Late Results of Conventional Versus All-Arterial Revascularization Based on Internal Thoracic and Radial Artery Grafting

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Background. **Use of one or more arterial grafts to revascularize two-vessel and three-vessel coronary artery disease has been shown to improve coronary artery bypass graft surgery (CABG) survival. Yet, the presumed long-term survival benefits of all-arterial CABG have not been quantified.**

Methods. **We compared propensity-adjusted 12-year survival in two contemporaneous multivessel primary CABG cohorts with all patients receiving 2 or more grafts: (1) all-arterial cohort (n = 612; 297 three-vessel disease [49%]); and (2) single internal thoracic artery (ITA) plus saphenous vein (SV) cohort (n = 4,131; 3,187 three-vessel disease [77%]).**

Results. **Early (30-day) deaths were similar for the all-arterial and ITA/SV cohorts (8 [1.30%] versus 69 [1.67%]) whereas late mortality was substantially greater for the ITA/SV cohort (85 [13.9%] versus 1,216 [29.4%]; $p < 0.0001$). The risk-adjusted 12-year survival was significantly better for all-arterial (with a risk ratio [RR] = 0.60; 95% confidence interval [CI]: 0.48 to 0.75; $p < 0.001$), but this benefit was true only for three-vessel disease (RR = 0.58; 95% CI: 0.43 to 0.78; $p < 0.001$) and not for two-vessel disease (RR = 0.97; 95% CI: 0.66 to 1.43; $p = 0.89$). The all-arterial survival benefit was also true for varying risk subcohorts: no diabetes mellitus (RR = 0.50; 95% CI: 0.37 to 0.69), diabetes mellitus (RR = 0.77; 95% CI: 0.56 to 1.07), ejection fraction 40% or greater (RR = 0.60; 95% CI: 0.45 to 0.78), and ejection fraction less than 40% (RR = 0.62; 95% CI: 0.40 to 0.98). Lastly, the multivariate analysis indicated a strong long-term effect of completeness of revascularization, particularly for all-arterial patients, so that compared with patients with two grafts, survival was significantly better when three grafts (RR = 0.54; 95% CI: 0.33 to 0.87) or four grafts (RR = 0.40; 95% CI: 0.21 to 0.76) were completed.**

Conclusions. **All-arterial revascularization is associated with significantly better 12-year survival compared with the standard single ITA with saphenous vein CABG operation, in particular for triple-vessel disease patients. The completeness of revascularization of the underlying coronary disease is critical for maximizing the long-term benefits of arterial-only grafting.**

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The left internal thoracic artery (LITA) to left anterior descending artery (LAD) graft has become the standard of care in coronary artery bypass graft surgery (CABG) after the long-term survival benefit demonstrated in the mid 1980s [1, 2]. This benefit is believed to be a result of the superior patency of LITA grafts compared with saphenous vein (SV) [1–4]. Consequently, surgeons have extrapolated their LITA results to other arterial conduits and are currently using the right internal thoracic artery (RITA) [5–10], radial artery (RA) [9–13], or gastroepiploic artery conduits with increasing frequency [14].

Over the past decade, several studies have reported an incremental survival benefit by increasing the number of arterial grafts [5, 6, 8, 11], and this has increased interest in avoiding vein grafts altogether in favor of all-arterial CABG for multivessel coronary disease. Such all-arterial revascularization is usually accomplished through varying combinations of multiple arterial conduits and grafting methods (eg, T or Y grafts) [15–17]. Most reports thus far have focused on perioperative results demonstrating that all-arterial CABG is a safe option with excellent early outcomes [18–20]. Yet, the corresponding midterm to long-term survival results for all-arterial CABG in two- and three-vessel disease patients is presently very limited [21, 22]—especially compared with the current standard ITA with vein operation [22].

In this investigation, we analyzed a large multivessel coronary revascularization experience with the primary aim of testing the hypothesis that all-arterial CABG will

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Abbreviations and Acronyms

CABG	= coronary artery bypass graft surgery
CI	= confidence interval
CRI	= completeness of revascularization index
ITA	= internal thoracic artery
LAD	= left anterior descending artery
LITA	= left internal thoracic artery
RA	= radial artery
RITA	= right internal thoracic artery
RR	= risk ratio
SV	= saphenous vein

confer a significant long-term survival benefit compared with the current standard-of-care operation of using a single ITA (usually LITA to LAD) with additional SV grafting. A second aim of this study was to determine if the all-arterial CABG survival benefit applies to specific comorbidity subcohorts of the surgical multivessel coronary artery disease population.

Material and Methods

This investigation is a retrospective analysis of a prospectively collected cardiac surgery database approved by the Institutional Review Board, and informed consent was waived for this study. The database is collected and reported in accordance with The Society of Thoracic Surgeons (STS) national database criteria.

The CABG patients were excluded if they had single-vessel disease only, in case of a single completed graft; if they underwent any concomitant acquired or congenital cardiac or aortic surgery; or if they had emergency salvage, in case of prior sternotomy or in case of preoperative renal failure. The all-arterial study population was derived from the 1992 to 2006 primary isolated two-vessel and three-vessel disease CABG patients revascularized with two or more arterial conduits. This grouping was based on actual constructed grafts, even if a vein graft was originally planned. A corresponding multigraft (two or more), primary and isolated CABG comparison cohort was derived from the contemporaneous single ITA with additional SV multivessel disease CABG population. Patients were excluded from the ITA/SV cohort if they received other arterial grafts. Cardiopulmonary bypass was used in a large majority of patients, with only 148 off-pump cases (3.1%) among the 4,773 overall patients, including 97 of 4,131 ITA/SV patients (2.3%) and 51 of 612 all-arterial patients (8.3%).

Coronary Grafts

The surgical approach and RA harvesting were previously described [11, 13]. Aortocoronary grafting was the method of choice (more than 95%) unless aorta quality was suboptimal or there were other considerations. All ITA/SV patients received a single ITA graft (usually a LITA to LAD unless no LAD disease) with one or more additional vein grafts. All-arterial revascularization (two or more grafts) was done using a combination of ITA and RA (556 of 612; 90.8%), ITA-only grafting (51 of 612; 8.3%), or RA-only grafting (0.8%; Table 1, and Appendix Table 1*). Bilateral dissections of RA (46%) and ITA (19%) were frequent, and they were commonly used as sequential grafts (178 of 612; 29.1%; Table 1).

*See note at end of article.

Table 1. Grafting Data for All-Arterial Multivessel CABG Patients and the Two-Vessel and Three-Vessel Subgroups[a]

Variable	All Patients Mean ± SD or %	Two-Vessel Disease Mean ± SD or %	Three-Vessel Disease Mean ± SD or %
No. of patients	612	315	297
No. of grafts (total)	2.62 ± 0.77	2.24 ± 0.51	3.02 ± 0.81
ITA (total)	1.20 ± 0.49	1.12 ± 0.39	1.30 ± 0.56
RA (total)	1.42 ± 0.81	1.13 ± 0.59	1.72 ± 0.89
2 grafts	53.8%	78.7	27.3%
3 grafts	32.5%	18.4	47.5%
>3 grafts	13.7%	2.9%	25.3%
ITA used	99.2%	98.4%	100.0%
Single ITA	86.6%	91.7	81.1%
Bilateral ITA	12.6%	6.7	18.9%
ITA only	8.3%	10.1	7.1%
RA used	91.7%	90.5%	92.9%
Single RA	65.4%	82.9%	46.8%
Bilateral RA	26.3%	7.6%	46.1%
RA only	0.8%	1.6%	0%
Sequential grafting	29.1%	19.7%	39.1%
Sequential ITA	8.3%	6.7%	10.1%
Sequential RA	21.7%	13.7%	30.3%

[a] See expanded Appendix Table 1.*

CABG = coronary artery bypass graft surgery; ITA = internal thoracic antery; RA = radial artery.

Table 2. Comparison of Selected Internal Thoracic Artery and Saphenous Vein (ITA/Vein) and All-Arterial Demographic, Preoperative, and Operative Data Shown for Their Respective Two-Vessel and Three-Vessel Disease Subcohorts[a]

	ITA/Vein		All-Arterial	
Variables	Two-Vessel Disease Mean ± SD or %	Three-Vessel Disease Mean ± SD or %	Two-Vessel Disease Mean ± SD or %	Three-Vessel Disease Mean ± SD or %
No. of patients	944	3187	315	297
Demographics				
Male	62.2%	68.8%	67.0%	76.1%
Age (years)	63 ± 11	66 ± 10	59 ± 10	61 ± 11
Body surface area (m^2)	1.99 ± 0.25	2.00 ± 0.23	2.08 ± 0.25	2.11 ± 0.26
Risk factors				
Diabetes mellitus	28.0%	35.8%	28.9%	34.0%
Insulin	8.5%	12.9%	8.9%	10.4%
Peripheral vascular disease	11.7%	14.3%	10.2%	19.9%
Cerebrovascular disease	19.3%	21.0%	14.0%	22.9%
Chronic lung disease	17.7%	19.6%	14.6%	18.2%
Myocardial infarction	53.9%	59.9%	44.8%	53.9%
Congestive heart failure	7.5%	10.9%	7.3%	8.4%
Three-vessel disease	0.0%	100.0%	0.0%	100.0%
Previous PCI	21.3%	16.2%	25.4%	17.2%
Ejection fraction (%)[b]	52 ± 11	49 ± 12	52 ± 9	49 ± 10
Operative data				
Emergency	7.9%	6.3%	5.1%	3.4%
Off-pump	5.7%	1.3%	13.0%	3.4%
Complete revascularization index (CRI)				
Index (CRI)				
Incomplete (CRI < 0)	0%	7.8%	0%	27.3%
Complete (CRI = 0)	51%	47.0%	78.7%	47.5%
Complete-plus (CR > 0)	49%	45.2%	22.3%	25.3%
Cross-clamp time (min)	37 ± 16	51 ± 18	34 ± 20	50 ± 22
All-arterial propensity score	0.203 ± 0.170	0.075 ± 0.082	0.392 ± 0.198	0.196 ± 0.157
Death	22.2%	33.6%	13.7%	16.8%
Follow-up (days)	3,011 ± 1,593	2,742 ± 1,587	2,539 ± 1,153	2,572 ± 1,148

[a] See expanded Appendix Table 2.* [b] Ejection fraction was not available in 383 patients, and was imputed using the mean value of 50% based on 4,360 patients.

PCI = percutaneous coronary intervention.

Follow-Up

Long-term all-cause mortality data were secured from our service patient follow-up and verified from individual patient queries of the United States Social Security Death Index database in December 2007 (available at: http://ssdi.genealogy.rootsweb.com). Database records were updated for missing death information when necessary. Allowing for a 3-month lag in the Social Security Death Index database, this corresponds to a minimum of 9 months (December 2006 patients) and a maximum of 189 months (January 1992 patients) of follow-up.

All-Arterial CABG Propensity Score Model

The all-arterial and ITA/SV cohorts exhibited significant demographic and risk factor differences (Table 2, and Appendix Table 2*). Such differences confound outcome comparisons in observational treatment groups [23, 24]. To minimize such confounding, we used propensity score adjustment where all-arterial grafting was considered as treatment [24]. Briefly, the probability that a patient received only arterial grafts was defined by a propensity score derived from a nonparsimonious logistic multivariate model applied to all patients. A total of 47 preoperative risk factors, demographics, and operative variables were entered into the model irrespective of their significance (Appendix Table 2*). Coronary artery disease and number of grafts were incorporated into the model through a completeness of revascularization index (CRI) defined as the difference between the number of grafts and vessel disease. Accordingly, patients were grouped as incomplete (CRI < 0), complete (CRI = 0), or complete-plus (CRI > 0). Time of surgery was also entered as a continuous month of series variable (January 1992 = 1, up to December 2006 = 180) to account for the varying frequency of all-arterial CABG over time. Highly redundant variables were avoided. Expectedly, the resulting propensity scores were distinctly different (mean ± SD: 0.296 ± 0.204 all-arterial versus 0.104 ±

*See note at end of article.

0.121 ITA/SV; $p = 0.0000$). The propensity model C-statistic (area under the receiver operating characteristic curve) was 0.823, indicating excellent discrimination.

Data Analysis and Statistical Methods

Continuous data were expressed as mean ± SD. When applicable, univariate comparisons were done with the χ^2 or Fisher's exact test for categorical variables and the unpaired *t* test for continuous variables. Because only 12 of 612 all-arterial multivessel CABG patients underwent CABG during 1992 through 1994 (all are currently alive), the survival analysis follow-up was truncated at 12 years so that the 77 deaths occurring after the 12th postoperative year for the ITA/SV cohort do not bias the analysis in favor of all-arterial CABG. Kaplan-Meier survival plots were derived and compared by the log-rank (Mantel-Cox) test. Risk-adjusted late survival comparisons were done using bivariate proportional hazard Cox regression analysis with the continuous logit propensity score and the grafting method (all-arterial versus ITA/SV) as the two covariates. Early deaths occurring within 30 days of CABG were excluded from this analysis to avoid violation of the proportional hazard assumption in the Cox regression model. Midterm (6-year) and long-term (12-year) survival data were also compared using standard Kaplan-Meier analysis based on propensity score quintile groups. Statistical analysis was conducted with SPSS version 15.0 software (SPSS, Chicago, IL). A *p* value less than 0.05 indicated significance.

Results

The overall study population consisted of 4,743 multivessel disease, multigraft CABG patients (32% female; median age, 65 years; range, 31 to 91) grouped as 612 all-arterial patients (13%) and 4,131 ITA/SV patients (87%). The all-arterial patients were evenly grouped into subcohorts of 315 two-vessel disease patients (51%) and 297 three-vessel disease patients (49%), whereas the ITA/SV cohort was predominantly three-vessel disease patients (n = 3,187; 77%). All-arterial grafting was systematically lower among older patients: less than 60 years, 303 of 1,474 (20.6%); 60 to 69 years, 190 of 1,602 (11.9%); and 70 years or more, 119 of 1,667 (7.1%); it was only slightly less among women (175 of 1,527 [11.5%]) compared with men (437 of 3,216 [13.6%]). Selected demographic, risk factors, and operative variables for the two cohorts are compared in Table 2 (see expanded Appendix Table 2*).

The number of completed grafts differed substantially for the all-arterial versus ITA/SV groups, with an average of 2.62 ± 0.77 versus 3.26 ± 0.83 total grafts, respectively ($p <$ 0.0001). The lower number of grafts in all-arterial patients was true in case of both two-vessel disease (2.24 ± 0.51 versus 2.58 ± 0.67; $p < 0.0001$) and three-vessel disease (3.02 ± 0.81 versus 3.46 ± 0.77; $p < 0.001$). Incomplete revascularization (Table 2) was more frequent in the all-arterial three-vessel disease subcohort compared with the corresponding ITA/SV group (incomplete, 27.3% versus 7.8%; $p < 0.001$). Note that the greater incidence of incomplete revascularization in the all-arterial three-vessel disease group is a result of two factors: (1) over the second half of the study, a majority of patients routinely receive two arterial grafts (1 ITA, 1 RA); and (2) hence, those with a planned third graft (venous or arterial) that could not be constructed were, by design, considered as incomplete all-arterial patients.

A total of 1,373 known deaths (28.9%) occurred in the 4,743 overall series, classified into 93 all-arterial deaths (15.2%) and 1280 ITA/SV deaths (31.0%). Early (30-day) mortality was similar for the all-arterial group (1.30%; 8 deaths) and the ITA/SV group (1.67%; 69 deaths). There were no deaths among the 12 all-arterial patients with follow-up of more than 12 years. In contrast, there were 77 known deaths among the 843 ITA/SV patients with more than 12 years of follow-up. Thus, heretofore, all survival analysis will be restricted to 12-year outcomes.

Unadjusted 12-year survival was substantially better for all-arterial patients ($p < 0.0001$; unadjusted risk ratio [RR] = 0.55; 95% confidence interval [CI]: 0.44 to 0.68). That, however, was less pronounced in two-vessel disease patients ($p = 0.12$; RR = 0.77; 95% CI: 0.55 to 1.08) compared with three-vessel disease patients ($p < 0.0001$; RR = 0.52; 95% CI: 0.38 to 0.71; Fig 1).

Results of the risk-adjusted all-arterial versus ITA/SV late survival comparisons are shown in Figure 2. Compared with ITA/SV survival, late CABG survival was significantly better for all-arterial multivessel CABG ($p < 0.001$; RR = 0.60; 95% CI: 0.48 to 0.95) indicating a 67% reduction in mortality for the postoperative period between 30 days and 12 years. However, separate analysis of the two-vessel disease and three-vessel disease subcohorts showed that this propensity-adjusted survival difference was entirely due to the all-arterial survival benefit in case of three-vessel disease ($p = 0.000$; RR = 0.58; 95% CI: 0.43 to 0.78), whereas in the case of two-vessel disease, survival was essentially identical ($p = 0.887$; RR = 0.97; 95% CI: 0.66 to 1.43).

A parallel analysis of Kaplan-Meier survival (includes all deaths within 12 years) based on propensity score quintile groups was consistent with the above propensity-adjusted analysis. The results of the propensity-quintile–based 6-year and 12-year survival are shown in Figure 3 for all multivessel patients as well as for the two-vessel disease and three-vessel disease subgroups. This analysis showed similar findings of minimal benefit in the case of two-vessel disease patients versus a more substantial and significant effect for three-vessel disease patients.

The derived risk adjusted all-arterial survival benefit was preserved, albeit to different extents, when the propensity adjustment was repeated for the subcohort without diabetes mellitus (RR = 0.50; 95% CI: 0.37 to 0.69; $p = 0.000$) versus the subcohort with diabetes mellitus (RR = 0.77; 95% CI: 0.56 to 1.07; $p = 0.116$), and for the preserved left ventricular function subcohort (ejection fraction > 40%: RR = 0.60; 95% CI: 0.45 to 0.78; $p = 0.000$) and diminished left ventricular function subcohort (ejection fraction ≥40%: RR = 0.62; 95% CI: 0.40 to 0.98; $p =$ 0.039) (see Appendix Table 3*).

Completeness of revascularization, or CRI, was another important determinant of risk-adjusted survival for the three-vessel disease CABG patients overall, and was

*See note at end of article.

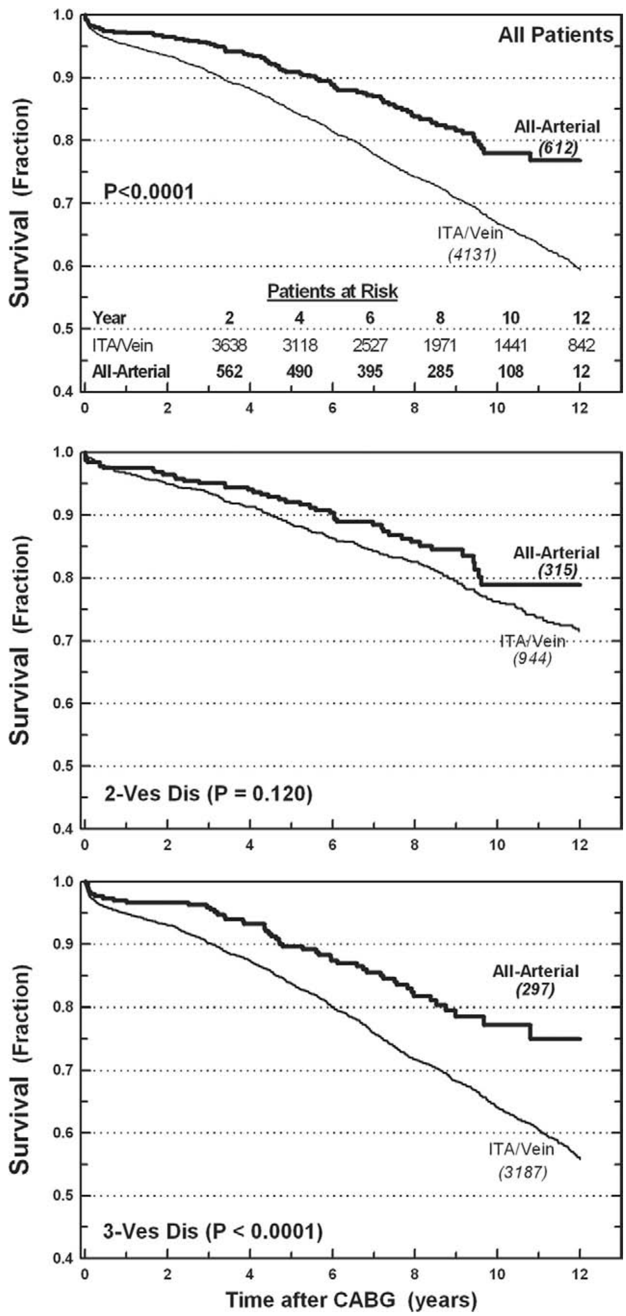


Fig 1. Unadjusted Kaplan-Meier survival: all-arterial versus internal thoracic artery/saphenous vein (ITA/Vein) 12-year coronary artery bypass graft surgery survival. (Top) All multivessel patients. (Middle) Two-vessel disease (2-Ves Dis). (Bottom) Three-vessel disease (3-Ves Dis). All p values by log-rank (Mantel-Cox) test.

more pronounced for the all-arterial cohort compared with ITA/SV patient cohort (Fig 4). Here, compared with patients with only two completed grafts, survival was significantly better for patients with three grafts (RR = 0.54; 95% CI: 0.33 to 0.87) or four or more grafts (RR = 0.40; 95% CI: 0.21 to 0.76). Alternatively, there was no significant effect on survival for all-arterial or ITA/SV two-vessel disease patients when two grafts (complete) versus three or more grafts (complete-plus) were used.

Other predictors of increased late mortality for this patient series as determined by multivariate Cox regression (with the logit propensity score forced as a continuous covariate) included older age, diabetes mellitus, hypertension, peripheral vascular disease, chronic lung disease, congestive heart failure, and decreased left ventricular ejection fraction. Additionally, for the three-vessel disease cohorts only, late mortality was also predicted by history of

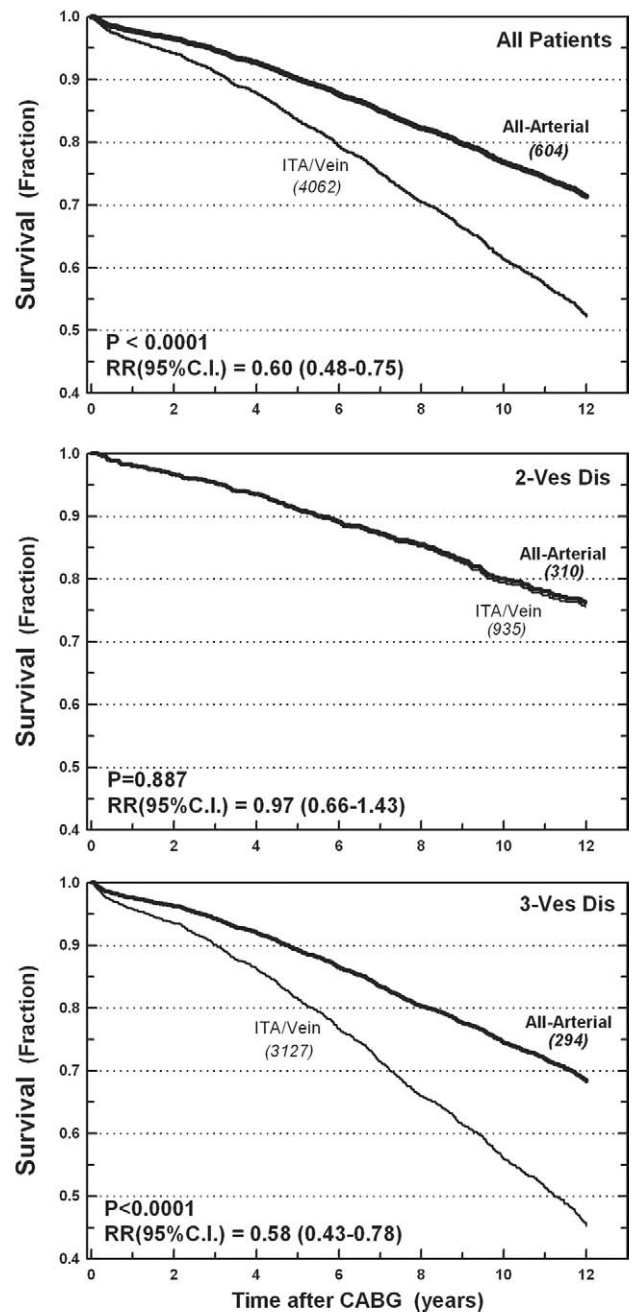
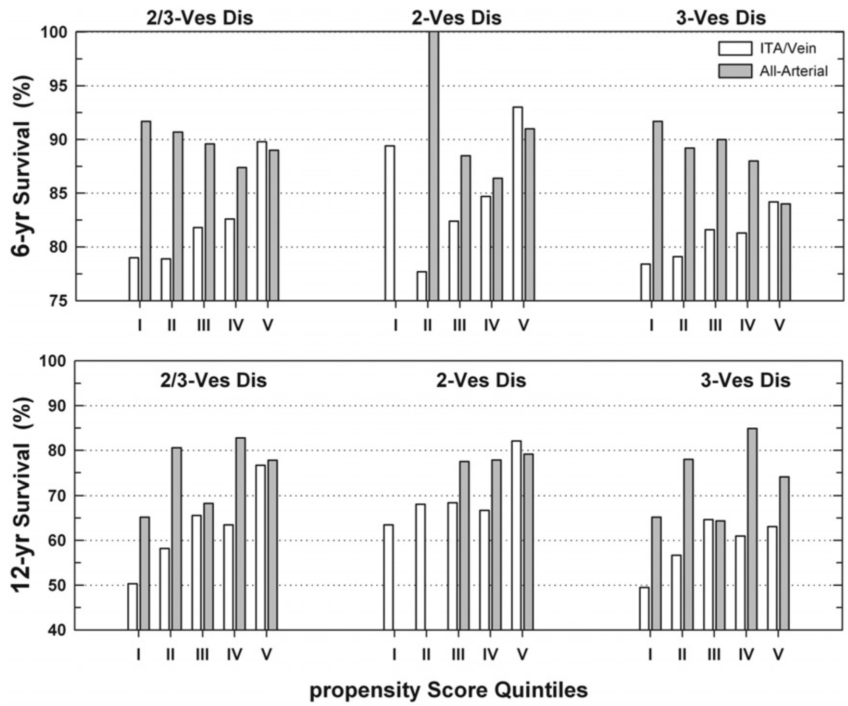


Fig 2. Propensity (logit) adjusted survival: all-arterial versus internal thoracic artery/saphenous vein (ITA/Vein) late coronary artery bypass graft surgery survival for all multivessel patients who survived beyond postoperative day 30. (Top) All multivessel patients. (Middle) Two-vessel disease (2-Ves Dis). (Bottom) Three-vessel disease (3-Ves Dis). (CI = confidence interval; RR = risk ratio.)



	2/3 - Ves Dis		2 - Ves Dis		3 - Ves Dis	
Quintile	ITA/Vein	All-Arterial	ITA/Vein	All-Arterial	ITA/Vein	All-Arterial
Group	N	N	N	N	N	N
I	939	12	48	0	891	12
II	926	22	106	3	820	19
III	867	81	164	18	703	63
IV	808	140	286	40	522	100
V	591	357	340	254	251	103
Total	4131	612	944	315	3187	297

Fig 3. Propensity quintile analysis (Kaplan-Meier survival). Summary of 6-year (top) and 12-year (bottom) survival results for all-arterial patients (shaded bars) and for internal thoracic artery/saphenous vein (ITA/Vein) patients (open bars) based on propensity score quintiles: (left) all patients, (middle), two-vessel disease (2-Ves Dis), and (right) three-vessel disease (3-Ves Dis). Table provides the number of all-arterial versus ITA/Vein patients for each quintile.

myocardial infarction, cerebrovascular disease, and larger body surface area.

Comment

Loop and coworkers [1] convincingly demonstrated more than 2 decades ago that patients receiving the LITA to LAD graft have superior late survival compared with patients undergoing vein-only CABG. They and others linked this result to evidence of superior late LITA patency compared with vein [1–3], which then became the foundation for expanding arterial conduit use to the RITA, RA, and gastroepiploic artery as a way to maximize arterial revascularization.

The practice of using multiple arterial conduits for CABG is supported by reports showing their early operative morbidity and mortality results to be equivalent or

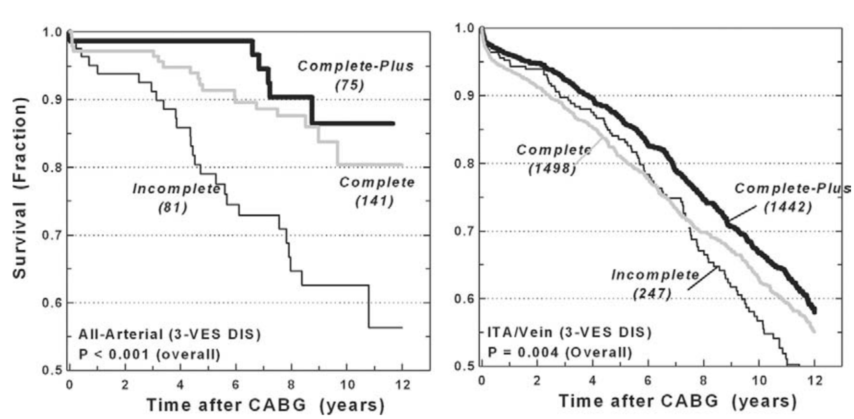


Fig 4. Effects of completeness of revascularization on 12-year Kaplan-Meier survival in triple-vessel disease (3-Ves Dis) patients. (Left) All-arterial patients. (Right) Internal thoracic artery/saphenous vein (ITA/Vein) patients. Incomplete = completeness of revascularization index (CRI) less than 1, or 2 grafts; complete CRI equal to 1, or 3 grafts; complete plus = CRI greater than 1, or 4 or more grafts. All p values by log-rank (Mantel-Cox) test. (CABG = coronary artery bypass graft surgery.)

better than for CABG with a single arterial graft [5–11]. Also, several authors have shown that bypass grafts constructed using RITA and RA exhibit superior patency compared with those constructed with vein [4, 11], and some have reported significantly better longer term outcomes when two rather than one arterial conduits are used for CABG [5, 7, 8, 11]. Lytle and coworkers [7] and Rankin and colleagues [8] analyzed large retrospective patient series and found a late survival benefit is achieved when two ITA grafts are used rather than one. More recently, comparing propensity-matched patient cohorts, we demonstrated that a significant survival benefit is achieved when RA is used as a second arterial graft versus LITA-LAD with additional vein grafts [11]. Guru and associates [12] reviewed the Ontario, Canada, CABG experience and showed that the use of multiple arterial grafts is associated with better survival and less morbidity. Such accumulating evidence favoring the use of a second arterial graft has increased interest in all-arterial revascularization as a presumed optimal form of CABG.

The objective evidence that all-arterial CABG will result in better long-term outcomes compared with the conventional single ITA plus vein operation is very limited. In a series of small randomized trials, Muneretto and coworkers [19, 20] reported similar perioperative morbidity and mortality for (1) all-arterial CABG—done through composite ITA and RA grafting—and (2) single ITA/SV CABG. However, they found all-arterial CABG to be associated with fewer midterm (less than 2 years) adverse outcomes defined as late death, nonfatal myocardial infarction, angina recurrence, graft occlusion, or percutaneous intervention. To our knowledge, only Légaré and colleagues [22] have reported survival data beyond 2 years comparing all-arterial revascularization achieved through ITA and RA grafting to the conventional single ITA with vein CABG. They, however, report statistically similar risk-adjusted 7-year all-cause mortality and composite mortality/cardiac readmission for the two grafting approaches [22].

Our long-term multivessel CABG results contrast sharply with the findings reported by Légaré and collagues [22]. We found that all-arterial CABG is associated with a significantly better 12-year all cause mortality, primarily owing to a large survival benefit observed among three-vessel coronary disease patients. Importantly, our analysis indicated that this long-term survival benefit is substantially dependent on the number of completed grafts—or completeness of revascularization (Fig 4). The latter underscores the need to address all (or as many as possible) of the coronary lesions during revascularization to maximize the achievable survival benefit of all-arterial CABG. Also noteworthy was that the observed all-arterial survival benefit versus single ITA with vein becomes evident as early as 2 to 3 years after CABG, and that is substantially earlier than the delayed survival benefit (more than 10 years) reported with bilateral ITA versus single ITA grafting [7, 8]. Although it is possible that this difference reflects a benefit of avoiding vein grafting altogether in all-arterial patients, this study is not designed to address this question.

An important characteristic of our all-arterial series is the predominant reliance on RA grafts (92% received RA grafts; Table 1), including the frequent use of both RA conduits and sequential RA grafts. Also, except for the LITA pedicle graft, a very large majority (more than 95%) of all other arterial grafts were aortocoronary grafts. We contend that this RA-heavy approach for secondary arterial conduits is justified by several factors. First, compared with RITA or gastroepiploic artery, RA conduit harvesting is less technically demanding and can be done while the LITA is being dissected, reducing time in the operating room and under anesthesia. Second, RA use is associated with substantially less harvest site morbidity compared with other arterial or SV conduits [25]. The presence of certain risk factors—such as diabetes, advanced age, significant obesity, or chronic lung disease—have historically limited use of bilateral ITA grafts [7]. Unfortunately, these patients represent an increasingly larger fraction of the surgical coronary revascularization population, which partly explains why only 4% to 5% of the population undergoing CABG in the United States received bilateral ITA grafts in 2006 and 2007, according to the STS national database. At our institution, nearly 60% of CABG patients received one or more RA grafts compared with fewer than 5% receiving RITA.

Long-term survival after coronary revascularization is presumed to be in direct correlation with the long-term patency of the constructed grafts. Consequently, the superior survival we observe among all-arterial patients compared with ITA/SV patients may be a reflection of increased vein graft failure. Some have suggested that using RA grafting in attempts to achieve total arterial revascularization may underserve patients [26]. That is contradicted, however, by several prospective and retrospective reports showing superior RA patency compared with vein [11, 27, 28]. The vasoactive response of arterial grafts to different stimuli has been the focus of extensive investigation, since it has been implicated as one of the most important causes of early graft failure [29, 30]. The angiographic vasospastic abnormalities observed in RA and other arterial grafts or "string sign" are predominantly seen in grafts placed to subcritically diseased coronary targets where a native vessel competitive flow is present [27]. This flow-dependent phenomenon is well illustrated and reported in angiographic studies [29, 30].

Limitations of our study include its retrospective and observational nature. Ideally, the question of whether all-arterial CABG will improve long-term outcomes is best addressed in randomized, prospective, and multicenter trials. Yet, the prospect of completing such a large long-term study is both impractical and prohibitively expensive. Second, the possibility of residual confounding factors is possible. However, we believe that the comprehensiveness of the propensity model used in the risk adjustment and the multivariate modeling mitigate this concern. Third, the cause of death among our patient population is unknown, and consequently, the death rate may be independent of cardiac factors. We contend that the likelihood of noncardiac deaths explaining the risk-adjusted differences in late survival is unlikely, especially after age adjustment. To minimize this concern, we excluded from this analysis all patients diagnosed with preoperative renal failure, given their propensity for late noncardiac death. This omission of preoperative renal failure patients also helped avoid potential residual confounding effects, given their greater prevalence among ITA/SV patients. Lastly, our analysis would have been enhanced substantially if long-term graft patency comparisons in these patients were available to explain the differences in survival data.

In conclusion, when compared with patients undergoing single ITA and SV CABG, all-arterial revascularization is associated with significantly better 12-year survival, in particular for triple-vessel disease patients. We present evidence that completeness of revascularization of the underlying coronary vessel disease is critical for maximizing the achievable long-term benefits of total arterial grafting.

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Appendix Table 1. Grafting Details For the Overall All-Arterial Multivessel CABG Cohorts and Subdivided to Its 2-Vessel (2-Ves Dis) and 3-Vessel (3-Ves Dis) Sub-Groups

Variable	All Pts N	(N = 612) Mean ± SD (%)	2-Ves Dis N	(N = 315) Mean ± SD (%)	3-Ves Dis N	(N = 297) Mean ± SD (%)
No. of grafts (Total)	1604	2.62 ± 0.77	707	2.24 ± 0.51	897	3.02 ± 0.81
# ITA (Total)	737	1.20 ± 0.49	352	1.12 ± 0.39	385	1.30 ± 0.56
# Radial (Total)	867	1.42 ± 0.81	355	1.13 ± 0.59	512	1.72 ± 0.89
2-grafts	329	53.8%	248	78.7	81*	27.3%
3-grafts	199	32.5%	58	18.4	141	47.5%
>3 grafts	84	13.7%	9	2.9%	75	25.3%
ITA Used	607	99.2%	310	98.4%	297	100.0%
Single ITA	530	86.6%	289	91.7	241	81.1%
Bilateral ITA	77	12.6%	21	6.7	56	18.9%
ITA Only	51	8.3%	30	10.1	21	7.1%
Radial Used	561	91.7%	285	90.5%	276	92.9%
Single Radial	400	65.4%	261	82.9%	139	46.8%
Bilateral Radial	161	26.3%	24	7.6%	137	46.1%
Radial Only	5	0.8%	5	1.6%	0	0%
Sequential Grafting	178	29.1%	62	19.7%	116	39.1%
Sequential ITA	51	8.3%	21	6.7%	30	10.1%
Sequential Radial	133	21.7%	43	13.7%	90	30.3%

* Incomplete re-vascularization defined as #Grafts < Vessel Disease occurred in 81 of the 612 All-Arterial patients (all were 3-Ves Dis).

Appendix Table 2. Demographics, Risk Factors and Operative Data Shown for the Entire ITA/Vein and All-Arterial Patient Cohorts and For Their Respective 2-Vessel and 3-Vessel Disease Sub-Cohorts

	ITA/Vein			All-Arterial		
Variables	All Pts Mean ± SD/%	2-Ves Dis Mean ± SD/%	3-Ves Dis Mean ± SD/%	All Pts Mean ± SD/%	2-Ves Dis Mean ± SD/%	3-Ves Dis Mean ± SD/%
No. of Patients	4131	944	3187	612	315	297
Demographics						
Male	67.3%	62.2%	68.8%	71.4%	67.0%	76.1%
Age (yrs)	65 ± 10	63 ± 11	66 ± 10	60 ± 11	59 ± 10	61 ± 11
Body Surface Area (m^2)	1.99 ± 0.24	1.99 ± 0.25	2.00 ± 0.23	2.09 ± 0.26	2.08 ± 0.25	2.11 ± 0.26
Risk Factors						
Current Smoker	22.8%	24.2%	22.4%	24.8%	24.4%	25.3%
Diabetes	34.0%	28.0%	35.8%	31.4%	28.9%	34.0%
Insulin	11.9%	8.5%	12.9%	9.6%	8.9%	10.4%
Hyperlipidemia	64.0%	66.4%	63.3%	73.7%	74.0%	73.4%
Hypertension	79.7%	76.9%	80.5%	76.5%	74.3%	78.8%
Peripheral Vascular Disease	13.7%	11.7%	14.3%	14.9%	10.2%	19.9%
Cerebrovascular Disease	20.6%	19.3%	21.0%	18.3%	14.0%	22.9%
Chronic Lung Disease	19.2%	17.7%	19.6%	16.3%	14.6%	18.2%
Myocardial Infarction	58.5%	53.9%	59.9%	49.2%	44.8%	53.9%
Congestive Heart Failure	10.1%	7.5%	10.9%	7.8%	7.3%	8.4%
Unstable Angina	37.4%	37.5%	37.3%	30.1%	30.5%	29.6%
Arrhythmia (Any)	14.4%	14.4%	14.4%	8.7%	8.3%	9.1%
Left Main Disease	20.8%	24.3%	19.7%	23.2%	25.4%	20.9%
Three Vessel Disease	77.1%	0.0%	100.0%	48.5%	0.0%	100.0%
Previous PCI	17.4%	21.3%	16.2%	21.4%	25.4%	17.2%
Angioplasty	9.7%	12.4%	8.9%	9.2%	10.5%	7.7%
Stent	7.6%	8.9%	7.3%	12.3%	14.9%	9.4%

Appendix Table 2. Continued

Variables	ITA/Vein			All-Arterial		
	All Pts Mean ± SD/%	2-Ves Dis Mean ± SD/%	3-Ves Dis Mean ± SD/%	All Pts Mean ± SD/%	2-Ves Dis Mean ± SD/%	3-Ves Dis Mean ± SD/%
Pre-operative IABP	6.9%	6.0%	7.2%	4.9%	4.8%	5.1%
Ejection Fraction (%)[a]	50 ± 12	52 ± 11	49 ± 12	50 ± 10	52 ± 9	49 ± 10
Operative Data						
Emergency	6.7%	7.9%	6.3%	4.2%	5.1%	3.4%
Off-pump	2.3%	5.7%	1.3%	8.3%	13.0%	3.4% ±
No. of Grafts	3.26 ± 0.83	2.58 ± 0.67	3.46 ± 0.77	2.62 ± 0.77	2.24 ± 0.51	3.02 ± 0.81
#Arterial	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	2.62 ± 0.77	2.24 ± 0.51	3.02 ± 0.81
#Vein	2.26 ± 0.83	1.58 ± 0.67	2.46 ± 0.77	—	—	—
Complete Revascularization Index						
Incomplete (CRI < 0)	6.0%	0%	7.8%	13.2%	0%	27.3%
Complete (CRI = 0)	47.9%	51%	47.0%	61.6%	78.7%	47.5%
Complete-plus (CRI > 0)	46.1%	49%	45.2%	23.5%	22.3%	25.3%
CPB Time (min)	80 ± 30	62 ± 26	86 ± 29	67 ± 33	56 ± 32	80 ± 29
Cross-clamp Time (min)	48 ± 18	37 ± 16	51 ± 18	42 ± 22	34 ± 20	50 ± 22
All-Arterial propensity score	0.104 ± 0.121	0.203 ± 0.170	0.075 ± 0.082	0.296 ± 0.204	0.392 ± 0.198	0.196 ± 0.157
Death	31.0%	22.2%	33.6%	15.2%	13.7%	16.8%
Follow-up (days)	2804 ± 1592	3011 ± 1593	2742 ± 1587	2555 ± 1150	2539 ± 1153	2572 ± 1148

Other variables included in the propensity model besides those in Table A-2 are: Race, Body mass index, Weight, New York Heart Association class, time of myocardial infarction, type of Arrhythmias, and preoperative medications (including aspirin, beta blockers, ACE inhibitors, anticoagulants).

[a] Ejection fraction was not available in 383 patients, and this data was imputed using the mean value of EF = 50% based on the values from 4360 patients.

PCI = percutaneous coronary intervention; IABP = intra-aortic balloon pump; CPB = cardiopulmonary bypass.

Appendix Table 3. All-Arterial Versus Conventional ITA/Vein CABG Late (31 day–12 years) Mortality Risk Ratios: Unadjusted and Adjusted Via the Logit Propensity Score

Patient Cohort	All-Arterial n	ITA/Vein N	All-Arterial vs. ITA/Vein			
			Unadjusted		Logit (propensity)-Adjusted	
			RR (95% C.I.)	*p* Value	RR (95% C.I.)	*p* Value
All Patients	604	4062	0.56 (0.45 – 0.70)	0.000	0.60 (0.48 – 0.75)	0.000
Coronary Vessel Disease						
2-Ves Dis	310	935	0.72 (0.51 – 1.02)	0.065	0.97 (0.66 – 1.43)	0.887
3-Ves Dis	294	3127	0.57 (0.43 – 0.77)	0.000	0.58 (0.43 – 0.77)	0.000
Diabetes (Any)						
Yes	188	1379	0.73 (0.53 – 1.00)	0.047	0.77 (0.56 – 1.07)	0.116
No	416	2683	0.47 (0.34 – 0.64)	0.000	0.50 (0.37 – 0.69)	0.000
Ejection Fraction (EF)[a]						
EF ≤40%	117	934	0.58 (0.37 – 0.91)	0.015	0.62 (0.40 – 0.98)	0.039
EF >40%	456	2783	0.56 (0.43 – 0.73)	0.000	0.60 (0.45 – 0.78)	0.000

[a] Ejection fraction was not available in 383 patients.

RR (95% CI) = risk ratio (95% confidence interval).