  0003-4975/$36.00
https://doi.org/10.1016/j.athoracsur.2024.01.008

Coronary: Research

Multiarterial vs Single-Arterial Coronary Surgery: 10-Year Follow-up of 1 Million Patients

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ABSTRACT

BACKGROUND Although many options exist for multivessel coronary revascularization, controversy persists over whether multiarterial grafting (MAG) confers a survival advantage over single-arterial grafting (SAG) with saphenous vein in coronary artery bypass grafting (CABG). This study sought to compare longitudinal survival between patients undergoing MAG and those undergoing SAG.

METHODS All patients undergoing isolated CABG with ≥2 bypass grafts in The Society of Thoracic Surgeons Adult Cardiac Surgery Database (2008-2019) were linked to the National Death Index. Risk adjustment was performed using inverse probability weighting and multivariable modeling. The primary end point was longitudinal survival. Subpopulation analyses were performed and volume thresholds were analyzed to determine optimal benefit.

RESULTS A total of 1,021,632 patients underwent isolated CABG at 1108 programs (100,419 MAG [9.83%]; 920,943 SAG [90.17%]). Median follow-up was 5.30 years (range, 0-12 years). After risk adjustment, all characteristics were well balanced. At 10 years, MAG was associated with improved unadjusted (hazard ratio, 0.59; 95% CI 0.58-0.61) and adjusted (hazard ratio, 0.86; 95% CI, 0.85-0.88) 10-year survival. Center volume of ≥10 MAG cases/year was associated with benefit. MAG was associated with an overall survival advantage over SAG in all subgroups, including stable coronary disease, acute coronary syndrome, and acute infarction. Survival was equivalent to that with SAG for patients age ≥80 years and those with severe heart failure, renal failure, peripheral vascular disease, or obesity. Only patients with a body mass index ≥40 kg/m^2 had superior survival with SAG.

CONCLUSIONS Multiarterial CABG is associated with superior long-term survival and should be the surgical multivessel revascularization strategy of choice for patients with a body mass index of less than 40 kg/m^2.

(Ann Thorac Surg 2024;117:780-8)

Many medical and interventional options exist for the management of patients with symptomatic multivessel coronary artery disease, including surgical coronary artery bypass grafting

The Supplemental Material can be viewed in the online version of this article [https://doi.org/10.1016/j.athoracsur.2024.01.008] on http://www.annalsthoracicsurgery.org.

Accepted for publication Jan 13, 2024.

Presented at the Sixtieth Annual Meeting of The Society of Thoracic Surgeons, San Antonio, TX, Jan 27-29, 2024.

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Abbreviations and Acronyms

ACSD = Adult Cardiac Surgery Database
CABG = coronary artery bypass grafting
HR = hazard ratio
IPW = inverse probability weighting
ITA = internal thoracic artery
MAG = multiarterial grafting
NDI = National Death Index
SAG = single-arterial grafting
STS = The Society of Thoracic Surgeons
SVG = saphenous vein graft

(CABG). Controversy persists regarding whether multiarterial grafting (MAG) improves long-term survival over CABG with single-arterial grafting (SAG) with saphenous vein conduits, thus limiting wider adoption in the United States. The time and technical requirements of MAG, often with bilateral internal thoracic artery (ITA) or radial artery conduits, are elevated compared with a SAG strategy. Although several single-center reports showed that patients who undergo MAG may experience better survival, more recent reports, including the randomized Arterial Revascularization Trial (ART) of single vs bilateral ITA CABG, did not detect an overall difference.[1-12] However, the secondary analyses of the ART trial did indeed identify a long-term survival benefit of MAG when stratified by as-treated groups and surgeon experience.[13]

The cumulative observation from the recent literature leaves the following knowledge gaps to inform clinical decision making: (1) defining whether the MAG benefit observed in single-center studies translates to a larger national cohort; (2) determining whether there are patients in whom MAG may not derive a benefit over SAG; and (3) defining whether a minimum center volume may exist to derive longitudinal MAG benefit. To address these gaps, The Society of Thoracic Surgeons (STS) Adult Cardiac Surgery Database (ACSD) was linked to the Centers for Disease Control and Prevention National Death Index (NDI) and analyzed. Our primary hypothesis was that MAG improves long-term survival compared with SAG across all subgroups.

PATIENTS AND METHODS

PATIENT DATA. The CABG surgery data were collected at institutions participating in the STS ACSD. The STS ACSD captures in-hospital and 30-day outcomes for 97% of CABG operations performed in the United States.[14] For this study, the STS ACSD was comprehensively linked to the longitudinal vital status data from the NDI. Waiver of informed consent for nonhuman subjects was obtained from the Northwestern University Institutional Review Board (#STU00206997).

The study cohort included isolated CABG operations performed in the United States between January 1, 2008, and March 31, 2019. The primary inclusion criteria were as follows: (1) the patient was a resident of the United States, and the CABG was performed in a center in the United States; (2) data completeness was sufficient for an NDI vital status match; and (3) nonemergency isolated primary CABG was performed for multivessel coronary artery disease in adult patients aged ≥18 years who received ≥2 bypass grafts, including an ITA (Supplemental Figure 1). Longitudinal follow-up through December 31, 2019 was derived from matched records, including linkage of the STS-ACSD and NDI by using matching algorithms on the basis of direct patient identifiers (first, middle, and last names; date of birth; sex; race; Social Security Number when available).[14,15] Matches were further adjudicated on the basis of comparison of key STS-ACSD and death certificate data elements (eg, surgery, discharge and mortality dates, state of residence).

STATISTICAL ANALYSIS. Summary statistics are presented as percentages and as means with SDs in case of categoric or continuous variables, respectively. Differences in baseline characteristics of patients undergoing MAG vs SAG were quantified using standardized differences and were compared using the Pearson χ^2 test for categoric variables and the Wilcoxon rank-sum test for continuous variables. Missingness is very low in STS data, and standard imputation methods were used.[14]

Propensity scores to estimate the probability of MAG or treatment were derived with the use of logistic regression to adjust for between-group differences in baseline characteristics of patients.[16] Stabilized inverse probability weighting (IPW) that was based on the propensity score was implemented to create balance and as the primary tool to adjust for differences between groups.[17]

The primary end point was all-cause mortality. Unadjusted survival curves for the MAG vs SAG groups were estimated using the Kaplan-Meier method. The treatment effect was quantified as a hazard ratio (HR; 95% CIs) estimated from proportional hazard Cox regression with stabilized IPW used for adjustment. If the proportional hazards assumption was not met, the results of a time-segmented Cox regression analysis, with the 12-year overall follow-up divided into early (0-1 year), intermediate (1-5 years), and late (5-12 years) time segments, were presented. The 12-year IPW-based comparisons were repeated within prospectively defined major demographic, patient risk, and operative subgroups to examine the potential variability of the treatment effect in these subcohorts. To examine the treatment effect of the MAG experience, we grouped the 1022 programs that performed multiarterial CABG into 12 program groups on the basis of the calculated annualized multiarterial volume, from ≤5 (lowest) to >100

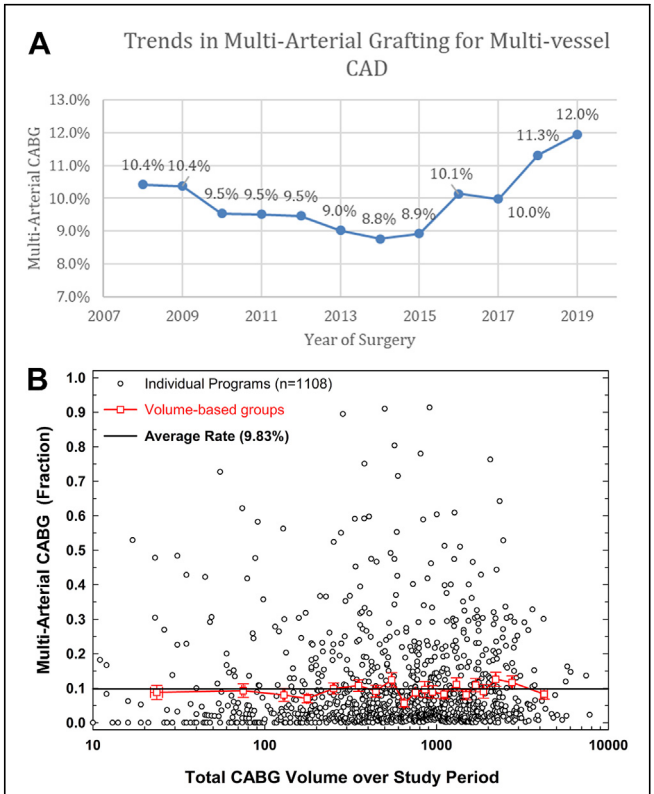


FIGURE 1 (A) The cumulative annual rate of multiarterial coronary artery bypass grafting (CABG) varied between 8.8% and 12.0%, with a notable increasing trend in the last 5 years of the study period. (B) The cumulative annual rate of multiarterial CABG did not vary systematically with programs' overall CABG volumes, with most programs performing multiarterial CABG at a rate lower than 5%. (CAD, coronary artery disease.)

(highest). The IPW-adjusted treatment effect was derived for each group compared with the entire single-arterial CABG group. We performed several sensitivity analyses to test the robustness of the main analysis, as further detailed in the Supplemental Methods section.

RESULTS

A total of 1,772,324 isolated CABG cases from 1252 US programs were available from the STS ACSD, with longitudinal mortality follow-up available from the NDI in 1,293,477 (73%) (Supplemental Table 1). After study exclusions, the final population consisted of 1,021,632 patients from 1108 programs, including 100,419 patients who underwent multiarterial CABG (9.83%) and 920,943 patients who underwent single-arterial CABG (90.17%). MAG was achieved through bilateral ITA (47.0%), 1 ITA and radial artery (45.5%), or 2 ITA and radial artery (7.5%) use. The cumulative annual rate of multiarterial CABG varied between 8.8% and 12.0% over the study period, with an increasing trend in the last 5 years (Figure 1, Supplemental Table 2). The majority of programs, 583 (53.6%), performed MAG at an annualized rate lower than 5%.

PATIENT CHARACTERISTICS. Demographic, risk, and comorbidity factors differed across the 2 study groups (Table). Patients in the MAG group were younger and were more frequently men. Heart failure, diabetes, hypertension, chronic lung disease, cerebrovascular disease, peripheral arterial disease, and reduced renal function were less frequent in the MAG group, and the ejection fraction and estimated glomerular filtration rate were higher. The distribution of 2-vessel, 3-vessel, and left main coronary artery disease was similar between the MAG and SAG groups.

After risk adjustment using IPW or propensity matching, all patient and clinical covariates were well balanced (Table). The balanced distribution of probability of treatment (MAG) or propensity scores among the overall study population overlapped substantially for the MAG vs SAG groups (median, 0.126 [interquartile range, 0.082-0.175] vs median, 0.082 [interquartile range, 0.051-0.126]; $P = .000$) (Supplemental Figure 2). Moreover, the mean total number of grafts was comparable in the SAG (mean ± SD, 3.5 ± 0.9) and MAG (mean ± SD, 3.6 ± 1.0) cohorts, and the incidence of incomplete revascularization was also similar at 6.5% and 6.4%, respectively (Table).

OPERATIVE OR 30-DAY MORTALITY. The unadjusted procedural or 30-day mortality was significantly greater in the overall SAG group vs MAG group (1.68% vs 1.00%; $P < .001$), but this difference in operative mortality was removed in risk-balanced groups after propensity score matching (1.06% vs 1.00%).

LONGITUDINAL OUTCOMES. The overall median follow-up time was 5.30 years (range, 0-12 years), with MAG 5.62 years and SAG 5.27 years. Unadjusted survival was substantially lower for patients undergoing SAG compared with MAG (Figure 2A), with a corresponding unadjusted HR of 0.59 (95% CI, 0.58-0.61). These findings were similar with a landmark analysis evaluating hazard at each period; early (0-1 year; HR, 0.58), intermediate (1-5 year; HR, 0.62), and late (5-12 year; HR, 0.58) follow-up (Figure 2B). After IPW risk adjustment, the association of improved survival with MAG at 12 years remained significant (adjusted HR, 0.86; 95% CI, 0.85-0.88; $P = .0001$), with a similar impact for early (HR, 0.87), intermediate (HR, 0.87), and late (HR, 0.85) follow-up by landmark analysis (Figure 2D). Moreover, the 12-year overall and time-interval survival in propensity-matched analyses were congruent with the results of the IPW-adjusted analysis and comprehensive covariate-adjusted Cox regression using all factors included in the propensity score calculation (Figure 2). Actuarial survival in the matched cohort was higher for patients undergoing

TABLE Patient Characteristics in Single-Arterial (Control) vs Multiarterial (Treatment) Patient Groups Undergoing Coronary Artery Bypass Grafting: All Cases Before and After Matched Subcohorts

	All Cases			Propensity Matched		
Patient Variables	Single-Arterial (N = 920,943)	Multiarterial (N = 100,419)	Std Diff, %	Single-Arterial (N = 100,404)	Multiarterial (N = 100,404)	Std Diff, %
Preoperative data						
Male sex	74.50	84.50	−25.00	84.10	84.50	−1.00
Age, y	65.6 ± 10.1	60.3 ± 10.1	52.50	60.2 ± 10.3	60.3 ± 10.1	−1.0
Body surface area, m^2	2.01 ± 0.24	2.05 ± 0.23	−16.90	2.05 ± 0.23	2.05 ± 0.23	−0.50
Preoperative eGFR, mL/min/1.73 m^2	75 ± 21	81 ± 20	−31.60	81 ± 20	81 ± 20	−0.50
BMI category, kg/m^2						
<21	2.40	1.60	5.80	1.60	1.60	0.40
21-24.99	19.70	18.10	4.00	18.20	18.10	0.20
25-29.99	37.60	39.80	−4.60	39.60	39.80	−0.50
30-34.99	24.50	25.90	−3.30	26.00	25.90	0.30
35-39.99	10.40	9.80	2.00	9.80	9.80	−0.20
≥40	5.40	4.70	3.10	4.70	4.70	−0.10
Diabetes						
Oral	30.50	25.60	11.00	25.10	25.60	−1.10
Insulin	16.10	12.00	11.70	12.00	12.00	−0.20
Chronic lung disease						
None	77.80	83.40	−14.30	83.30	83.40	−0.40
Mild	12.20	10.10	6.50	10.10	10.10	−0.30
Moderate	5.80	4.10	8.00	4.20	4.10	0.40
Severe	4.20	2.30	10.50	2.50	2.30	1.10
Hypertension	88.20	84.00	12.30	84.00	84.00	0.10
Home oxygen use	0.70	0.40	4.00	0.50	0.40	0.70
Cerebrovascular disease	17.40	12.20	14.80	12.20	12.20	0.10
Peripheral vascular disease	13.90	11.00	8.70	11.20	11.00	0.60
Liver disease	1.80	1.60	1.50	1.50	1.60	−0.40
Immunosuppression	2.40	1.80	4.20	1.80	1.80	0.10
Left main coronary artery disease	32.70	29.40	7.00	29.30	29.40	−0.20
3-vessel disease	80.20	81.70	−3.80	81.70	81.70	0.00
Previous myocardial infarction						
<6 h	0.30	0.20	1.40	0.20	0.20	0.60
6-24 h	1.70	1.50	0.90	1.60	1.50	0.20
1-21 d	29.50	27.00	5.50	27.30	27.00	0.70
Heart failure, NYHA functional class						
I-III	12.90	10.20	8.40	10.20	10.20	0.10
IV	3.50	2.10	8.50	2.20	2.10	0.80
Cardiac shock	0.30	0.20	2.50	0.20	0.20	0.20
Ejection fraction, %						
≥55	56.30	60.70	−9.00	59.40	60.70	−2.60
40-54	21.40	21.90	−1.30	23.00	21.90	2.60
30-39	16.50	13.70	7.70	13.80	13.70	0.10
20-29	4.80	3.10	8.80	3.20	3.10	0.50
10-19	1.00	0.60	5.20	0.60	0.60	0.60
Previous PCI, stents	23.60	22.80	1.90	22.80	22.80	0.20
Surgical priority						
Elective	39.80	42.60	−5.70	42.30	42.60	−0.60
Urgent	60.20	57.40	5.70	57.70	57.40	0.60
Operative mortality[a]	15,445 (1.68)	1009 (1.0)	…	1066 (1.06)	1008 (1.0)	…
Operative data						
Time on CPB, min	94 ± 35	102 ± 37	−22.40	94 ± 35	102 ± 37	−21.50
Cross-clamp time, min	68 ± 28	76 ± 30	−27.20	68 ± 28	76 ± 30	−24.90
Incomplete revascularization[b]	64,252 (7)	6388 (6.4)	…	6567 (6.5)	6387 (6.4)	…
Total grafts	3 [3-4]	4 [3-4]	…	3.5 ± 0.9	3.6 ± 1.0	…
Vein	2 [2-3]	1 [0-2]	…	2.4 ± 0.9	1.2 ± 1.0	…
Arterial	1 [1-1]	2 [2-3]	…	1.0 ± 0.2	2.4 ± 0.7	…
IMA	1 [1-1]	2 [1-2]	…	1.0 ± 0.2	1.7 ± 0.7	…

(*Continued*)

TABLE Continued

Patient Variables	All Cases			Propensity Matched		
	Single-Arterial (N = 920,943)	Multiarterial (N = 100,419)	Std Diff, %	Single-Arterial (N = 100,404)	Multiarterial (N = 100,404)	Std Diff, %
Radial	0 [0-0]	1 [0-1]	…	0.0 ± 0.0	0.7 ± 0.8	…
SITA/SVG	920,943 (100)	0 (0.0)	…	100,404 (100)	0 ± 0.0	…
SITA/RA	0 (0.0)	45,662 (45.5)	…	0 (0.0)	45,654 (45.5)	…
BITA/SV	0 (0.0)	47,222 (47.0)	…	0 (0.0)	47,216 (47.0)	…
BITA/RA/SV	0 (0.0)	7535 (7.5)	…	0 (0.0)	7534 (7.5)	…

[a]Operative mortality was defined as in-hospital death during index admission or within 30 days of index surgery after discharge from hospital alive; [b]Incomplete revascularization was defined as cases where the total number of completed grafts was less than the multivessel coronary artery disease type (2 vessel or 3 vessel). Values are %, mean ± SD, n (%), or median [interquartile range{Q1-Q3}]. BITA, bilateral internal thoracic artery; BMI, body mass index; CPB, cardiopulmonary bypass; eGFR, estimated glomerular filtration rate; IMA, internal mammary artery; NYHA, New York Heart Association; PCI, percutaneous coronary intervention; Q, quartile; RA, radial artery; SITA, single internal thoracic artery; Std Diff, standard difference; SV, saphenous vein; SVG, saphenous vein graft.

MAG vs SAG at 1 (97.8% vs 97.5%), 3 (95.2% vs 94.7%), 5 (91.8% vs 90.8%), 7 (86.9% vs 85.2%), 9 (81.2% vs 78.8%), and 11 (75.1% vs 72.1%) years.

MAG was associated with a longitudinal survival benefit across nearly all demographic, comorbidity, coronary artery disease, and surgical subgroups (Figure 3, Supplemental Table 3). The observed difference in the MAG group was systematically greater in younger patients and was larger in men compared with women. Generally, the magnitude of the survival benefit was reduced with increased levels of morbidity, such as more severe chronic lung disease, worse heart failure, and substantial renal dysfunction. Importantly, when severe organ dysfunction was present, specifically New York Heart Association functional class IV, severe lung disease, and chronic kidney disease (glomerular filtration rate <45), the survival between the MAG and SAG groups was similar (Figure 3). However, in the severely obese subgroup of patients with a body mass index (BMI) >40 kg/m^2, SAG was associated with superior survival compared with MAG (adjusted HR, 1.08; 95% CI, 1.01-1.16). The MAG treatment benefit was similar in cases of urgent and elective CABG, whereas it was less pronounced in cases of off-pump compared with on-pump CABG surgery.

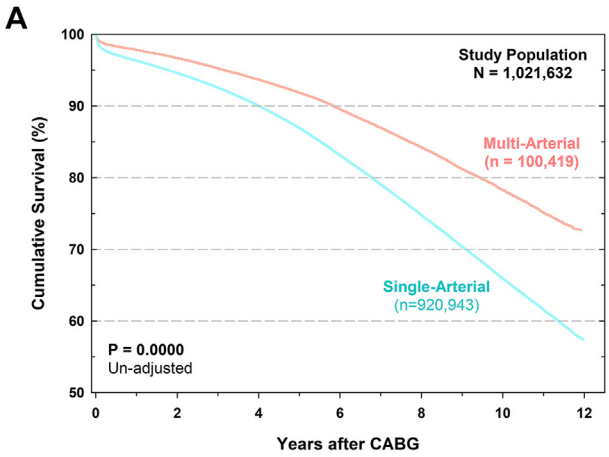
CENTER VOLUME. Center-level outcomes categorized by annualized MAG volumes (lowest [1-5] to highest [>100] cases/year) were compared with the overall SAG group (Figure 4). This analysis demonstrated that MAG revascularization was associated with a survival benefit across all program volume categories (adjusted HRs, 0.75-0.91; all $P < .001$). The exception was in programs performing fewer than 5 multiarterial revascularizations annually (adjusted HR, 1.11; 95% CI, 1.05-1.17; $P = .0005$). MAG was associated with benefit once a center performed 10 cases annually (Figure 4).

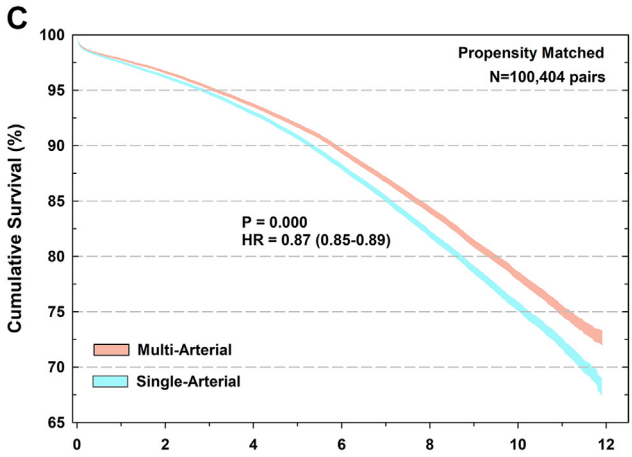
SENSITIVITY ANALYSES. To explore the potential for uncontrolled patient selection bias, we compared survival in the MAG group derived from programs with >10% frequency of MAG (N = 77,484; 317 programs) to survival achieved in the SAG group derived from programs with rare (0% to 4%; <2% overall) use of MAG (N = 453,629 from 544 programs). This analysis resulted in IPW-adjusted treatment effect estimates essentially identical to those in the full analysis (adjusted HR, 0.85; 95% CI, 0.83-0.87) (Supplemental Table 4).

Propensity score and IPW validation was performed. An analysis on the basis of propensity score quintile groupings showed a significantly better IPW survival in all patient quintiles except in patients whose characteristics closely resembled patients who underwent SAG (quintile 1) (IPW-adjusted HR, 0.98; 95% CI, 0.940-1.01), and progressively larger and significantly better survival was associated with MAG in quintiles 2 to 5 (adjusted HR, 0.95, 0.91, 0.78, and 0.75, respectively) (Supplemental Table 5).

COMMENT

This study investigated the survival difference of multiarterial CABG vs single-arterial CABG with saphenous vein for the surgical management of multivessel coronary artery disease by using the STS-ACSD linked to the NDI. Linking these 2 databases permitted a real-world contemporary analysis of long-term survival in more than 1 million patients, representative of >97% of all patients undergoing CABG surgery in the United States. There were several key findings. First, patients undergoing MAG had a significant improvement in long-term survival compared with those who underwent SAG. Second, the superiority of MAG survival was observed in nearly all patients undergoing CABG, except in patients older than 80 years of age and those with comorbidities graded as severe, where MAG and SAG survival was equivalent. Third, the only subgroup where SAG had better survival than MAG was the severely obese cohort (BMI >40 kg/m^2). Fourth, these results were consistent across all centers performing MAG, except in the smallest-volume programs (<5 MAG/year). Finally, because our findings confirm the safety of MAG, thereby

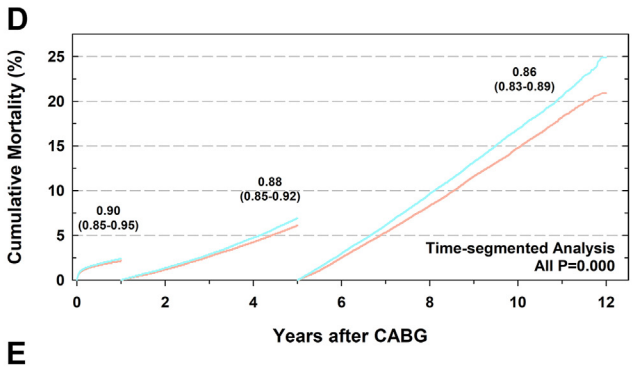




B

Treatment Effect HR (95% C.I.)		Un-adjusted	Stabilized IPW Adjusted	Covariate Adjusted	Propensity Matched
Follow-up	0 - 12 years	0.59 (0.58-0.61)	0.86 (0.85-0.88)	0.85 (0.84-0.87)	0.87 (0.85-0.89)
	Time-Segmented Analysis				
	Early: 0 -1 year	0.58 (0.56-0.61)	0.87 (0.83-0.91)	0.90 (0.86-0.94)	0.90 (0.85-0.95)
	Intermediate: 1-5 years	0.62 (0.60-0.64)	0.87 (0.84-0.90)	0.87 (0.84-0.89)	0.88 (0.85-0.92)
	Late: 5-12 years	0.58 (0.56-0.59)	0.85 (0.83-0.88)	0.83 (0.81-0.85)	0.86 (0.83-0.89)

All Comparisons P<0.001



E

Year	1	3	5	7	9	11
#Events	2,468	4,986	7,834	10,856	13,278	14,570
	2,220	4,442	6,784	9,334	11,432	12,589
#At Risk	95,934	77,063	57,466	39,347	22,841	6,960
	95,532	74,250	55,350	38,907	23,019	7,266
Survival %	97.5	94.7	90.8	85.2	78.8	72.1
	97.8	95.2	91.8	86.9	81.2	75.1

FIGURE 2 (A) Unadjusted survival was worse for single-arterial compared with multiarterial coronary artery bypass grafting (CABG), with a corresponding unadjusted 0- to 12-year hazard ratio (HR) of 0.59 (95% CI, 0.58-0.61). (B) A similar association was observed for early (HR, 0.58), intermediate (HR, 0.62), and late (HR, 0.58) follow-up. After adjustment with inverse probability weighting (IPW), the treatment effect remained significant (P = .0001), but it was lower with the 0- to 12-year adjusted HR of 0.86 (95% CI, 0.85-0.88). The IPW-adjusted treatment effects were similar for the early (HR, 0.87), intermediate (HR, 0.87), and late (HR, 0.85) terms. (C-E) The 12-year survival patterns in propensity-matched and time-segmented early, intermediate, and late cumulative all-cause mortality largely confirmed the results of the IPW-adjusted analysis, as did another sensitivity analysis on the basis of comprehensive covariate-adjusted cox regression using all factors included in the propensity score calculation. (CABG, coronary artery bypass grafting.)

corroborating other experiences in the literature,[18-20] while definitively elucidating MAG survival benefit, it is hoped that this new information may affect the relatively low (12%) adoption of this beneficial therapy currently across the United States.

OVERALL SURVIVAL. The present study clarifies the previous controversy on MAG survival. The current findings are consistent with recent meta-analyses highlighting the survival benefit of multiarterial CABG.[21-24] These data are also in line with the recently published multicenter observational cohort study PRedictIng long term Outcomes afteR Isolated coronary arTery bypass surgerY (PRIORITY), including 10,988 patients who underwent isolated CABG and highlighting improved 10-year survival and freedom from repeat revascularization and myocardial infarction.[25] However, our findings are in contrast to those of the ART trial, which did not demonstrate a benefit of bilateral ITA vs single ITA graft use at 10 years.[1] Although the ART trial has been widely discussed, given the concerns over treatment crossover, radial artery use, and surgeon experience, further analysis did identify a MAG survival benefit (including patients with radial artery grafts) in an as-treated analysis and when stratifying by surgeon

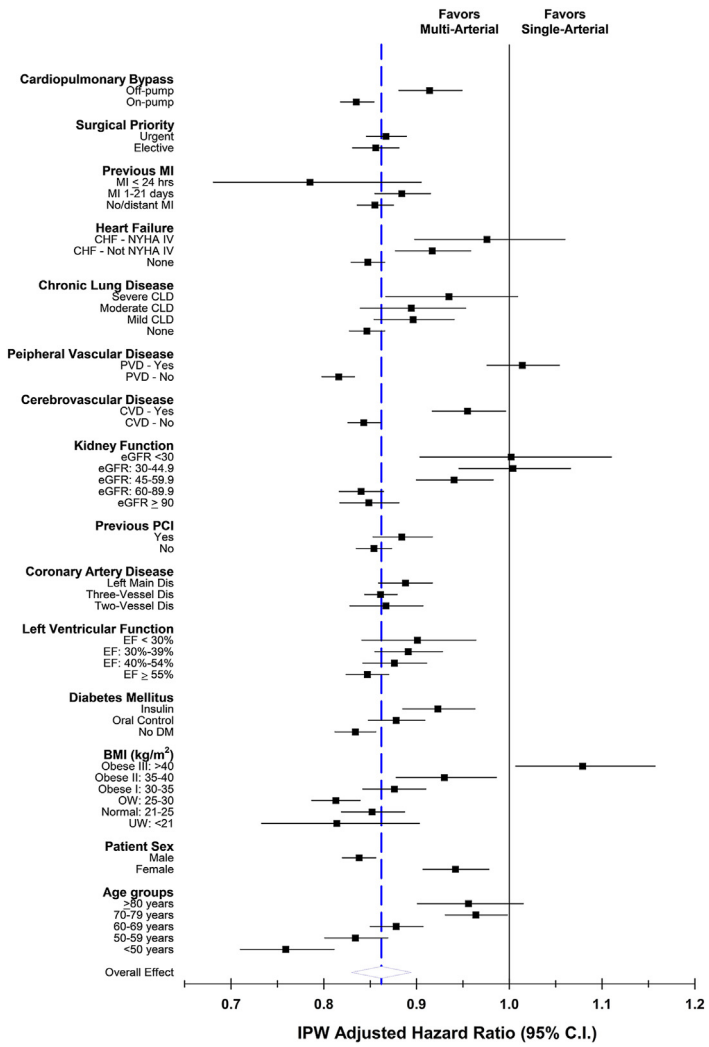


FIGURE 3 Multiarterial grafting was associated with a 12-year survival benefit in nearly all demographic, comorbidity, coronary artery disease, and surgical subgroups. The multiarterial benefit was systematically greater in decreasing age groups and was noticeably larger in men, who were also younger on average compared with women. Generally, the magnitude of the survival benefit was reduced with increased levels of morbidity such as more severe chronic lung disease (CLD), worse heart failure, and substantial renal dysfunction. In case of certain severe dysfunction, the survival advantage was no longer significant. Only, the very obese (body mass index [BMI] >40 kg/m^2) subgroup showed relatively better survival with single-arterial coronary artery bypass grafting (adjusted hazard ratio, 1.08; 95% CI, 1.01-1.16). The multiarterial treatment benefit was comparable in cases of urgent and elective surgery, whereas it was less pronounced in cases of off-pump compared with on-pump coronary artery bypass grafting surgery. (CHF, congestive heart failure; CVD, cardiovascular disease; Dis, disease; DM, diabetes mellitus; EF, ejection fraction; eGFR, estimated glomerular filtration rate; IPW, inverse probability weighting; MI, myocardial infarction; NYHA, New York Heart Association; OW, overweight; PCI, percutaneous coronary intervention; PVD, peripheral vascular disease; UW, underweight.)

experience with MAG.[13] Although there is conflicting evidence on the long-term survival benefit of radial artery grafting, a recent meta-analysis of randomized trials demonstrated a reduction in adverse cardiovascular outcomes at 10 years in patients receiving a radial artery as a second arterial graft vs saphenous vein.[26] Importantly, our study establishes the importance of MAG that includes not only ITA grafts but also radial artery grafts. The Randomized comparison of the clinical Outcome of single vs Multiple Arterial grafts (ROMA) randomized trial will further examine this; however, the results are a few years away.[27] Therefore, the results of the current study of more than 1 million patients and 10-year survival serve as the current outcome benchmark for CABG survival outcomes.

PATIENT POPULATIONS. Notably, the present study did identify populations in which there was no benefit from MAG over SAG, including patients aged >80 years, patients in New York Heart Association functional class IV, those with a glomerular filtration rate <45 mL/min/1.73 m^2, and patients with peripheral vascular disease. Furthermore, in patients with a BMI >40 kg/m^2, not only was there no benefit to MAG, but SAG was also found be beneficial. This finding clarifies another long-held presumption that may be related to sternal healing risks previously reported.[18,28,29] The relative benefits of MAG in special populations, including patients with an reduced ejection fraction, those with diabetes, patients with renal failure, and patients aged more than 80 years, have previously been evaluated in small series, but the current data confirm these findings.[7,11,30-32]

The outcomes of the current study provide much needed clarity for clinical decision making informed by patient safety and longitudinal outcome of MAG. There are numerous factors affecting surgical decision making, including coronary artery anatomy and quality of targets; however, there is a clear longitudinal benefit to MAG whenever possible.[9]

CENTER VOLUME. Our data highlight the low minimum center MAG volume necessary to obtain benefits from MAG, with a stable survival benefit across the spectrum of center MAG volume once the program crests the achievable bar of 10 cases annually. Specifically, the volume-outcome relationship seen in other complex surgical procedures is not present for MAG, thus highlighting its applicability to all practices. As nonsurgical treatment options expand for patients with multivessel disease, it will be essential to provide patients access to the best and most durable surgical therapy available.

STUDY LIMITATIONS. This study has several important limitations. Although the STS ACSD captures 97% of CABG operations in the United States to provide the most comprehensive assessment and remains the gold standard for clinical outcomes,[14] the retrospective nature of all registry data limits demonstration of

causality. Furthermore, the STS ACSD does not provide detailed anatomic information to assess the relative candidacy of each treatment group, including frailty and conduit suitability. Because this was an observational study, our findings may reflect a selection bias. To address a possible selection bias, we performed doubly robust analyses by using IPW scores on the basis of validated risk models,[33] multivariable regression, and time-to-event analysis. Additionally, multiple sensitivity analyses were performed to ameliorate the effects of selection bias, all of which confirmed the primary findings.

CONCLUSION. his contemporary real-world analysis of more than 1 million patients undergoing isolated CABG demonstrates that multiarterial CABG was associated with markedly improved survival compared with single-arterial CABG. These data support expanded use of multiarterial CABG for nearly all patients undergoing CABG and establishes a benchmark for comparison of other therapies for multivessel coronary disease.

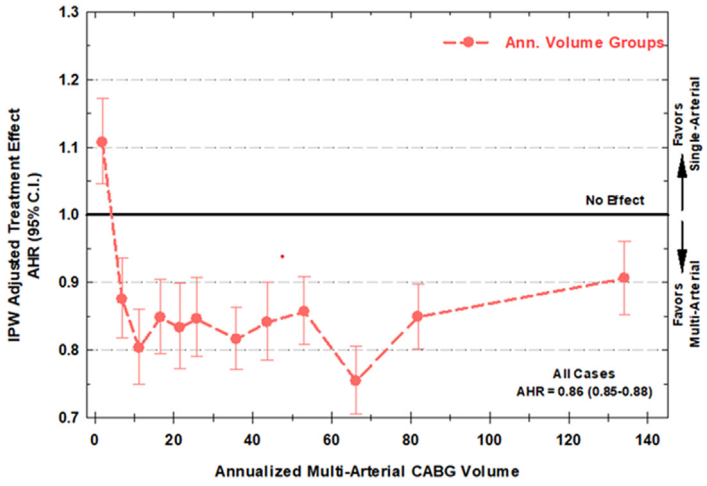
The authors would like to thank The Society of Thoracic Surgeons Research and Analytic Center for their assistance with data acquisition, linkage, and statistical analysis.

FUNDING SUPPORT

This work was supported by The Society of Thoracic Surgeons.

DISCLOSURES

The authors have no conflicts of interest to disclose.



Sub-cohort		1	2	3	4	5	6	7	8	9	10	11	12
Ann. MA Volume	Range	1-5	6-10	11-15	16-20	21-25	26-30	31-40	41-50	51-60	61-75	76-100	>100
	mean	1.9	6.9	11.2	16.6	21.5	25.8	35.8	43.6	53.0	66.1	81.8	134.1
	#Cases	9,146	8,325	8,137	8,031	6,721	6,396	10,183	6,935	8,823	8,747	9,993	8,982
	#Programs	583	134	84	54	35	30	29	19	18	14	13	9

FIGURE 4 Multiarterial grafting 0- to 12 -ear "treatment effect" quantified by inverse probability weighting (IPW)–adjusted hazard ratios (AHR; circles) with 95% CIs (error bars) in 12 multiarterial (MA) coronary artery bypass grafting (CABG) subcohorts grouped on the basis of annualized (Ann.) multiarterial volume at individual hospitals. Each multiarterial CABG group is compared with the overall single-arterial CABG cohort (N = 920,943).

REFERENCES

1. Taggart DP, Benedetto U, Gerry S, et al. Bilateral versus single internal-thoracic-artery grafts at 10 years. *N Engl J Med*. 2019;380:437-446.

2. 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;78:2005-2012 [discussion: 2012-2004].

3. 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*. 2001;358:870-875.

4. Zacharias A, Schwann TA, Riordan CJ, Durham SJ, Shah AS, Habib RH. Late results of conventional versus all-arterial revascularization based on internal thoracic and radial artery grafting. *Ann Thorac Surg*. 2009;87:19-26. e12.

5. Hemo E, Mohr R, Uretzky G, et al. Long-term outcomes of patients with diabetes receiving bilateral internal thoracic artery grafts. *J Thorac Cardiovasc Surg*. 2013;146:586-592.

6. Takagi H, Goto SN, Watanabe T, Mizuno Y, Kawai N, Umemoto T. A meta-analysis of adjusted hazard ratios from 20 observational studies of bilateral versus single internal thoracic artery coronary artery bypass grafting. *J Thorac Cardiovasc Surg*. 2014;148:1282-1290.

7. Schwann TA, Al-Shaar L, Tranbaugh RF, et al. Multi versus single arterial coronary bypass graft surgery across the ejection fraction spectrum. *Ann Thorac Surg*. 2015;100:810-817 [discussion: 817-818].

8. Samadashvili Z, Sundt TM 3rd, Wechsler A, et al. Multiple versus single arterial coronary bypass graft surgery for multivessel disease. *J Am Coll Cardiol*. 2019;74:1275-1285.

9. Bakaeen FG, Ravichandren K, Blackstone EH, et al. Coronary artery target selection and survival after bilateral internal thoracic artery grafting. *J Am Coll Cardiol*. 2020;75:258-268.

10. Formica F, Maestri F, D'Alessandro S, et al. Survival effect of radial artery usage in addition to bilateral internal thoracic arterial grafting: a meta-analysis. *J Thorac Cardiovasc Surg*. 2023;165:2076-2085.e9.

11. Hayashi Y, Maekawa A, Sawaki S, et al. Left-sided complete revascularization with bilateral internal thoracic arteries in patients with diabetes. *Ann Thorac Surg*. 2019;107:1727-1735.

12. Dimitrova KR, Hoffman DM, Geller CM, et al. Radial artery grafting in women improves 15-year survival. *J Thorac Cardiovasc Surg*. 2013;146:1467-1473.

13. Taggart DP, Altman DG, Flather M, et al. Associations between adding a radial artery graft to single and bilateral internal thoracic artery grafts and outcomes: insights from the Arterial Revascularization Trial. *Circulation*. 2017;136:454-463.

14. Jacobs JP, Shahian DM, Grau-Sepulveda M, et al. Current penetration, completeness, and representativeness of The Society of Thoracic Surgeons Adult Cardiac Surgery Database. *Ann Thorac Surg*. 2022;113:1461-1468.

15. Jacobs JP, O'Brien SM, Shahian DM, et al. Successful linking of The Society of Thoracic Surgeons Database to Social Security data to examine the accuracy of Society of Thoracic Surgeons mortality data. *J Thorac Cardiovasc Surg*. 2013;145:976-983.

16. Rosenbaum PR, Rubin DB. The central role of the propensity score in observational studies for causal effects. *Biometrika*. 1983;70:41-55.

17. Austin PC. An introduction to propensity score methods for reducing the effects of confounding in observational studies. *Multivariate Behav Res*. 2011;46:399-424.

18. Deo SV, Shah IK, Dunlay SM, et al. Bilateral internal thoracic artery harvest and deep sternal wound infection in diabetic patients. *Ann Thorac Surg*. 2013;95:862-869.

19. Medalion B, Mohr R, Ben-Gal Y, et al. Arterial coronary artery bypass grafting is safe and effective in elderly patients. *J Thorac Cardiovasc Surg*. 2015;150:607-612.

20. Schwann TA, Habib RH, Wallace A, et al. Operative outcomes of multiple-arterial versus single-arterial coronary bypass grafting. *Ann Thorac Surg*. 2018;105:1109-1119.

21. Urso S, Sadaba R, Gonzalez Martin JM, Nogales E, Tena MA, Portela F. Bilateral internal thoracic artery versus single internal thoracic artery plus radial artery: a double meta-analytic approach. *J Thorac Cardiovasc Surg*. 2024;167:183-195.e3.

22. Yanagawa B, Verma S, Juni P, et al. A systematic review and meta-analysis of in situ versus composite bilateral internal thoracic artery grafting. *J Thorac Cardiovasc Surg*. 2017;153:1108-1116.e1116.

23. Gaudino M, Bakaeen F, Benedetto U, et al. Use rate and outcome in bilateral internal thoracic artery grafting: insights from a systematic review and meta-analysis. *J Am Heart Assoc*. 2018;7:e009361.

24. Gaudino M, Di Franco A, Rahouma M, et al. Unmeasured confounders in observational studies comparing bilateral versus single internal thoracic artery for coronary artery bypass grafting: a meta-analysis. *J Am Heart Assoc*. 2018;7:e008010.

25. Barili F, Onorati F, D'Errigo P, et al. Bilateral internal thoracic arteries improve 10-year outcomes of coronary artery bypass grafting. *Ann Thorac Surg*. 2023;116:52-60.

26. Gaudino M, Benedetto U, Fremes S, et al. Association of radial artery graft vs saphenous vein graft with long-term cardiovascular outcomes among patients undergoing coronary artery bypass grafting: a systematic review and meta-analysis. *JAMA*. 2020;324:179-187.

27. Taggart DP. The role of multiple arterial grafts in CABG: all roads lead to ROMA. *J Am Coll Cardiol*. 2019;74:2249-2253.

28. Vrancic JM, Piccinini F, Camporrotondo M, et al. Bilateral internal thoracic artery grafting increases mediastinitis: myth or fact? *Ann Thorac Surg*. 2017;103:834-839.

29. Kieser TM, Rose MS, Aluthman U, Montgomery M, Louie T, Belenkie I. Toward zero: deep sternal wound infection after 1001 consecutive coronary artery bypass procedures using arterial grafts: implications for diabetic patients. *J Thorac Cardiovasc Surg*. 2014;148:1887-1895.

30. Galbut DL, Kurlansky PA, Traad EA, Dorman MJ, Zucker M, Ebra G. Bilateral internal thoracic artery grafting improves long-term survival in patients with reduced ejection fraction: a propensity-matched study with 30-year follow-up. *J Thorac Cardiovasc Surg*. 2012;143:844-853.e844.

31. Kai M, Okabayashi H, Hanyu M, et al. Long-term results of bilateral internal thoracic artery grafting in dialysis patients. *Ann Thorac Surg*. 2007;83:1666-1671.

32. Gaudino M, Di Franco A, Flather M, et al. Association of age with 10-year outcomes after coronary surgery in the Arterial Revascularization Trial. *J Am Coll Cardiol*. 2021;77:18-26.

33. Shahian DM, Bowdish ME, Bloom JP, et al. The Society of Thoracic Surgeons coronary artery bypass graft composite measure: 2021 methodology update. *Ann Thorac Surg*. 2022;113:1954-1961.