New Technologies in Coronary Artery Surgery

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ABSTRACT

Coronary artery disease remains the leading cause of death in developed countries. Major recent studies such as SYNTAX and FREEDOM have confirmed that coronary artery bypass grafting (CABG) remains the gold standard treatment in terms of survival and freedom from myocardial infarction and the need for repeat revascularization. The current review explores the use of new technologies and future directions in coronary artery surgery, through 1) stressing the importance of multiple arterial conduits and especially the use of bilateral mammary artery; 2) discussing the advantages and disadvantages of off-pump coronary artery bypass; 3) presenting additional techniques, e.g. minimally invasive direct coronary artery bypass grafting, hybrid, and robotic-assisted CABG; and, finally, 4) debating a novel external stenting technique for saphenous vein grafts.

KEY WORDS: Coronary artery disease, external stent, minimally invasive grafting, multiple arterial conduits, off-pump coronary artery bypass

Abbreviations: BIMA, bilateral internal mammary artery; CABG, coronary artery bypass grafting; CAD, coronary artery disease; CPB, cardiopulmonary bypass; IMA, internal mammary artery; LAD, left anterior descending; LIMA, left internal mammary artery; LIMA–SV, LIMA plus saphenous veins; MIDCAB, minimally invasive direct coronary artery bypass grafting; MultArt, multiple arterial grafting; PCI, percutaneous coronary intervention; RA, radial artery; RIMA, right internal mammary artery; SV, saphenous vein; SVG, saphenous vein grafts; TECAB, totally endoscopic coronary artery bypass.

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Conflict of interest: Professor Taggart currently serves as a consultant to RAD BioMed, the manufacturer of the FLUENT SVG device. Professor Bolotin has served as a consultant to RAD BioMed, the manufacturer of the FLUENT SVG device.

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MULTIPLE ARTERIAL CABG PROCEDURES

Late survival after coronary artery bypass grafting (CABG) is improved when the left internal mammary artery (LIMA) is grafted to the left anterior descending artery (LAD). LIMA has been recognized as the optimal conduit in CABG because of its superior patency rate and freedom from arteriosclerosis compared with the saphenous vein (SV). In anticipation of additional advantages with the use of a second arterial graft, surgeons currently use the right internal mammary artery (RIMA), radial artery (RA), or gastroepiploic artery as the bypass conduit. Several retrospective analyses have documented an incremental survival benefit by increasing the number of arterial grafts, and two independent meta-analyses have corroborated a long-term benefit. Despite this compelling information in the published literature, multiple arterial grafting (MultArt) is currently performed in <13% of CABG operations.

A recent observational, retrospective study reviewed 8,622 Mayo Clinic patients who had isolated primary coronary artery bypass graft surgery for multivessel coronary artery disease from 1993 to 2009. Patients were stratified by number of arterial grafts into the LIMA plus saphenous veins (LIMA–SV) group (n = 7,435) or the MultArt group (n = 1,187). Propensity score analysis matched 1,153 patients. Operative mortality was 0.8% (n = 10) in the MultArt and 2.1% (n = 154) in the LIMA–SV (P = 0.818 for the propensity-matched analysis). Late survival was greater for MultArt versus LIMA–SV (10- and 15-year survival rates were 84% and 71% versus 61% and 36%, respectively (P < 0.001), in unmatched groups and 83% and 70% versus 80% and 60%, respectively (P = 0.0025), in matched groups). MultArt subgroups with bilateral internal mammary artery (BIMA)–SV (n = 589) and BIMA only (n = 271) had improved 15-year survival (86% and 76%; 82% and 75% at 10 and 15 years, P < 0.001), and patients with BIMA–RA (n = 147) and LIMA–RA (n = 169) had greater 10-year survival (84% and 78%, P < 0.001) versus LIMA–SV. In multivariate analysis, MultArt grafts remained a strong independent predictor of survival (hazard ratio 0.79, 95% confidence interval 0.66–0.94, P = 0.007). These findings suggest that in patients undergoing isolated coronary artery bypass graft surgery with LIMA to left anterior descending artery, arterial grafting of the non-left anterior descending vessels conferred a survival advantage at 15 years compared with SV grafting. It is still unproven whether these results apply to higher-risk subgroups of patients.

Despite previous reports of greater benefit from left than right coronary system grafting with the second arterial graft, a careful review of the literature indicates that use of two internal mammary artery (IMA) grafts demonstrates excellent long-term results with no demonstrable difference in outcome between right and left coronary system patients. Indeed, in the study by Locker et al., 20% of MultArt patients received the second arterial bypass to the right system only, with no additional arterial grafting to the circumflex coronary system.

BILATERAL INTERNAL MAMMARY ARTERIES

Almost three decades ago, in a seminal study, the Cleveland Clinic Group reported that a single internal mammary artery (SIMA) resulted in superior survival benefit as well as a reduced subsequent incidence of myocardial infarction, recurrent angina, and the need for repeat revascularization. This improvement in survival has now been reported to persist into the second and third decades of follow-up. More than a decade ago our own group published a systematic review including a meta-analysis of 15,962 patients receiving SIMA or BIMA grafts. The hazard ratio for death with BIMA grafts was 0.81, with a 95% confidence interval of 0.70–0.94. Although this was not a randomized trial the patients were matched for age, gender, diabetes, and ventricular function, four factors which give a likely indication of longevity even independent of the presence of coronary artery disease.

The most likely explanation for the survival benefit of IMA grafting is its greatly superior rates of patency in comparison to vein grafts. Whereas 10 years after bypass grafting up to three-quarters of all vein grafts are occluded or severely diseased, in contrast the patency rates of IMA grafts remain in excess of 90% even into the second decade of follow-up.

The IMA graft is a unique artery both in anatomical structural terms (with a high proportion of elastic rather than muscle or adventitia composition) and in physiological function (it produces much greater levels of nitric oxide and decreased release of vasconstrictors in comparison to other vessels), resulting in potent anti-atherosclerotic effects.
Despite strong clinical evidence in favor of the use of BIMA grafts, their use in current practice remains disappointingly low, being around 5% of patients in the USA and fewer than 10% in Europe.

In an effort to add more scientific data to the debate of SIMA or BIMA grafting, the Arterial Revascularization Trial (ART) randomized 3,102 patients in 28 centers in seven countries. The 1-year outcomes showed 30-day mortalities of just over 1% in both groups and just over 2% at 1 year, with no significant difference in the incidence of stroke, myocardial infarction, and repeat revascularization (i.e. safety end-point), which were all around 2%. This clearly demonstrated that there was no increase in mortality or myocardial infarction with BIMA grafts. Furthermore the use of a second IMA graft added 23 minutes to the operative procedure which in itself took 3–4 hours.

The one note of caution was that there was indeed an increase in sternal wound reconstruction from 0.6% in the SIMA group to 1.9% in the BIMA group, i.e. an absolute difference of 1.3% or a number needed to harm of 78 patients. However, it is noteworthy that while one-quarter of all patients in the ART Trial had diabetes almost half the patients requiring sternal wound reconstruction had diabetes. It is highly likely that with more judicious patient selection (avoiding BIMA grafts in obese diabetics or those with impaired lung function) and more precise harvesting techniques (skeletonization rather than pedicle to preserve collateral circulation) the incidence of sternal wound reconstruction would be significantly lower.

While the results of recent trials of CABG versus stents in general populations (such as the SYNTAX Trial) and in diabetics (the FREEDOM Trial) confirm the significant superiority of CABG over stents in terms of superior survival and freedom from subsequent myocardial infarction or repeat revascularization, the low use of BIMA grafts in current practice is a poor reflection of optimal surgical therapy. The recommendations in guidelines support the use of more arterial grafts during CABG, and the National Societies of Cardio-thoracic Surgery should give increased recognition to and promote more use of BIMA grafts.

OFF-PUMP SURGERY
For almost three decades there has been controversy as to the potential benefits of off-pump CABG in relation to on-pump CABG. The initial rationale for off-pump CABG was mainly driven by economic considerations in developing countries where the economic cost of cardiopulmonary bypass made CABG an unrealistic proposition in many patients. Despite much skepticism by its opponents, off-pump CABG was gradually introduced into developed countries where its proponents recognized its potential to mitigate the adverse effects of extracorporeal circulation in an increasingly elderly population undergoing CABG. The views of supporters and opponents of off-pump CABG have remained essentially unchanged in the intervening period.

A meta-analysis by Afilalo and colleagues of almost 9,000 patients from 59 randomized trials showed no difference between the two techniques in postoperative mortality and myocardial infarction but did report a lower incidence of stroke in the off-pump group (1.4% versus 2.1%, odds ratio 0.7, 95% CI 0.49–0.99). However, an important consideration in many of the randomized trials was the question about the actual surgical experience of those performing the off-pump surgery. Indeed, two trials reporting worse outcomes with off-pump surgery were severely criticized on the basis of the inexperience of the participating surgeons—emphasized by high rates of conversion from off-pump to on-pump surgery.

Two recently published trials provide far more definitive answers. First, the CORONARY Trial, which enrolled 4,752 patients in 79 centers in 19 countries, had previously reported no significant difference at 30 days in the primary composite outcome of death, myocardial infarction, stroke, or new renal failure between the two techniques. The trial has now reported the 1-year outcomes and showed no significant difference in the primary composite outcome between off-pump and on-pump CABG (12.1% off-pump versus 13.3% on-pump, hazard ratio 0.91, P = 0.24). In particular, there was no difference in the incidence of individual components of the primary outcome in terms of death, myocardial infarction, stroke, or new renal failure. Furthermore, and in contrast to previous studies, there was no significant increase in the incidence of repeat revascularization for off-pump CABG at 1 year. Additionally, there was no difference in neurocognitive outcomes at 1 year between the two groups. The most likely explanation of the differences between the findings of the CORONARY Trial and two of the largest previous trials reporting inferior outcomes for off-pump CABG is that the CORONARY Trial not only enrolled a far greater
number of patients but, crucially, recruited surgeons with a far higher level of surgical expertise in off-pump surgery.

A second trial (GOPCABE), which randomized 2,539 patients aged 75 years or older to on-pump and off-pump CABG, has been published very recently.27 Again, the primary outcome was a composite of death, stroke, myocardial infarction, repeat revascularization, or new renal replacement therapy at 30 days and at 1 year after surgery. The authors reported no significant differences in the composite outcome either at 30 days (7.8% off-pump versus 8.2% on-pump, \( P = 0.74 \)) or at 12 months (13.1% versus 14%, \( P = 0.48 \)). Of particular note in this trial is the fact that the surgeons were highly experienced; for off-pump surgeons the average number of off-pump surgeries was 514 and for on-pump surgeons 1,378. Although the average number of coronary anastomoses was 2.7 in the off-pump group and 2.8 in the on-pump group \((P < 0.001)\), this is highly unlikely to be of any clinical significance. The only remaining question now would appear to be whether off-pump surgery in association with a no-touch aortic technique significantly reduces the risk of perioperative stroke. It is noteworthy that in the GOPCABE Trial the most common reason for conversion from on-pump to off-pump CABG after the skin incision was a calcified ascending aorta.

In summary, the postulated benefits of off-pump surgery have not materialized in clinical practice for most patients, possibly due to the fact that advances in extracorporeal perfusion have made cardiopulmonary bypass much safer. For most patients undergoing CABG today the use of bilateral internal mammary arteries is far more important than whether surgery is performed on or off pump.

MINIMALLY INVASIVE DIRECT CORONARY ARTERY BYPASS GRAFTING

Minimally invasive direct coronary artery bypass grafting (MIDCAB) utilizes a small anterior left thoracotomy incision and harvesting of the left internal mammary artery with an anastomosis performed to the left anterior descending artery without cardiopulmonary bypass. MIDCAB was initially described for single-vessel bypass to the left anterior descending (LAD) artery.28 Many variations have been described, including the single left internal mammary artery (LIMA) to LAD bypass, the multivessel complete revascularization, and the saphenous vein graft from the axillary artery to the LAD. Mammary harvest variations include robotic and thoracoscopic takedown. Finally, MIDCABs have been done with and without cardiopulmonary bypass (CPB).29

Patients for the MIDCAB approach are to be selected carefully; the ideal candidate would have severe stenosis or complete occlusion of the proximal LAD. It is imperative that the distal LAD is visualized either by collateral filling or by computed tomographic angiography in cases in which the patient has complete occlusion. Importantly, obesity is a relative contraindication; although the LIMA takedown is technically possible in obese patients, the pressure placed on the wound edges by the retractor can lead to tissue necrosis and wound infections. Similarly, female patients with large breasts are at increased risk of wound necrosis.30

The most pivotal factors in the postoperative management of MIDCAB patients are analgesia and early mobilization; many patients are extubated on the table, but if a period of postoperative ventilator support is required, the endotracheal tube is changed to a single-lumen tube. Non-steroidal anti-inflammatory medications are used in addition to narcotics, and occasionally a thoracic epidural catheter is placed for pain control. Intravenous fluids are restricted, and patients are usually allowed to get out of bed the same evening. Monitoring lines and chest tubes are removed on the first postoperative day, and patients ambulate aggressively. Once pain is well controlled with oral medications, patients are discharged home usually on the third or fourth postoperative day.

The overall reported results of MIDCAB have been excellent,31-35 as: 1) Procedural success is estimated at 98%; 2) Operative mortality is < 1% in most series; 3) Reoperation rates for bleeding vary from 1% to 3%; 4) Chest wound complications occur in 2%-3%; 5) Pulmonary complications are seen in 1%-3% of patients; 6) Angiographic patency in the early postoperative period and at 6 months has been outstanding; and 7) Re-intervention for ischemic events has been atypical.

HYBRID MIDCAB APPROACH

Recently, several studies reported a fruitful use of a hybrid approach combining minimally invasive LIMA–LAD bypass procedures with catheter-based interventions on the circumflex or right coronary arteries for the treatment of multivessel disease. In
most series, the catheter-based interventions, which generally necessitate the placement of a drug-eluting stent, were performed several days before or several days after the surgical revascularization,\textsuperscript{36} although a same-day hybrid approach has also been described\textsuperscript{37}; both methodologies suggest that integrated revascularization treatment plans provide minimally invasive options for patients with multivessel coronary artery disease.

A very recent study\textsuperscript{38} evaluated the long-term outcomes of minimally invasive hybrid revascularization based on a 13-year long database (1997–2011) of 810 MIDCAB procedures of isolated revascularization in 644 patients; MIDCAB, as a part of hybrid revascularization, was associated with percutaneous coronary intervention (PCI) in 166 patients. In line with previous reports, results indicated the following: 1) Overall mortality: 0.24%; 2) Perioperative acute myocardial infarction: 1.6%; 3) Early reoperation: 0.74%; 4) Reopening for bleeding: 1.2%; 5) Case rate of hemotransfusion: 3.1%; and 6) Mean hospital postoperative stay: 4 ± 2.5 days. Postoperative angiographic control prior to PCI and in symptomatic patients showed patent left internal mammary artery in 100% of cases. Notably, in the hybrid revascularization group, at the mean follow-up of 4.5 ± 2.3 years, freedom from related cardiac death was 93% and freedom from cardiac re-intervention was 83%.

Theoretically, hybrid procedures provide a complete revascularization while keeping the survival benefit and angina relief of a LIMA–LAD graft and avoiding the morbidity of sternotomy.\textsuperscript{39} The ideal candidate for the hybrid approach may be a patient with double- or triple-vessel disease with low syntax score or a patient with high syntax score and high Euroscore. Before prevalent implementation of this approach will occur, however, patency and outcome data are required. Though more laborious and cost-intensive compared to traditional CABG or stenting, improvements in the techniques and co-ordination between the surgeon and interventional cardiologists will probably increase the effectiveness and value of the hybrid approach.\textsuperscript{39} A designated hybrid operative room will allow performing a single-session procedure at one place without the need to transfer the patient from the operating room to the catheterization laboratory.

ROBOTIC-ASSISTED CABG

The surgical robot is an elegant microprocessor-controlled, electromechanical instrument that allows the surgeon to remotely manipulate fully articulating videooscopic instruments by way of master–slave servos and microprocessor control. These long, thin instruments, which can be inserted into the closed chest through half-inch incisions, are designed to allow multiple degrees of freedom and can precisely emulate the surgeon’s movements at the control console.\textsuperscript{40} A clear benefit to the robotic approach over other methods, however, has not been demonstrated.

Since the introduction of surgical robotics in the 1990s, there has been a progressive increase in utilization for thoracic surgical procedures. Although mitral valve and non-cardiac thoracic procedures account for the majority of cases, there are increasing reports of robotic-assisted coronary revascularization procedures. These reports include robotic LIMA harvest followed by a traditional MIDCAB\textsuperscript{41} or left thoracotomy off-pump CABG,\textsuperscript{45} totally endoscopic coronary artery bypass (TECAB) on the arrested heart,\textsuperscript{42,43} and totally endoscopic bypass without CPB (OP-TECAB).\textsuperscript{43} Although most TECABs and OP-TECABs involve only a LIMA–LAD graft, recent reports described a series of multivessel revascularization procedures.\textsuperscript{42} These series have demonstrated that each of these methods of limited access off-pump coronary bypass is associated with a shorter hospital stay, less time on mechanical ventilation, fewer transfusions, and a more rapid return to full activity. The operative times are considerably longer than for open procedures, but improved time efficiency with experience is the norm. Also, questions related to graft patency and long-term results persist. Several earlier reports suggested a conversion to an open procedure in > 50% of cases, but with increased experience conversion in the ≤ 10% range is more common.\textsuperscript{43}

Because of the added expense and difficulty with learning the technique, the routine use of surgical robotics in CABG surgery does not seem likely in the near future. The robot has and will continue to evolve. Improved video resolution, lower-mass arms, the addition of a fourth tele-manipulator, and the availability of an elegant robotic coronary
stabilizer will likely increase its effectiveness and extend its application. Refinement of automated distal anastomotic devices may further increase the growth of robotic coronary revascularization surgery.

**PATENCY OF GRAFT**

Coronary artery disease (CAD) remains the leading cause of death in developed countries, and recent studies such as SYNTAX and FREEDOM have confirmed that CABG remains the gold standard treatment in terms of survival and freedom from myocardial infarction and the need for repeat revascularization. Despite strong evidence of an additional survival benefit of BIMA over a SIMA, only around 5%–10% of patients receive BIMA or additional arterial grafts. The saphenous vein graft (SVG) is still the most commonly used conduit because of its abundance, ease of harvest, and “user friendliness.” However, its main disadvantage is its relatively poor long-term patency compared to IMA grafts, with graft failure in as many as 20% of veins within the first year and in as many as 50% at 10 years and with further significant disease in half of the remaining patent grafts (in comparison to perfect patencies of 90%–95% of IMA grafts). SVG failure can result in major adverse clinical sequelae (including myocardial infarction, re-interventions, and death).

Vein graft failure appears to result from both medial and neo-intimal thickening, caused by migration and proliferation of smooth muscle cells and the late appearance of mature lipid-laden atherosclerotic plaques. These changes can compromise flow directly or promote thrombotic occlusion. Diffuse neo-intimal tissue proliferation, the origin of vein graft disease, develops in 75% of grafts within 1 year of implantation. This occurs because the vein graft is exposed to a “new” mechanical environment in the arterial circulation, with relatively high pressures and shear stress. In the first few weeks, shear-induced remodeling leads to luminal enlargement followed by a later phase typified by wall tension-induced remodeling leading to wall thickening (intimal hyperplasia) and stiffening. It is also believed that luminal irregularities of the native vein and its valves are additional triggers for aggressive focal intimal hyperplasia, further increasing the risk of vein graft failure. Neither antiplatelet therapy nor avoidance of surgical preparative injury has been shown conclusively to eliminate medial and neo-intimal thickening in either experimental models or human vein grafts.

**METHODS TO EXTEND SAPPHENOUS VEIN GRAFT PATENCY**

In addition to the clinically well-established ways of improving vein graft patency, such as a low-cholesterol diet and smoking cessation, new in vitro and in vivo experimental attempts have been made to reach the same pivotal goal. The employed experimental strategies include the use of 1) phar-

**Figure 1. Angiography 12 Months Post-CABG.**
The unsupported vein graft show marked non-uniform expansion compared to the supported grafts.
macological agents, such as lidocaine, which was studied *in vitro* using standard tissue bath techniques\(^{45}\); 2) gene targeting, e.g. short interfering RNA (siRNA)-mediated silencing of adhesion molecule\(^{46}\); and two additional methods that are elaborated hereunder: 3) vein harvesting, and 4) external stents.

Various vein harvesting techniques were explored in order to extend the SVG patency, including the “no-touch” saphenous vein harvesting, which refers to the saphenous vein removal with minimal trauma and preservation of the normal architecture\(^{51}\); notably, the “no-touch” technique seems to produce a superior graft with long-term patency comparable to the internal thoracic artery. Moreover, reducing the distending pressure while harvesting the SVG was suggested to increase the SVG patency.\(^{47}\)

**THE VENOUS EXTERNAL SUPPORT TRIAL (VEST)**

Using an external stent to prevent vein graft dilation and mitigate luminal irregularities and wall tension has been hypothesized to reduce intimal hyperplasia and consequently vein graft failure. However, previous attempts at external stenting of vein grafts have failed for a variety of reasons. VGS FLUENT (RAD BioMed, Tel-Aviv, Israel), a novel external support device for SVGs, is a cobalt chrome braid, with a unique combination of different types of wires which provide it with axial plasticity (i.e. can stretch to cover the entire length of a vein graft) and radial elasticity (makes the vein graft crush- and kink-resistant while providing beneficial biomechanical properties by reducing wall tension and the diameter mismatch with the host artery). The stent maintains its position without any additional fixation such as using glue and can be applied in less than a minute without affecting current grafting technique.

A CABG study in sheep demonstrated the FLUENT’s safety along with excellent efficacy in reducing intimal hyperplasia, preventing vein graft dilation/deformation, and eliminating thrombus formation. Following these successful animal studies the FLUENT has been evaluated in a randomized controlled study (Venous External Support Trial) in the UK, which recruited 30 patients in Oxford and Brompton/Harefield who, in addition to an IMA graft to the LAD, required vein grafts to the right coronary artery and the circumflex artery. Patients were randomized for one vein graft to receive the stent and the other to act as a control. Patients are now undergoing 12-month-post-procedure angiography (Figure 1), intravascular ultrasound, and optical coherence tomography (Figure 2) to compare the experimental and control grafts’ patency, lumen uniformity, and plaque volume (intimal and medial hyperplasia). If the VEST successfully reproduces the findings in the sheep model, then the VEST investigators plan to undertake a multicenter trial in Europe, including

![Figure 2. Optical Coherence Tomography Cross-Sections of Vein Grafts 12 Months Post-CABG.](image)

The supported vein graft has a thinner and more uniform intima layer.
several UK centers. If the stent is successful in significantly reducing intimal hyperplasia, it will undoubtedly become a “game changer.”

REFERENCES

1. Loop FD, Lytle BW, Cosgrove DM, 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. Full Text
2. Zeff RH, Kogtahworn C, Iannone LA, et al. Internal mammary artery versus saphenous vein graft to the left anterior descending artery: prospective randomized study with 10-year follow-up. Ann Thorac Surg 1988;45:533–6. Full Text
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;334:216–19. Full Text
4. Pick AW, Orszulak TA, Anderson BJ, Schaff HV. Single versus bilateral internal mammary artery grafts: 10-year outcome analysis. Ann Thorac Surg 1997;64:599–605. Full Text
5. Taggart DP, D’Amico R, Altman DG. Effect of arterial revascularization on survival: a systematic review of studies comparing bilateral and single internal mammary arteries. Lancet 2001;358:870–5. Full Text
6. 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. Full Text
7. Calafiore AM, Di Mauro M, D’Alessandro S, et al. Revascularization of the lateral wall: long-term angiographic and clinical results of radial artery versus right internal thoracic artery grafting. J Thorac Cardiovasc Surg 2002;123:225–31. Full Text
8. Caputo M, Reeves B, Marchetto G, Mahesh B, Lim K, Angelini GD. Radial versus right internal thoracic artery as a second arterial conduit for coronary surgery: early and midterm outcomes. J Thorac Cardiovasc Surg 2003;126:39–47. Full Text
9. Zacharias A, Habib RH, Schwann TA, Riordan CJ, Durham SJ, Shah A. Improved survival with radial artery versus vein conduits in coronary bypass surgery with left internal thoracic artery to left anterior descending artery grafting. Circulation 2004;109:1489–96. Full Text
10. Veeger NJ, Panday GF, Voors AA, Grandjean JG, van der Meer J, Boonstra PW. Excellent long-term clinical outcome after coronary artery bypass surgery using three pedicled arterial grafts in patients with threevessel disease. Ann Thorac Surg 2008;85:508–12. Full Text
11. Rankin JS, Tuttle RH, Wechsler AS, Teichmann TL, Glower DD, Califf RM. Techniques and benefits of multiple internal mammary artery bypass at 20 years of follow-up. Ann Thorac Surg 2007;83:1008–14. Full Text
12. Rizoli G, Shiavon L, Bellini P. Does the use of bilateral internal mammary artery (IMA) grafts provide incremental benefit relative to the use of a single IMA graft? A meta-analysis approach. Eur J Cardiothorac Surg 2002;22:781–6. Full Text
13. 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 2011;124:1321–9. Full Text
14. Locker C, Schaff HV, Dearani JA, et al. Multiple arterial grafts improve late survival of patients undergoing coronary artery bypass graft surgery: analysis of 8622 patients with multivessel disease. Circulation 2012;126:1023–30. Full Text
15. Schmidt SE, Jones JW, Thornby JI, Miller CC 3rd, Beall AC Jr. Improved survival with multiple left-sided bilateral internal thoracic artery grafts. Ann Thorac Surg 1997;64:9–14. Full Text
16. Sabik JF 3rd, Stockins A, Nowicki ER, et al. Does location of the second internal thoracic artery graft influence outcome of coronary artery bypass grafting? Circulation 2008;118(suppl):S210–15. Full Text
17. Kurlansky PA, Traad EA, Dorman MJ, Galbut DL, Zucker M, Ebra G. Location of the second internal mammary artery graft does not influence outcome of coronary artery bypass grafting. Ann Thorac Surg 2011;91:1378–84. Full Text
18. Naunheim KS, Barner HB, Fiore AC. 1990: Results of internal thoracic artery grafting over 15 years: single versus double grafts. 1992 update. Ann Thorac Surg 1992;53:716–18. Full Text
19. Taggart DP, Altman DG, Gray AM, et al.; on behalf of ART Investigators. 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 2010;31:2470–81. Full Text
20. Peterson MD, Borger MA, Rao V, Peniston CM, Feindel CM. Skeletonization of bilateral internal thoracic artery grafts lower the risk of sternal infection in patients with diabetes. J Thorac Cardiovasc Surg 2003;126:1314–19. Full Text
21. Wijns W, Kolh P, Danchin N, et al. Guidelines on myocardial revascularization. The Task Force on
Myocardial Revascularization of the European Society of Cardiology (ESC) and the European Association for Cardio-Thoracic Surgery (EACTS). Eur Heart J 2010;31:2501–55. Full Text

22. Hillis LD, Smith PK, Anderson JL, et al. 2011 ACCF/AHA guidelines for coronary artery bypass surgery: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. Circulation 2011;124:e652–753. Full Text

23. Afi lalo J, Rasti M, Ohayon SM, Shimony A, Eisenberg MJ. Off-pump vs. on-pump coronary artery bypass surgery: an updated meta-analysis and meta-regression of randomized trials. Eur Heart J 2012;33:1257–67. Full Text

24. Khan NE, De Souza A, Mister R, et al. A randomized comparison of off-pump and on-pump multivessel coronary-artery bypass surgery. N Engl J Med 2004;350:21–8. Full Text

25. Shroyer AL, Grover FL, Hattler B, et al.; Veterans Affairs Randomized On/Off Bypass (ROOBY) Study Group. On-pump versus off-pump coronary-artery bypass surgery. N Engl J Med 2009;361:1827–37. Full Text

26. Lamy A, Devereaux PJ, Prabhakaran D, et al. Off-pump or on-pump coronary-artery bypass grafting at 30 days. N Engl J Med 2012;366:1489–97. Full Text

27. Diegeler A, Börgermann J, Kappert U, et al. Off-pump versus on-pump coronary-artery bypass grafting in elderly patients. N Engl J Med 2013;368:1189–98. Full Text

28. Benetti FJ, Ballester C. Use of thoracoscopy and a minimal thoracotomy in mammary coronary bypass to left anterior descending artery without extracorporeal circulation: experience in 2 cases. J Cardiovasc Surg 1995;36:159–61.

29. Jegaden O, Wautot F, Sassard T, et al. Is there an optimal minimally invasive technique for left anterior descending coronary artery bypass? J Cardiothorac Surg 2011;6:37. Full Text

30. Reddy RC. Minimally invasive direct coronary artery bypass: technical considerations. Semin Thorac Cardiovasc Surg 2011;23:216–19. Full Text

31. Mack MJ, Magovern JA, Acuff TA, et al. Results of graft patency by immediate angiography in minimally invasive coronary artery surgery. Ann Thorac Surg 1999;68:383–90. Full Text

32. Calafiore AM, Vitolla G, Mazzei V, et al. The LAST operation: techniques and results before and after the stabilization era. Ann Thorac Surg 1998;66:998–1001. Full Text

33. Doty JR, Fonger JD, Salazar JD, et al. Early experience with minimally invasive direct coronary artery bypass grafting with the internal thoracic artery. J Thorac Cardiovasc Surg 1999;117:873–80. Full Text

34. Repossini A, Moriggia S, Cianci V, et al. The LAST operation is safe and effective: MIDCABG clinical and angiographic evaluation. Ann Thorac Surg 2000;70:74–8. Full Text

35. Holzhey DM, Jacobs S, Mochalski M, et al. Seven year follow-up after minimally invasive direct coronary artery bypass: experience with more than 1300 patients. Ann Thorac Surg 2007;83:108–14. Full Text

36. Katz MR, van Praet F, De Canniere D, et al. Integrated coronary revascularization: percutaneous coronary intervention plus robotic totally endoscopic coronary artery bypass. Circulation 2006;114(Suppl):I473–6. Full Text

37. Kiai B, McClure RS, Stewart P, et al. Simultaneous integrated coronary artery revascularization with long-term angiographic follow-up. J Thorac Cardiovasc Surg 2008;136:702–8. Full Text

38. Repossini A, Tespili M, Saino A, et al. Hybrid revascularization in multivessel coronary artery disease. Eur J Cardiothorac Surg 2013 Feb 26. [Epub ahead of print] Full Text

39. Sellke FW, Chu LM, Cohn WE. Current state of surgical myocardial revascularization. Circ J 2010;74:1031–7. Full Text

40. Sellke FW, Ruel M. Atlas of Cardiac Surgical Techniques. 1st ed. Philadelphia, PA: Elsevier; 2010.

41. Srivastava S, Gadasalli S, Agusala M, et al. Use of bilateral internal thoracic arteries in CABG through lateral thoracotomy with robotic assistance in 150 patients. Ann Thorac Surg 2006;81:800–6. Full Text

42. Bonatti J, Schachner T, Bonaros N, et al. Robotic totally endoscopic double-vessel bypass grafting: a further step toward closed-chest surgical treatment of multivessel coronary artery disease. Heart Surg Forum 2007;10:E239–42. Full Text

43. de Canniere D, Wimmer-Greinecker G, Cichon R, et al. Feasibility, safety, and efficacy of totally endoscopic coronary artery bypass grafting: multicenter European experience. J Thorac Cardiovasc Surg 2007;134:710–16. Full Text

44. Harskamp RE, Lopes RD, Baisden CE, de Winter RJ, Alexander JH. Saphenous vein graft failure after coronary artery bypass surgery: pathophysiology, management, and future directions. Ann Surg 2013;257:824–33. Full Text
45. Gur O, Ege T, Gurkan S, et al. In vitro effects of lidocaine hydrochloride on coronary artery bypass grafts. J Cardiovasc Surg (Torino) 2012;53:665–9.

46. Walker T, Müller I, Raabe C, et al. Effective silencing of adhesion molecules on venous endothelial cells for protection of venous bypass grafts. Eur J Cardiothorac Surg 2011;40:1241–7.

47. Ozturk N, Sucu N, Comelekoglu U, Yilmaz BC, Aytacoglu BN, Vezir O. Pressure applied during surgery alters the biomechanical properties of human saphenous vein graft. Heart Vessels 2013;28:237–45. Full Text