery surgery has the potential to prevent up to two-thirds of strokes after CABG. The authors' group has published several systematic reviews of anaortic OPCAB versus other revascularization techniques [8,14,15]. Figure 1 is a Forest plot of studies comparing anaortic OPCAB first with OPCAB with a side-biting clamp, and second with conventional CABG, clearly demonstrating the stroke-reduction benefit of anaortic OPCAB. The stroke rate for traditional on-pump CABG in most series and databases is between 1 and 3%, whereas the stroke rate for anaortic OPCAB in most series and in the systematic review evidence is between 0.2 and 0.4% [8]. While the authors are unable to definitely prove that the three- to five-fold reduction in stroke after anaortic OPCAB is due to the elimination of emboli, the fact that two-thirds of stroke cases after cardiac surgery are embolic makes this fact more than coincidental. The risk of stroke

(A)

Study (year)	Anaortic (n)		Side clamp (n)		Weight (%)	Risk ratio, M–H (random, 95% CI)	Ref.
	Events	Total	Events	Total			
Calafiore *et al.* (2002)	3	1533	5	460	16.2	0.18 (0.04–0.75)	[21]
Emmert *et al.* (2011)	2	271	13	567	15.2	0.32 (0.07–1.42)	[19]
Kapetanakis *et al.* (2004)	4	476	40	2527	27.5	0.53 (0.19–1.48)	[22]
Kim *et al.* (2002)	0	222	1	123	3.7	0.19 (0.01–4.52)	[23]
Leacche *et al.* (2003)	0	84	5	556	4.5	0.60 (0.03–10.68)	[70]
Lev-Ran *et al.* (2005)	1	429	6	271	8.1	0.11 (0.01–0.87)	[71]
Osawa *et al.* (2011)	2	451	1	9	6.8	0.04 (0.00–0.40)	[72]
Patel *et al.* (2002)	3	597	2	520	11.0	1.31 (0.22–7.79)	[69]
Vallely *et al.* (2002)	1	1201	3	557	7.1	0.15 (0.02–1.48)	[24]
Total (95% CI)		**5264**		**5590**	**100**	**0.30 (0.16–0.55)**	

Total events: 16 76
Heterogeneity: $\tau^2 = 0.10$; $\chi^2 = 8.94$, df = 8 ($p = 0.35$); $I^2 = 11\%$
Test for overall effect: $Z = 3.81$ ($p = 0.0001$)



(B)

Study (year)	Anaortic (n)		CABG (n)		Risk ratio, M–H (random, 95% CI)	Ref.
	Events	Total	Events	Total		
Calafiore *et al.* (2002)	3	1533	41	2830	0.14 (0.04–0.44)	[21]
Emmert *et al.* (2011)	2	271	51	2111	0.31 (0.07–1.25)	[19]
Izumoto *et al.* (2009)	1	59	2	132	1.12 (0.10–12.10)	[68]
Kapetanakis *et al.* (2004)	4	476	94	4269	0.38 (0.14–1.03)	[22]
Kim *et al.* (2002)	0	222	3	76	0.05 (0.00–0.94)	[23]
Patel *et al.* (2002)	3	597	19	1210	0.32 (0.10–1.08)	[69]
Total (95% CI)		**3158**		**10,628**	**0.28 (0.16–0.48)**	

Total events: 13 210
Heterogeneity: $\tau^2 = 0.00$; $\chi^2 = 4.60$, df = 5 ($p = 0.47$); $I^2 = 0\%$
Test for overall effect: $Z = 4.52$ ($p < 0.0001$)

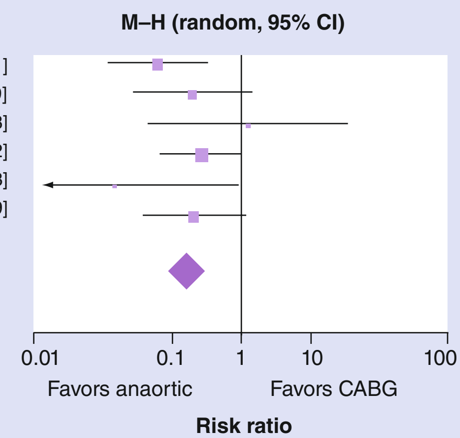


Figure 1. The influence of aortic manipulation on the rate of stroke. (A) OPCAB with side clamp versus anaortic OPCAB; **(B)** anaortic OPCAB versus conventional CABG.
CABG: Coronary artery bypass grafting; df: Degrees of freedom; M–H: Mantel–Haenszel; OPCAB: Off-pump coronary artery bypass grafting.
Reproduced with permission from [8,15].

increases with age and comorbidities. There are several papers that demonstrate a benefit of anaortic OPCAB in the reduction of stroke in elderly and high-risk patients [12,16,17].

While the authors prefer to completely avoid aortic manipulation, the use of clampless anastomotic devices, such as the HEARTSTRING (Maquet, Rastatt, Germany) is preferable to a side clamp if an aortocoronary anastomosis is required [18]. These are associated with a lower rate of stroke than the use of a side clamp [19].

Where is the evidence for anaortic OPCAB?

The authors have previously described how they perform anaortic total arterial OPCAB [20]. Briefly, all graft in-flow is based on one or both internal mammary arteries (IMAs; or the gastroepiploic artery) using composite ‘T’ or ‘Y’ grafts (or a combination; Figure 2). The second limb to the graft may be the right IMA, radial artery or indeed the long saphenous vein graft (although the authors’ group avoids this approach). Pericardial release incisions allow for excellent exposure of the target arteries and intracoronary shunts are used routinely to allow for distal perfusion, a bloodless surgical field and to reduce technical errors, such as catching the back wall of the artery with a suture. The technique is reproducible and is used as the routine revascularisation technique by two out of the five surgeons in the authors’ unit.

All of these techniques have been validated with large, early, single-center studies [21–24], which are summarized in Table 1. The vast majority of this work has been published in the cardiothoracic surgery literature and has not formed part of any randomized controlled trials. This has meant that evidence for the true benefit of anaortic OPCAB and its ability to eliminate aortic manipulation and the risk of cerebral and systemic emboli may not have reached the wider medical community.

The desire to have randomized controlled trial evidence to demonstrate the benefits of one technique over another is admirable. However, the large randomized trials comparing CABG and OPCAB published to date have failed to include high-risk patients (known to benefit most from OPCAB), have not been performed using the anaortic technique, or have been performed by surgeons without adequate OPCAB expertise. Such trials, thus, underestimate the potential of anaortic OPCAB and are biased towards CABG. Puskas and colleagues’ excellent single-surgeon

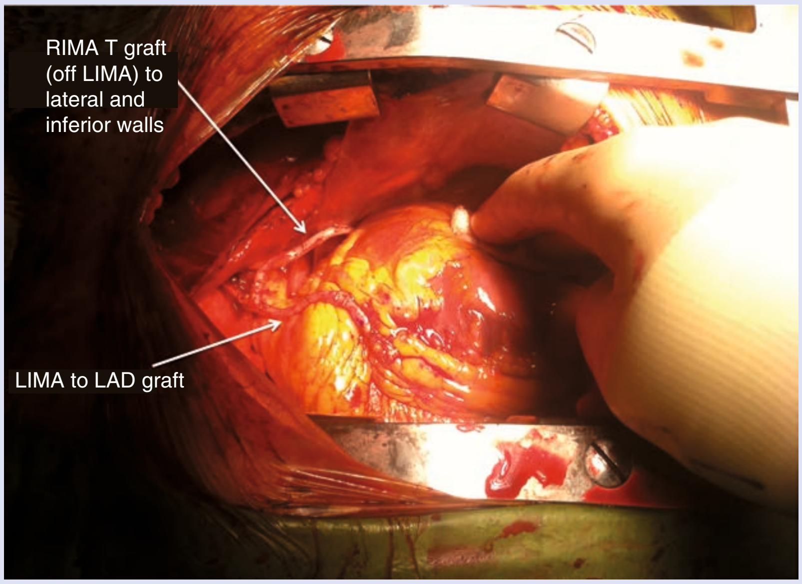


Figure 2. T graft *in situ*. The LIMA is anastomosed to the LAD and the RIMA has been anastomosed to the LIMA as a T graft to supply the lateral and inferior walls of the heart.
LAD: Left anterior descending artery; LIMA: Left internal mammary artery; RIMA: Right internal mammary artery.

randomized controlled trial of 200 patients comparing OPCAB with CABG demonstrated equivalent, excellent immediate and 1-year graft patency rates and outcomes between the two techniques [25]. There are several large series of anaortic OPCAB demonstrating excellent morbidity and mortality results that should be considered when weighing up the evidence for each of the techniques [26].

A later retrospective study from Puskas’ group of over 14,000 patients clearly demonstrated the benefits of OPCAB over CABG in high-risk patients [16]. The results are demonstrated graphically in Figure 3. This can then be contrasted with the randomized controlled ROOBY trial that demonstrated disappointing results in both the on-pump CABG and OPCAB group, with the OPCAB group having a high conversion to on-pump CABG and poorer graft patency rates [27]. Clearly the expertise and experience of Puskas *et al.* accounts for the excellent results and the clear benefit for OPCAB over CABG [16].

There is no doubt that anaortic OPCAB is a technically more challenging procedure, associated with a learning curve. This has been seen as a barrier to the uptake of the technique in some centers. Training can be undertaken in centers with dedicated OPCAB surgeons: this is especially useful in order to develop the techniques required for cardiac positioning to revascularize the inferior and lateral walls. An

Table 1. Trials demonstrating safety and efficacy of composite grafts.

Study (year)	Design	Follow-up (standard deviation)	n		Patency (%)		p-value	Survival (%)		p-value	Ref.
			Composite	*Conventional*	*Composite*	*Conventional*		*Composite*	*Conventional*		
Barner *et al.* (2012)	Retrospective; CABG; radial T graft vs radial free graft; nonprotocol angiography	7.4 (3.8) years	269	103	1 year: 99.6 10 years: 62.9	1 year: 97.1 10 years: 75.4	0.146	1 year: 100 10 years: 87.6	1 year: 100 10 years: 87.7	0.5	[73]
Nasso *et al.* (2009)	RCT; CABG; LIMA/RIMA T graft vs LIMA/RIMA *in situ*	2 years	204	202				96.5	97.5	0.62	[49]
Lemma *et al.* (2004)	Retrospective; CABG; LIMA/radial composite vs free; symptomatic angiography	14.9 months LIMA/RA 27.1 months RA free	176	336	80 (in 4.6% patients with angina and/or positive EST)	74 (in 6.6% patients with angina and/or positive EST)	0.59	98.8	97.7	0.75	[74]
Maniar *et al.* (2003)	Retrospective; CABG; comparison composite vs free radial artery; symptomic angiography	26.1 (18.5) months	111	92	LAD: 83 Cx: 76 RCA: 59 Critical: 92 Severe: 72 Moderate: 58	LAD: 79 Cx: 77 RCA: 57 Critical: 73 Severe: 74 Moderate: 67	NS	–	–	–	[75]
Muneretto *et al.* (2003)	Prospective RCT; CABG in patients >70 years; total arterial grafting (LIMA + RIMA/RA composite) vs CABG (LIMA/SVG); protocol angiography	15 (4) years	100	100	RIMA: 100 RA: 96.7	SVG: 84	0.009	95	96	0.99	[76]
Lev-Ran *et al.* (2002)	Retrospective; CABG; *in situ* BIMA vs LIMA/RIMA T graft	4 years	649	351	–	–	–	89.8	93.2	0.07	[77]

BIMA: Bilateral internal mammary artery; CABG: Coronary artery bypass grafting; Cx: Circumflex artery; EST: Exercise stress test; LAD: Left anterior descending artery; LIMA: Left internal mammary artery; NS: Not significant; RA: Radial artery; RCA: Right coronary artery; RCT: Randomized controlled trial; RIMA: Right internal mammary artery; SVG: Saphenous vein graft.

on-pump beating heart technique can be used to help traverse the learning curve. Exposure of OPCAB techniques to trainees is important and there is evidence that in the correct environment, with adequate supervision, the results of trainees can be equivalent to those of trained surgeons [28,29].

Anaortic OPCAB versus PCI

PCI is often put forward as a lower risk alternative to CABG, particularly in the elderly. Benefits of PCI over surgery include significantly lower 30-day morbidity and a more rapid return to usual activities. However, PCI involves several potential issues, particularly in the elderly. Elderly patients often have multivessel disease with calcified vessels that are not particularly suitable for PCI and, therefore, the patient may be incompletely revascularized. PCI involves passing a wire across the aortic arch into the ascending aorta and there is a risk of embolic stroke [30,31]. Bare-metal stents have a risk of in-stent restenosis and drug-eluting stents have a risk of sudden thrombosis mandating at least 12 months of treatment with dual antiplatelet therapy [32]. A total of 5% of patients require subsequent noncardiac surgical procedures within the first 12 months of a PCI, risk of death/myocardial infarction/stent thrombosis is up to 35% when surgery is performed within the first month and is <10% after 6–12 months [33]. This exposes patients to the risk of bleeding if the antiplatelet therapy is continued and to stent thrombosis if it is discontinued, a classic 'catch 22'. If patients are offered anaortic OPCAB then the antiplatelet therapy can be interrupted when performing subsequent surgical procedures, reducing bleeding and not exposing the patients to the risk of acute stent thrombosis.

A recent paper by Halbersma *et al.* compared 400 patients undergoing total arterial anaortic OPCAB with outcomes from the SYNTAX trial [34]. The 30-day mortality was 0.2%, the 30-day stroke rate was 0.2 % and the 30-day symptomatic graft occlusion was 0.2%, impressive by any standards. The authors compared the 12-month outcomes with the SYNTAX trial 12-month outcomes (Table 2). The outcomes for anaortic OPCAB versus CABG and PCI in the SYNTAX trial are striking. Anaortic OPCAB with total arterial grafts provides a significant reduction in stroke, major adverse cardiac and cerebrovascular events, and reintervention when compared with CABG and PCI as conducted within the SYNTAX trial.

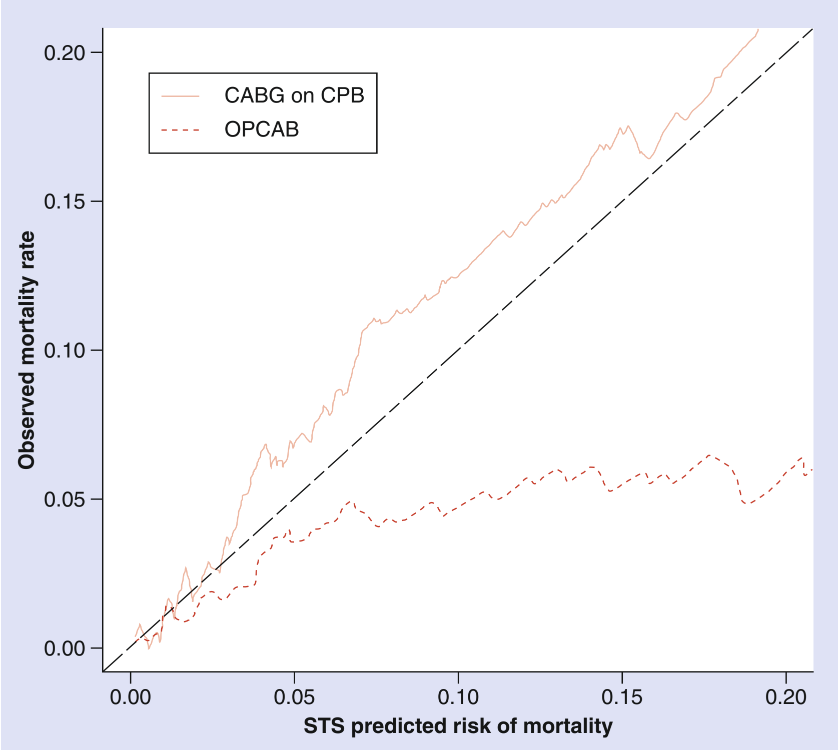


Figure 3. High-risk patients benefit disproportionately from off-pump coronary artery bypass grafting.
CABG: Coronary artery bypass grafting; CPB: Cardiopulmonary bypass; OPBAB: Off-pump coronary artery bypass grafting; STS: Society of Thoracic Surgeons.
Reproduced with permission from [16].

Bilateral mammary arteries

There are several compelling arguments for the use of skeletonized bilateral IMAs (BIMA) in CABG. These include a clear survival benefit [35–38], obtaining two conduits from a single sternotomy (reducing morbidity from other harvest sites) and providing two in-flows to the heart without having to perform a proximal anastomosis during OPCAB surgery. However, there is a disappointingly low usage of BIMA in most countries performing CABG [39]. Surgeons often quote a 'lack of evidence' for their use, increased sternal morbidity, increased operative time and that elderly patients should receive vein grafts as they will not obtain the survival benefit conferred in younger patients.

Data from the Cleveland Clinic (OH, USA) have established the superiority of both single and later double IMA grafts over saphenous vein grafts [36]. An excellent meta-analysis by Taggart *et al.* clearly demonstrates the survival benefits of using bilateral, rather than single, mammary artery grafts [35,40]. Since this paper, there have been numerous institutional series [37,38] demonstrating the survival benefit of a second mammary artery, and the authors are

Table 2. A series of anaortic off-pump coronary artery bypass grafting with total arterial grafts compared with the SYNTAX trial results.

12-month follow-up	Anaortic OPCAB (%)	CABG SYNTAX (%)	TAXUS™ SYNTAX (%)	p-value (anaortic OPCAB vs CABG)	p-value (anaortic OPCAB vs TAXUS)
All-cause death	1.8	3.5	4.4	NS	0.02
Myocardial infarction	2.0	3.3	4.8	NS	0.02
Stroke	0.8	2.2	0.6	0.07	NS
Repeat revascularization	1.3	5.9	13.5	<0.001	<0.001
Symptomatic graft occlusion	0.8	3.4	3.3	0.03	0.04
MACCE	5.3	12.4	17.8	<0.001	<0.001

CABG: Coronary artery bypass grafting; MACCE: Major adverse cardiac and cerebrovascular event; NS: Not significant; OPCAB: Off-pump coronary artery bypass grafting.
Adapted with permission from [34].

awaiting the medium- and long-term data from the ART trial [41].

Sternal morbidity is reduced if the arteries are harvested in a skeletonized fashion and if care is taken not to injure the veins and muscle behind the sternum [42–44]. Certainly female, obese, diabetic patients who have BIMA harvested with a muscle and vein pedicle are at significant risk of devastating sternal wound complications [44,45]; and HbA1c is a predictor of sternal wound infection [46]. There are several clinical and basic science studies demonstrating the superior sternal perfusion offered by skeletonized IMA harvesting [47,48].

The procedural time is increased when BIMAs are harvested. However, as surgeons become more proficient, this time decreases. The authors' philosophy is that in the short term, you may save the patient an extra incision for alternative conduit harvest and that the increased survival benefit makes the extra time and effort worth it.

Being elderly should not preclude a patient from the benefits of arterial grafts; patients >75 years have better cardiac event-free survival when two arterial grafts (compared with one) are used [49]. The use of BIMA grafts in the elderly means that, more often than not, the entire procedure can be conducted via a sternotomy, sparing the legs and arms to facilitate more rapid mobilization and return to normal function. The use of vein grafts requires aortic in-flow that must be obtained with the use of bypass and aortic cross-clamping or the use of a partial occlusion side-biting clamp with the inherent risk of atheroemboli and iatrogenic type A dissection. Elderly patients often have varicose or calcified veins that are suboptimal conduit and prone to early occlusion. The IMAs, by contrast, are often large with slightly thickened walls, facilitating easy harvesting and manipulation during CABG (Figure 2).

Radial artery grafts, composite grafts & competitive flow

There is an increasing body of literature demonstrating the superiority of the radial artery over saphenous vein grafts, especially in studies reporting long-term follow-up [50]. Harvest of the radial artery is less likely to result in wound complications compared with the saphenous vein [51,52]. While early patency rates of vein grafts are excellent, in the mid-term they develop aggressive atherosclerosis [53] that is hard to treat with PCI [54] and is potentially dangerous if manipulated during redo coronary surgery [55]. The method of arterial graft failure is more often a 'string sign'; it is unclear whether this represents an occluded state or a physiological response to flow. Of radial arterial grafts displaying the string sign in the randomized RAPS trial, 50% had a thrombolysis in myocardial infarction (TIMI) flow of >2 and were asymptomatic [56]. A recent publication from Hayward *et al.* demonstrated a 90% radial artery patency at 5 years [57]. Even more importantly, the radial arteries that were patent were completely free of disease. This contrasts strongly with vein grafts at 10 years, which often have significant endoluminal disease [58].

Much of the radial artery patency data are based on aortocoronary grafts, rather than on the use of composite extension grafts or T grafts. The diameter of the ascending aorta is 30 mm in most people, while the radial artery is a fourth order artery with a diameter of 3–4 mm. Anastomosis of a radial graft to the aorta exposes it to high wall shear stress, potentially causing endothelial injury, radial artery spasm and subsequent graft failure. On the other hand, anastomosing the radial artery to the IMA (either as an extension graft or a T graft) is technically easy and there is an excellent caliber match, eliminating turbulent flow and maintaining usual pulse wave forms. The more physiological state is probably protective for the radial artery, and the proximal IMA's ability to dilate according to need means that a single in-flow is sufficient for revascularization.

The single biggest criticism for the radial artery graft is the patency where the target artery stenosis is less than 80% [59]. This creates a competitive flow situation causing vasoconstriction of the muscular radial artery in order to maintain its wall shear stress, resulting in occlusion. Our argument is that it is not the fault of the radial artery and that the vessel probably did not require a graft in the first instance. Angiographic assessment of the severity and significance of coronary disease is often a subjective one. Objective evidence can be obtained by assessing the fractional flow reserve; the FAME 1 [60] and FAME 2 [61] studies have clearly demonstrated that physiological assessment with the fractional flow reserve and appropriate targeted PCI achieves a better outcome.

This raises the issue as to whether coronary angiography should be the only assessment prior to surgery? The argument that a lesion is only moderately diseased and should, therefore, have a vein graft is somewhat flawed. Equivocal lesions (maybe even all target-vessel lesions) should be assessed with the fractional flow reserve and those that are significant should have revascularization with arterial grafts, and those that are not significant should be left alone. This obviously requires more time and effort at diagnostic angiography, but in line with the FAME studies and PCI, the outcomes for surgical revascularization can only be improved.

The fear of some surgeons when using T grafts is the potential implications of losing the left IMA (LIMA) to the left anterior descending artery (LAD) component of the graft, and then removing the huge benefit that a patent LIMA to LAD affords a patient [62]. Early graft failure is often related to technical mishaps when constructing the T graft and care must be taken when performing this anastomosis. Later failure is often related to competitive flow, either in the LAD or from the other target arteries. This reinforces the need to objectively assess lesions prior to making decisions on grafting strategies. The long-term patency and patient survival data after composite grafting have been reported in several single-center studies. The results of these are summarized in Table 1.

Another concern expressed by some surgeons is that a single IMA in-flow is insufficient for total cardiac revascularization. However, the IMA is usually significantly larger than the left main coronary artery and this supplies the vast majority of the heart. The LIMA also has the capacity to dilate according to demand and this happens immediately and over time [63,64]. The use of two IMAs for anaortic OPCAB is obviously ideal, but the authors often use a LIMA/left radial T graft for elderly or morbidly obese patients requiring three-vessel revascularization, thus reducing operative times and potential morbidity.

Conclusion

Complete coronary revascularization using total-arterial grafts without touching the aorta and without using CPB is possible in the vast majority of patients. It requires greater training and considerable care and attention. This is the same as in other cardiac surgical procedures, such as mitral repair or aortic surgery. It is often expected that all surgeons in a unit will perform CABG as part of their service workload, with subspecialization after that into areas of interest, such as mitral valve or aortic work. For the standard of CABG to improve (much like the standard of PCI has improved), then surgeons and units must be willing to invest the time and effort into pursuing more advanced techniques. There must also be a willingness of surgeons to refer patients who would benefit from anaortic OPCAB to a subspecialist surgeon if they do not feel comfortable with the technique.

CABG with a LIMA to the LAD and vein grafts to other territories was a good operation in the 1980s. However, since the 1980s there have been improvements, such as multiple IMA grafting, the revival of the radial artery as a graft [65], and the use of OPCAB and minimally invasive techniques. As with all human endeavours, surgeons must be willing to change and improve their techniques to get the best outcomes for their patients.

Kolessov, a pioneering Russian surgeon, presented the first LIMA to LAD anaortic OPCAB series in the late 1960s [66]. His work was initially received with almost universal skepticism, both in Europe and the USA. It was not until Favaloro's landmark saphenous vein aortocoronary bypass series was published in 1970 that CABG was accepted in the mainstream [67]. The LIMA to LAD forms the backbone of coronary revascularization and the irony of Kolessov's reception is not lost on the authors of this article.

Anaortic OPCAB provides the opportunity for surgeons to completely revascularize the heart with all-arterial grafts, without using CPB and without manipulating the aorta. This may lead to the virtual elimination of stroke from CABG and a significant reduction in morbidity. It takes more effort to learn the technique and the operation time is extended by the routine use of BIMA, but surely the outcomes justify the effort?

Future perspective

Some groups are developing the techniques of minimally invasively anaortic OPCAB, performed using endoscopic and robotic technology. Complete revascularization using anaortic OPCAB is possible using this technology and the goal is to perform this surgery with less pain, shorter time in hospital and faster recovery time.

Financial & competing interests disclosure

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties.

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Executive summary

- Coronary artery bypass grafting is the standard of care for patients with multivessel coronary artery disease, but the higher rate of stroke compared with percutaneous coronary intervention remains a concern.
- The rate of stroke in coronary artery bypass grafting is most likely related to the degree of manipulation of the ascending aorta.
- Anaortic, off-pump coronary artery bypass grafting is a technique that allows complete revascularization of the heart, using all arterial grafts, without any manipulation of the ascending aorta.
- The rate of stroke associated with anaortic off-pump coronary artery bypass grafting is <0.5%.
- Anaortic off-pump coronary artery bypass grafting allows patients the advantages of surgical revascularization (lower rates of mid- to long-term mortality, myocardial infarction and need for repeat revascularization) compared with percutaneous coronary intervention.

References

Papers of special note have been highlighted as:
▪ of interest
▪▪ of considerable interest

1 Weintraub WS, Grau-Sepulveda MV, Weiss JM *et al*. Comparative effectiveness of revascularization strategies. *N. Engl. J. Med.* 366(16), 1467–1476 (2012).

▪ **Large registry study (n = 189,793) demonstrating the survival benefit 4 years after coronary artery bypass grafting compared with percutaneous coronary intervention.**

2 Kappetein AP, Feldman TE, Mack MJ *et al*. Comparison of coronary bypass surgery with drug-eluting stenting for the treatment of left main and/or three-vessel disease: 3-year follow-up of the SYNTAX trial. *Eur. Heart J.* 32(17), 2125–2134 (2011).

▪ **Most relevant randomized comparison of coronary artery bypass grafting versus percutaneous coronary intervention in the era of drug-eluting stents.**

3 Farkouh ME, Domanski M, Sleeper LA *et al*. Strategies for multivessel revascularization in patients with diabetes. *N. Engl. J. Med.* 367(25), 2375–2384 (2012).

▪ **FREEDOM trial demonstrates that diabetic patients with multivessel disease benefit from surgery compared with percutaneous coronary intervention.**

4 Mohr FW, Morice MC, Kappetein AP *et al*. Coronary artery bypass graft surgery versus percutaneous coronary intervention in patients with three-vessel disease and left main coronary disease: 5-year follow-up of the randomised, clinical SYNTAX trial. *Lancet* 381(9867), 629–638 (2013).

5 Selnes OA, Gottesman RF, Grega MA, Baumgartner WA, Zeger SL, McKhann GM. Cognitive and neurologic outcomes after coronary-artery bypass surgery. *N. Engl. J. Med.* 366(3), 250–257 (2012).

6 Serruys PW, Morice MC, Kappetein AP *et al*. Percutaneous coronary intervention versus coronary-artery bypass grafting for severe coronary artery disease. *N. Engl. J. Med.* 360(10), 961–972 (2009).

7 Lamy A, Devereaux PJ, Prabhakaran D *et al*. Off-pump or on-pump coronary-artery bypass grafting at 30 days. *N. Engl. J. Med.* 366(16), 1489–1497 (2012).

8 Edelman JJ, Yan TD, Bannon PG, Wilson MK, Vallely MP. Coronary artery bypass grafting with and without manipulation of the ascending aorta – a meta-analysis. *Heart Lung Circ.* 20(5), 318–324 (2011).

▪▪ **Examines the relationship between the degree of aortic manipulation during coronary artery bypass grafting and the rate of stroke.**

9 Thourani VH, Guyton RA. Graft patency after off-pump coronary artery bypass surgery. *Circulation* 125(23), 2806–2808 (2012).

10 Puskas JD, Mack MJ, Smith CR. On-pump versus off-pump CABG. *N. Engl. J. Med.* 362(9), 851; author reply 853–854 (2010).

11 Taggart DP. On-pump versus off-pump CABG. *N. Engl. J. Med.* 362(9), 852; author reply 853–854 (2010).

12 Cooper EA, Edelman JJ, Wilson MK, Bannon PG, Vallely MP. Off-pump coronary artery bypass grafting in elderly and high-risk patients – a review. *Heart Lung Circ.* 20(11), 694–703 (2011).

13 Likosky DS, Marrin CA, Caplan LR *et al*. Determination of etiologic mechanisms of strokes secondary to coronary artery bypass graft surgery. *Stroke* 34(12), 2830–2834 (2003).

14 Edelman JJ, Yan TD, Padang R, Bannon PG, Vallely MP. Off-pump coronary artery bypass surgery versus percutaneous coronary intervention: a meta-analysis of randomized and nonrandomized studies. *Ann. Thorac. Surg.* 90(4), 1384–1390 (2010).

15 Edelman JJ, Yan TD, Vallely MP. Anaortic off-pump coronary artery bypass grafting: the criterion standard for minimization of neurologic injury. *J. Thorac. Cardiovasc. Surg.* 143(1), 251–252; author reply 252 (2012).

16 Puskas JD, Thourani VH, Kilgo P *et al*. Off-pump coronary artery bypass disproportionately benefits high-risk patients. *Ann. Thorac. Surg.* 88(4), 1142–1147 (2009).

▪▪ **Demonstrates the benefit of off-pump coronary artery bypass grafting surgery to high-risk patients.**

17 Pawlaczyk R, Swietlik D, Lango R, Rogowski J. Off-pump coronary surgery may

reduce stroke, respiratory failure, and mortality in octogenarians. *Ann. Thorac. Surg.* 94(1), 29–37 (2012).

18 Vettath MP, Kannan AV, Peeceeyen CS, Baburajan AK, Vahab A, Sujith MP. Vettath's anastamotic obturator – our experience of 269 proximal anastomoses. *Heart Lung Circ.* 13(3), 288–290 (2004).

19 Emmert MY, Seifert B, Wilhelm M, Grünenfelder J, Falk V, Salzberg SP. Aortic no-touch technique makes the difference in off-pump coronary artery bypass grafting. *J. Thorac. Cardiovasc. Surg.* 142(6), 1499–1506 (2011).

20 Vallely MP, Yan TD, Edelman JJB, Hayman M, Brereton RJL, Ross DE. Anaortic, total-arterial, off-pump coronary artery bypass surgery: how to do it. *Heart Lung Circ.* 19(9), 555–560 (2010).

■■ **Description of the authors' technique of anaortic off-pump coronary artery bypass grafting.**

21 Calafiore AM, Di Mauro M, Teodori G *et al*. Impact of aortic manipulation on incidence of cerebrovascular accidents after surgical myocardial revascularization. *Ann. Thorac. Surg.* 73(5), 1387–1393 (2002).

22 Kapetanakis EI, Stamou SC, Dullum MK *et al*. The impact of aortic manipulation on neurologic outcomes after coronary artery bypass surgery: a risk-adjusted study. *Ann. Thorac. Surg.* 78(5), 1564–1571 (2004).

23 Kim K-B, Kang CH, Chang W-I *et al*. Off-pump coronary artery bypass with complete avoidance of aortic manipulation. *Ann. Thorac. Surg.* 74(4), S1377–S1382 (2002).

24 Vallely MP, Potger K, McMillan D *et al*. Anaortic techniques reduce neurological morbidity after off-pump coronary artery bypass surgery. *Heart Lung Circ.* 17(4), 299–304 (2008).

25 Puskas JD, Williams WH, Mahoney EM *et al*. Off-pump vs conventional coronary artery bypass grafting: early and 1-year graft patency, cost, and quality-of-life outcomes: a randomized trial. *JAMA* 291(15), 1841–1849 (2004).

26 Angelini GD, Culliford L, Smith DK *et al*. Effects of on- and off-pump coronary artery surgery on graft patency, survival, and health-related quality of life: long-term follow-up of 2 randomized controlled trials. *J. Thorac. Cardiovasc. Surg.* 137(2), 295–303 (2009).

27 Shroyer AL, Grover FL, Hattler B *et al*. On-pump versus off-pump coronary-artery bypass surgery. *N Engl. J. Med.* 361(19), 1827–1837 (2009).

28 Ascione R, Reeves BC, Pano M, Angelini GD. Trainees operating on high-risk patients without cardiopulmonary bypass: a high-risk strategy? *Ann. Thorac. Surg.* 78(1), 26–33 (2004).

29 Murphy GJ, Rogers CA, Caputo M, Angelini GD. Acquiring proficiency in off-pump surgery: traversing the learning curve, reproducibility, and quality control. *Ann. Thorac. Surg.* 80(5), 1965–1970 (2005).

30 Batchelor WB, Anstrom KJ, Muhlbaier LH *et al*. Contemporary outcome trends in the elderly undergoing percutaneous coronary interventions: results in 7,472 octogenarians. National Cardiovascular Network Collaboration. *J. Am. Coll. Cardiol.* 36(3), 723–730 (2000).

31 Yan BP, Ajani AE, Clark DJ *et al*. Recent trends in Australian percutaneous coronary intervention practice: insights from the Melbourne Interventional Group registry. *Med. J. Aust.* 195(3), 122–127 (2011).

32 Levine GN, Bates ER, Blankenship JC *et al*. 2011 ACCF/AHA/SCAI guideline for percutaneous coronary intervention: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines and the Society for Cardiovascular Angiography and Interventions. *Circulation* 58(24), e44–e122 (2011).

33 Savonitto S, Caracciolo M, Cattaneo M, De Servi S. Management of patients with recently implanted coronary stents on dual antiplatelet therapy who need to undergo major surgery. *J. Thromb. Haemost.* 9(11), 2133–2142 (2011).

34 Halbersma WB, Arrigoni SC, Mecozzi G *et al*. Four-year outcome of OPCAB no-touch with total arterial Y-graft: making the best treatment a daily practice. *Ann. Thorac. Surg.* 88(3), 796–801 (2009).

35 Taggart DP, D'Amico R, Altman DG. Effect of arterial revascularisation on survival: a systematic review of studies comparing bilateral and single internal mammary arteries. *Lancet* 358(9285), 870–875 (2001).

36 Lytle BW, Blackstone EH, Loop FD *et al*. Two internal thoracic artery grafts are better than one. *J. Thorac. Cardiovasc. Surg.* 117(5), 855–872 (1999).

■ **First large registry study to highlight the survival benefits of using both internal mammary arteries.**

37 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.* 143(4), 844–853.e4 (2012).

38 Ruttmann E, Fischler N, Sakic A *et al*. Second internal thoracic artery versus radial artery in coronary artery bypass grafting: a long-term, propensity score-matched follow-up study. *Circulation* 124(12), 1321–1329 (2011).

39 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.* 143(2), 273–281 (2012).

40 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.* 78(6), 2005–2012; discussion 12–14 (2004).

41 Taggart DP, Altman DG, Gray AM *et al*. Randomized trial to compare bilateral vs. single internal mammary coronary artery bypass grafting: 1-year results of the Arterial Revascularisation Trial (ART). *Eur. Heart J.* 31(20), 2470–2481 (2010).

42 Peterson MD, Borger MA, Rao V, Peniston CM, Feindel CM. Skeletonization of bilateral internal thoracic artery grafts lowers the risk of sternal infection in patients with diabetes. *J. Thorac. Cardiovasc. Surg.* 126(5), 1314–1319 (2003).

43 Calafiore AM, Vitolla G, Iaco AL *et al*. Bilateral internal mammary artery grafting: midterm results of pedicled versus skeletonized conduits. *Ann. Thorac. Surg.* 67(6), 1637–1642 (1999).

44 Saso S, James D, Vecht JA *et al*. Effect of skeletonization of the internal thoracic artery for coronary revascularization on the incidence of sternal wound infection. *Ann. Thorac. Surg.* 89(2), 661–670 (2010).

45 Hirose H, Amano A, Takanashi S, Takahashi A. Skeletonized bilateral internal mammary artery grafting for patients with diabetes. *Interact. Cardiovasc. Thorac. Surg.* 2(3), 287–292 (2003).

46 Halkos ME, Thourani VH, Lattouf OM, Kilgo P, Guyton RA, Puskas JD. Preoperative hemoglobin a1c predicts sternal wound infection after coronary artery bypass surgery with bilateral versus single internal thoracic artery grafts. *Innovations (Phila.)* 3(3), 131–138 (2008).

47 Boodhwani M. 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* 114(8), 766–773 (2006).

48 Parish MA, Asai T, Grossi EA *et al*. The effects of different techniques of internal mammary artery harvesting on sternal blood flow. *J. Thorac. Cardiovasc. Surg.* 104(5), 1303–1307 (1992).

49 Nasso G, Coppola R, Bonifazi R, Piancone F, Bozzetti G, Speziale G. Arterial revascularization in primary coronary artery bypass grafting: direct comparison of 4 strategies – results of the Stand-in-Y Mammary Study. *J. Thorac. Cardiovasc. Surg.* 137(5), 1093–1100 (2009).

50 Cao C, Manganas C, Horton M *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.* doi:10.1016/j.jtcvs.2012.07.014 (2012) (Epub ahead of print).

▪ **Meta-analysis that demonstrates the benefit of radial artery versus saphenous grafts.**

51 Saeed I, Anyanwu AC, Yacoub MH, Amrani M. Subjective patient outcomes following coronary artery bypass using the radial artery: results of a cross-sectional survey of harvest site complications and quality of life. *Eur. J. Cardiothorac. Surg.* 20(6), 1142–1146 (2001).

52 Damgaard S, Lund JT, Lilleør NB *et al.* Comparable three months' outcome of total arterial revascularization versus conventional coronary surgery: Copenhagen Arterial Revascularization Randomized Patency and Outcome trial. *J. Thorac. Cardiovasc. Surg.* 135(5), 1069–1075 (2008).

53 Motwani JG, Topol EJ. Aortocoronary saphenous vein graft disease: pathogenesis, predisposition, and prevention. *Circulation* 97(9), 916–931 (1998).

54 Hakeem A, Helmy T, Munsif S *et al.* Safety and efficacy of drug eluting stents compared with bare metal stents for saphenous vein graft interventions: a comprehensive meta-analysis of randomized trials and observational studies comprising 7,994 patients. *Catheter Cardiovasc. Interv.* 77(3), 343–355 (2011).

55 Raja SG, Amrani M. Reoperative off-pump coronary artery bypass grafting: current outcomes, concerns and controversies. *Expert Rev. Cardiovasc. Ther.* 8(5), 685–694 (2010).

56 Miwa S, Desai N, Koyama T *et al.* Radial artery angiographic string sign: clinical consequences and the role of pharmacologic therapy. *Ann. Thorac. Surg.* 81(1), 112–118; discussion 9 (2006).

57 Hayward PA, Hare DL, Gordon I, Buxton BF. Effect of radial artery or saphenous vein conduit for the second graft on 6-year clinical outcome after coronary artery bypass grafting. Results of a randomised trial. *Eur. J. Cardiothorac. Surg.* 34(1), 113–117 (2008).

58 Tatoulis J, Buxton BF, Fuller JA *et al.* Long-term patency of 1108 radial arterial–coronary angiograms over 10 years. *Ann. Thorac. Surg.* 88(1), 23–29; discussion 9–30 (2009).

59 Desai ND, Naylor CD, Kiss A *et al.* Impact of patient and target-vessel characteristics on arterial and venous bypass graft patency: insight from a randomized trial. *Circulation* 115(6), 684–691 (2007).

60 Tonino PA, De Bruyne B, Pijls NH *et al.* Fractional flow reserve versus angiography for guiding percutaneous coronary intervention. *N. Engl. J. Med.* 360(3), 213–224 (2009).

61 De Bruyne B, Pijls NHJ, Kalesan B *et al.* Fractional flow reserve-guided PCI versus medical therapy in stable coronary disease. *N. Engl. J. Med.* 367(11), 991–1001 (2012).

62 Légaré JF, Buth KJ, Sullivan JA, Hirsch GM. Composite arterial grafts versus conventional grafting for coronary artery bypass grafting. *J. Thorac. Cardiovasc. Surg.* 127(1), 160–166 (2004).

63 Gaudino M, Di Mauro M, Iacò AL, Canosa C, Vitolla G, Calafiore AM. Immediate flow reserve of Y thoracic artery grafts: an intraoperative flowmetric study. *J. Thorac. Cardiovasc. Surg.* 126(4), 1076–1079 (2003).

64 Glineur D, Boodhwani M, Poncelet A *et al.* Comparison of fractional flow reserve of composite Y-grafts with saphenous vein or right internal thoracic arteries. *J. Thorac. Cardiovasc. Surg.* 140(3), 639–645 (2010).

65 Acar C, Ramsheyi A, Pagny JY *et al.* The radial artery for coronary artery bypass grafting: clinical and angiographic results at five years. *J. Thorac. Cardiovasc. Surg.* 116(6), 981–989 (1998).

66 Kolessov VI. Mammary artery–coronary artery anastomosis as method of treatment for angina pectoris. *J. Thorac. Cardiovasc. Surg.* 54(4), 535–544 (1967).

67 Favaloro RG. Direct revascularization with vein grafts. *NY State J. Med.* 70(15), 1990–1992 (1970).

68 Izumoto H, Oka T, Kawazoe K, Ishibashi K, Yamamoto F. Individualized off-pump all internal thoracic artery revascularization. *Ann. Thorac. Cardiovasc. Surg.* 15(3), 155–159 (2009).

69 Patel NC, Deodhar AP, Grayson AD *et al.* Neurological outcomes in coronary surgery: independent effect of avoiding cardiopulmonary bypass. *Ann. Thorac. Surg.* 74(2), 400–405; discussion 5–6 (2002).

70 Leacche M, Carrier M, Bouchard D *et al.* Improving neurologic outcome in off-pump surgery: the 'no touch' technique. *Heart Surg. Forum* 6(3), 169–175 (2003).

71 Lev-Ran O, Braunstein R, Sharony R *et al.* No-touch aorta off-pump coronary surgery: the effect on stroke. *J. Thorac. Cardiovasc. Surg.* 129(2), 307–313 (2005).

72 Osawa H, Inaba H, Kinoshita O, Akashi O, Minegishi S. Off-pump coronary artery bypass grafting with an aortic nonclamping technique may reduce the incidence of cerebral complications. *Gen. Thorac. Cardiovasc. Surg.* 59(10), 681–685 (2011).

73 Barner HB, Bailey M, Guthrie TJ *et al.* Radial artery free and T graft patency as coronary artery bypass conduit over a 15-year period. *Circulation* 126(11 Suppl. 1), S140–S144 (2012).

74 Lemma M, Mangini A, Gelpi G, Innorta A, Spina A, Antona C. Is it better to use the radial artery as a composite graft? Clinical and angiographic results of aorto–coronary versus Y-graft. *Eur. J. Cardiothorac. Surg.* 26(1), 110–117 (2004).

75 Maniar HS, Barner HB, Bailey MS *et al.* Radial artery patency: are aortocoronary conduits superior to composite grafting? *Ann. Thorac. Surg.* 76(5), 1498–1503; discussion 503–504 (2003).

76 Muneretto C, Bisleri G, Negri A *et al.* Total arterial myocardial revascularization with composite grafts improves results of coronary surgery in elderly: a prospective randomized comparison with conventional coronary artery bypass surgery. *Circulation* 9(108 Suppl. 1), II29–II33 (2003).

77 Lev-Ran O, Paz Y, Pevni D *et al.* Bilateral internal thoracic artery grafting: midterm results of composite versus *in situ* crossover graft. *Ann. Thorac. Surg.* 74(3), 704–710; discussion 10–11 (2002).