

The outcomes of robotic-assisted coronary artery bypass grafting surgery in the Atlantic demographic – a systematic review and meta-analysis of the literature

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Background: Coronary artery bypass grafting (CABG) has significantly reduced the morbidity and mortality of patients suffering from ischemic heart disease over its six decades of practice. In recent years, minimally invasive techniques have been increasingly described and utilized, with the promise of providing patients with the same standard of care without the need for the traditional full sternotomy, and in select cases without cardiopulmonary bypass, and thus providing improved recovery metrics. The present systematic review and meta-analysis sought to determine the outcomes of all patients receiving robotic-assisted CABG in an Atlantic patient demographic.

Methods: The methods for this systematic review and meta-analysis adhered to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement. Four databases were searched, using appropriate search terminology. Meta-analysis using proportions or means, as appropriate, were applied, and were presented as per routine practice. Kaplan-Meier curves were digitized and aggregated using previously reported, validated techniques. Quality assessment and risk of bias of each study were assessed systematically. Patient populations were subcategorized as per established technical definitions.

Results: Thirty-five studies were identified through the literature search, with three studies having subgroupings appropriate for separate analysis (yielding 42 data points maximally). A total of 9,078 patients (69% male), with a mean age of 62.3 years, were identified across the study period. On actuarial assessment, survival at yearly assessment from 1-, 2-, 3-, 4- and 5-yearly intervals was determined to be 95%, 94%, 92%, 90%, and 88%, respectively.

Conclusions: The present systematic review and meta-analysis demonstrated that short-term mortality, operative time, and admission [intensive care unit (ICU) and overall length of stay] outcomes were encouraging in the Atlantic demographic. Freedom from long-term mortality assessment of a smaller cohort showed encouraging results. A major caveat to the present analysis is the high degree of heterogeneity in the reporting of data. Analysis of future randomized controlled trials will be vital in establishing these procedures as commonplace.

Keywords: Robotic surgery; coronary grafting; meta-analysis



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Introduction

Coronary artery bypass grafting (CABG) or coronary artery graft surgery (CAGS) has now saved the lives of innumerable patients with ischemic heart disease over its six decades of practice, and exists as one of the most heavily performed and researched operations in the modern era (1). Whilst CABG remains an excellent operation with proven long-term durability of revascularization, particularly with respect to the robustness of the left internal mammary artery (LIMA)-left anterior descending (LAD) graft, it remains an operation that, for the most part, imparts non-inconsequential short-term morbidity in the way of a sternotomy, with all of the associated downstream effects on recovery, quality of life, and delayed return to active society (2,3). Minimally invasive direct coronary artery bypass grafting (MIDCAB grafting—typically through an anterior thoracotomy) and totally endoscopic coronary artery bypass grafting (TECAB grafting—purely through thoroscopic or robotic suite use) are increasingly being utilized, providing patients with equivalent revascularization outcomes in appropriate cases without the aforementioned deficits. As the patient population becomes increasingly older, frailer, and more medically comorbid, minimal access procedures like robotic coronary grafting are attractive for a number of stakeholders and may indeed form an essential tool in the future cardiothoracic surgeon's armamentarium (4). Whilst that being the case, such strategies are as of yet not widely adopted, and have proven difficult to reproduce generally. Detailed work on this topic has been published by our group intermittently since 2013, though no other research summarizes the up-to-date outcomes in a purely Atlantic (i.e., North America and European) cohort (5,6). This systematic review and meta-analysis sought to determine the outcomes of patients in the Atlantic demographic undergoing all forms of robotically assisted CABG.

Methods

Literature search strategy

The methods for this systematic review adhered to the guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) updated statement (7). Four electronic databases were used to perform the literature searches, encompassing Embase, Ovid MEDLINE, PubMed, and Scopus. These databases

were searched from the date of database inception through to February 2024. For the examination of the outcomes of robotic CABG in the Atlantic demographic, a search strategy using the combination of keywords and Medical Subject Headings (MeSH) including (coronary artery bypass grafting OR CABG OR CAGS OR CAG) AND (robotic OR robotic-assisted OR robotic assisted OR minimally invasive OR endoscopic) was utilized and is visually presented by the PRISMA flow diagram (see [Figure S1](#)). Predefined selection criteria were applied to assess for inclusion or exclusion (see "Inclusion and exclusion criteria"). Studies were individually assessed for location *post-hoc* and were included or excluded accordingly.

Each study was screened independently by three co-authors (A.R.W.S., C.J.W.S., J.S.S.), with any conflicts resolved prior to progression through mutual agreement. Where the title and/or abstract provided insufficient detail in the determination of relevance for additional screening, a full-text review of the record was carried out in the first instance. The reference lists of included studies were manually assessed to identify any missed papers from the literature search that were also eligible for assessment. In the instance of multiple studies produced by the same author with the same cohort, the most recent paper was included. In the instance where concern regarding duplication existed but was not clear in the manuscript, the authors were contacted to clarify if the cohorts were distinct.

Inclusion and exclusion criteria

Studies were included in the review if: (I) they examined the perioperative and postoperative outcomes of interest in patients undergoing robotic CABG through any means (e.g., MIDCAB, TECAB, open/mix, on- and off-pump) (see "Primary and secondary endpoints"). Series remained eligible for inclusion in the instance of 'hybrid'/mixed approaches, as in the case of a median sternotomy with robotic coronary artery harvesting. Studies were excluded for: (I) non-English reporting; (II) narrative reports; (III) studies without clear recruiting details; (IV) no mention of perioperative and postoperative patient outcomes; (V) redo coronary revascularization procedures in the emergent setting; (VI) no specification as to which cardiac procedure was performed; (VII) nil reporting of postoperative outcomes; (VIII) non-adult patients, or those with congenital disorders; (IX) less than 10 patients in their sample sizes.

Primary and secondary endpoints

The primary endpoints of analysis were operation time, hospital and intensive care unit (ICU) length of stay (hLOS/iLOS), and 30-day mortality. Secondary endpoints included baseline demographic data (i.e., age, sex, cross-clamp and cardiopulmonary bypass time if appropriate), post-operative atrial fibrillation (POAF), preoperative left ventricular ejection fraction (LVEF), long-term mortality (as represented through Kaplan-Meier graphs).

Data extraction, critical appraisal, and quality assessment

Two independent reviewers extracted data directly from publication texts, tables, and figures (J.S.S., W.L.). A third reviewer independently reviewed and confirmed all extracted data (A.R.W.S.). Differing opinions between the two main reviewers were resolved through discussion led by the primary investigator (A.R.W.S.). Attempts were made to clarify insufficient/indistinct data from authors of included studies, as required. Data was extracted in a way that each study was effectively treated as a case series, irrespective of underlying design. The Canadian Institute of Health Economics Quality Appraisal score was used as the quality assessment tool (8). Studies were defined as low quality with scores $\leq 11/18$, moderate quality ≥ 12 – $14/18$, and high quality $\geq 15/18$.

Statistics

A meta-analysis of proportions or means were performed for categorical and continuous variables, as appropriate, by an independent reviewer. A random effects model was used in the first instance to account for differing regions, surgeon experience, surgical technique and equipment, and management protocols across the included studies; in subgroups with insufficient samples, a common effects model was utilized. Means and standard deviations (SDs) were calculated from the median, where reported, using the methods described by Wan and colleagues (9). Pooled data and SDs or standard error (SE) are presented as N (%) $\pm$ SD or SE with 95% confidence intervals (CIs). For outcome data, heterogeneity amongst studies was assessed using the I^2 statistic. Thresholds for these values were considered as low, moderate, and high heterogeneity as 0–49%, 50–75% and $>75\%$, respectively. Meta-analysis of proportions or means were performed using Stata (version

17.0, StataCorp, Texas, USA). Risk of bias was assessed using the “Risk of Bias in Non-randomized Studies - of Interventions” (ROBINS-I) tool and has been visually presented (see [Figure S2](#), risk of bias assessment) (10). Reporting of individual variables is also noted. Funnel plots were generated using R {R Core Team (2021) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. R Studio [RStudio Team (2020)] in the R Studio environment (RStudio: Integrated Development Environment for R. RStudio, PBC, Boston, MA, USA)}, with Egger’s tests were applied for assessment of small-study effects and publication bias. Cohorts underwent sub-group analysis based on their index operation, into the following cohorts: (I) all patients undergoing robotic CABG; (II) those undergoing off-pump coronary grafting; (III) those undergoing on-pump coronary grafting; (IV) those undergoing TECAB; (V) those undergoing MIDCAB; (VI) those undergoing open-access with robotic conduit harvesting; and (VII) mixed (i.e., mini-sternotomy with thoracoscopic harvesting). These subgroups were decided prior to statistical analysis. Forest plots of covariates are presented in [Figure S3–S22](#).

Results

Baseline demographic, perioperative, and postoperative data of all-patient cohort

Total patient cohort

On application of the search terms, a total of 2,362 studies were identified. Following use of the inclusion and exclusion criteria, 35 studies were identified for inclusion, with detailed study characteristics provided in [Tables S1–S4](#). Three papers reported clinical data with appropriate subgroup data splitting, so were considered as “separate” for the purposes of data analysis. Detailed demographic and post-operative outcomes for each cohort are reported in [Table 1](#). A total of 9,078 patients were identified, of which 75% (95% CI: 72.3–77.3%) were male with a mean age of 62.3 years (95% CI: 60.8–63.9). A significant difference between on-pump and off-pump patients was demonstrated for age ($P < 0.01$; $I^2 = 93.5\%$) and across the access types ($P = 0.01$; $I^2 = 93.5\%$). The mean preoperative LVEF was 55% (95% CI: 52.4–57.7%). Thirty-one percent of the cohort was diabetic, 9% had a diagnosis of peripheral arterial disease of any severity, 11.5% had chronic obstructive pulmonary disease (COPD), and 80.9% had hypertension on medical therapy of any type and grade. Study variables

Table 1 Demographic characteristics and post-operative outcomes

Surgical cohort by procedure type	All-patient/total	Off-pump	On-pump	TECAB	MIDCAB	Open
Cohort (N)	9,078	7,684	328	5,847	3,087	88
Cohort age, years, N [95% CI]	62.3 [60.8–63.9]	64.9 [63.4–66.4]	59.4 [56.7–62.1]	61.6 [59.5–63.7]	63.9 [60.9–66.9]	63.9 [57.1–70.7]
Cohort male, % [95% CI]	74 [72–77]	71 [65–77]	83 [75–90]	73 [67–79]	74 [68–81]	83 [71–95]
Pre-op LV, % [95% CI]	55 [53–57]	53 [53–54]	56 [55–57]	55 [54–56]	55 [54–56]	54 [53–55]
Cohort comorbidities						
T2DM	3,218/8,422, 38%	3,032/7,544, 37%	43/296, 14.5%	1,866/5,223, 35.7%	1,329/3,087, 43%	9/56, 16%
PVD	718/7,140, 10%	647/5,778, 11%	6/296, 2%	512/5,247, 9.8%	204/1,837, 11%	2/56, 3.6%
COPD	605/5,488, 11%	520/4,777, 10.9%	30/211, 14%	528/4,890, 10.8%	70/542, 12.9%	7/56, 12.5%
HTN	5,704/6,842, 83%	5,078/6,046, 83.8%	220/296, 74%	4,189/5,131, 81.6%	1,442/1,599, 90%	41/56, 73%
Op time, N [95% CI]	288 [269–308]	276 [254–299]	327 [262–392]	291 [268–313]	308 [307–311]	NR
POAF, % [95% CI]	15 [13–17]	15 [13–17]	8 [5–14]	15 [13–17]	12 [6–23]	NR
hLOS day, N [95% CI]	4.5 [3.8–5.2]	3.8 [3.3–4.3]	7.3 [3.9–10.8]	4.3 [3.7–5]	4.1 [3.7–4.6]	6.6 [5.7–7.5]
iLOS day, N [95% CI]	1.4 [1.3–1.6]	1.5 [1.3–1.7]	1.4 [1.2–1.5]	1.4 [1.3–1.5]	1.6 [1.4–1.7]	1.4 [0.6–2.2]
30-d morality [%]	1 [0.8–1.4]	0.6 [0.4–0.8]	0 [0–1.1]	0.7 [0.5–1]	0.4 [0.2–0.7]	0 [0–2]
Comorbidities presented as aggregate mean (overall sampled cohort) + percentage of cohort. TECAB, totally endoscopic coronary artery bypass; MIDCAB, minimally invasive direct coronary artery bypass; N, number; CI, confidence interval; Pre-op, preoperative; LV, left ventricular; T2DM, type 2 diabetes; PVD, peripheral vascular disease; COPD, chronic obstructive pulmonary disease; HTN, hypertension; Op, operative; POAF, post-operative atrial fibrillation; hLOS, hospital length of stay; iLOS, intensive care unit length of stay; 30-d, thirty-day.						

reported too infrequently for analysis included: number of cases proceeding to reoperation/reintervention, number of cases receiving repeated revascularization (of any time course), freedom from angina, freedom from major adverse cardiac events (MACEs), flow rates (i.e., via coronary ultrasound)/pulse index, body mass index and body mass index $>30 \text{ kg/m}^2$, previous arrhythmia history (of any diagnosis), LVEF $<40\%$, previous cardiac surgery (any operation), concomitant procedures. Eighty percent of included studies were single-institutional studies. Of these studies, 50% were retrospective cohort studies.

Sub-grouped cohorts—off-pump, on-pump, TECAB, and MIDCAB

In the off-pump, on-pump, TECAB, and MIDCAB cohorts, 7,684, 328, 5,847, and 3,087 patients were identified. The majority of reported studies (27/35) were from North

American centers. The preoperative LVEFs across these cohorts were 52% (95% CI: 48.6–55.3%), 60.2% (95% CI: 57–63.4%), 55.4 (95% CI: 51.6–59%) and 53.9% (95% CI: 52–55.7%), respectively. A significant difference was identified between the off-pump and on-pump groups with respect to preoperative LVEF, though this difference was marginal and unlikely to be clinically relevant ($P \leq 0.01$; $I^2 = 98\%$). Type 2 diabetes mellitus across the examined cohorts represented approximately 36%, 15%, 28%, and 41% of patients, respectively. Peripheral arterial disease of any severity was demonstrated in 12%, 3%, 9%, and 12% of patients in the off-pump, on-pump, TECAB, and MIDCAB cohorts, respectively. COPD of any degree of clinical severity was demonstrated in 11%, 15%, 11%, and 13% of patients in the off-pump, on-pump, TECAB, and MIDCAB cohorts, respectively. Hypertension was demonstrated in 81%, 79%, 80% and 89% of the

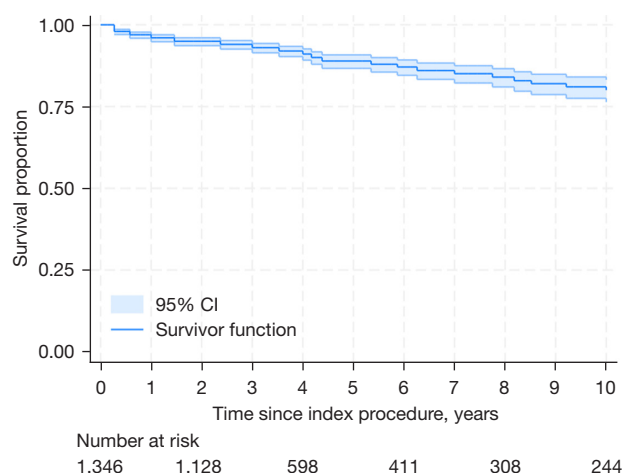


Figure 1 Kaplan-Meier survival assessment—robotic coronary artery bypass grafting. CI, confidence interval.

patient cohorts examined. Mean operative times were found to be 276 minutes (95% CI: 254–299), 327 minutes (95% CI: 262–392), 291 minutes (95% CI: 268–313), and 308 minutes (95% CI: 307–311), respectively. No significant difference was found between pump groups with respect to operation times ($P=0.62$; $I^2=98\%$).

Postoperative rates of atrial fibrillation were 15.2% (95% CI: 13.1–17.5%), 8.1% (95% CI: 4.7–13.5%), 15% (95% CI: 13.3–16.9%), and 11.7% (95% CI: 5.7–22.8%), respectively. No significant difference between off-pump and on-pump cohorts was identified ($P=0.06$; $I^2=69.4\%$), or access groups ($P=0.54$; $I^2=69.4\%$). Mean hLOS was 3.8 days (95% CI: 3.3–4.3), 7.3 days (95% CI: 3.9–10.7), 4.3 days (95% CI: 3.7–5), and 4.1 days (95% CI: 3.7–4.6), respectively. A significant difference was found between off-pump and on-pump cohorts with respect to hLOS ($P<0.01$; $I^2=99\%$). A significant difference was identified between access approaches ($P\leq 0.01$; $I^2=99\%$). Mean iLOS across the cohorts was demonstrated to be 1.5 days (95% CI: 1.3–1.6), 1.4 days (95% CI: 1.2–1.5), 1.4 days (95% CI: 1.3–1.5), and 1.6 days (95% CI: 1.4–1.7), respectively. No significant difference between pump cohorts was identified ($P=0.12$; $I^2=86\%$). A difference between access approaches was identified ($P\leq 0.01$; $I^2=86\%$). Thirty-day mortality rates across the cohorts was found to be 0.6% (95% CI: 0.4–0.8%), 0% (95% CI: 0–1%), 0.7% (95% CI: 0.5–1%), and 0.4% (95% CI: 0.2–0.7%), respectively. No difference across pump cohorts or access approaches ($P=0.5$; $I^2=0\%$) was identified.

Egger's test of small-study effects and publication bias

On assessment of small-study effects and publication bias for 30-day mortality, Egger's test ($t=-0.59$; $P=0.56$; bias estimate $=-0.18$; SE $=0.30$) indicated no significant plot asymmetry. Similarly, the meta-analysis of operative time ($t=-1.57$; $P=0.13$; bias estimate $=-3.58$; SE $=2.29$), was not significant for plot asymmetry, and indicated no strong evidence of publication bias. For the meta-analysis of length of stay (LOS), Egger's test ($t=-0.31$; $P=0.76$; bias estimate $=-0.85$; SE $=2.77$) no significant plot asymmetry was demonstrated, and no subsequent evidence of publication bias. The meta-analysis of ICU stay did not reveal a significant result, indicating no evidence of publication bias ($t=2.04$; $P=0.052$; bias estimate $=1.37$; SE $=0.67$).

Quality and risk of bias assessment

Four studies were deemed to be low quality (11–14). Twenty-three studies were deemed to be of moderate quality (15–37). Eight studies were deemed to be of high quality (38–45). Inter-rater reliability between authors assessing study quality was high, with concordance of rating of 95%. Twenty-one studies were deemed to be of low risk of bias, with the remaining fourteen studies deemed as moderate (11,12,14,17,18,20,27,28,31,34,35,37,45,46) (see Figure S2).

Kaplan-Meier assessment of robotic CABG freedom from mortality

All-patient freedom from mortality as derived from aggregated Kaplan-Meier curves from reporting studies (16,17,21,27,28,30,33,36,39,47) is illustrated by Figure 1.

Kaplan-Meier survival assessment—robotic CABG

Actuarial survival at yearly assessment from 12- to 60-month intervals was determined to be 95%, 94%, 92%, 90%, and 88%, respectively.

Discussion

CABG has significantly reduced the morbidity and mortality of patients suffering from ischemic heart disease and appears to have a secure future with an ever-increasingly comorbid, frailer patient population. Ongoing refinements

in mini-access techniques and technologies has led to safe, effective revascularization options in the MIDCAB and TECAB strategies, without the need for a full sternotomy. Indeed, however, in amongst a discussion of the utility of any mini-access therapy should be the acknowledgment that the primary aim is to achieve robust revascularization, long-term freedom from secondary major cardiac adverse events, to enhance quality of life, and to return patients to a high level of pre-morbid functionality. So, if required, a full sternotomy with a traditional approach—if that is what is clinically mandated—should be undertaken accepting the short- to intermediate-term morbidity. The present systematic review and meta-analysis demonstrates in the appropriately selected patient, they can indeed benefit from lower mortality, shorter operations, and reduced admission periods with robotically assisted coronary grafting.

In recent decades, beating-heart, off-pump, and minimally invasive access surgery have become increasingly considered in the tailored, individualized management of patients in order to spare them from any unnecessary trauma/physiologic disturbance of cardiopulmonary bypass and open-heart surgery. Some of these techniques, such as off-pump surgery, have seen tempered utilization, and minimally invasive surgery has largely been constrained by the ability of the operator to graft lateral and inferior lesions, and thus only indicated in select pathologies such as single to double vessel disease (48,49). That being said, bilateral mammary harvesting is quite feasible for proximal lateral and inferior lesions, as is previously reported (18). Indeed, Cerny *et al.* in their European status report illustrate exceptionally low rates of conversion, low rates of major complications, and that the majority of procedures are performed beating-heart (50). The majority of the included studies in the present systematic review performed totally endoscopic, off-pump surgery, with an average of 1.1 grafts for the all-patient cohort. Robotic coronary grafting clearly has a number of benefits for these patients; easier harvest for the operator with improved dexterity and vessel visibility—and thereby lower risk of inadvertent conduit trauma and minimized handling—faster recovery times in ICU and in hospital overall, and in the instance of purely endoscopic robotic therapy, less pain and subsequent analgesic uptake compared to a traditional, full sternotomy. Especially in cases where only 1–2 vessels require grafting, the avoidance of a full sternotomy is a major benefit.

The results of the present meta-analysis demonstrate a mean length of hospital stay of 4.5 and 4.3 days, in the all-patient and TECAB cohorts, respectively. These

results are even more favorable than previously reported meta-analytical data for TECAB cohorts, where data had demonstrated superior results when compared to conventional CABG in a meta-analysis by Cao *et al.* (6,17,37,51). While presumably mediated by surgeon skill in high-volume centers, recent reports have also demonstrated that carefully selected, robotic-coronary bypass patients can be discharged the day following operation with no significant risk of readmission, though far more data are needed to solidify this metric (28). While the widespread adoption of robotic coronary surgery is limited outside of major centers of excellence—as denoted by the overwhelming majority of studies coming from the same, expected institutions—TECAB may actually be cost-effective across the long term and in institutions where there are protocols designed to rapidly recover patients post-operatively (29). Additional cost-effectiveness analyses are currently underway in this respect, the results of which will be critical in guiding practice as the obvious drawback in the initial establishment of robotic programs is the cost of the suites, the proctoring/subspecialty training required, and the ongoing upkeep in the way of maintenance.

Limitations

There are a number of limitations of the present meta-analysis. Firstly, the majority of studies incorporated were of a non-randomized, observational nature. As these procedures are increasingly utilized, both in the North American/European demographics and worldwide, adequately powered, randomized controlled trials are required for confirming the utility of this approach compared to conventional coronary artery bypass surgery. Additionally, desired pre-, peri-, and postoperative variables were not holistically reported. Mortality assessment was constrained by all-cause assessment, as opposed to cardiac-specific mortality events. Key reporting variables, such as number of grafts performed, were poorly reported overall, and typically reported without variance or SD, or in a non-numeric format. This hampered the ability to perform meta-analysis stratified by number of targeted vessels, despite this being a fundamental and presumably commonsense datapoint of consideration. Furthermore, rates of conversion to open CAGS were also not universally reported, with many studies excluding these patients from analysis. This introduces an inherent risk of both selection and reporting bias, as many of these studies were retrospective in nature. Despite the risk of bias assessment

in this study illustrating an overall low risk of bias, having access to conversion rate data would be beneficial for future studies. Assessment of post-operative pain and subsequent analgesic uptake was not possible quantitatively, as these metrics are very poorly reported on, if at all—despite this being a key selling factor.

Conclusions

The present systematic review and meta-analysis demonstrated through all-patient and subgroup analysis that short-term mortality, operative time, and admission (ICU and overall length of stay) outcomes were encouraging in the Atlantic demographic. Freedom from long-term mortality Kaplan-Meier assessment of a smaller cohort showed similarly encouraging results. Analysis of future randomized controlled trials will be vital in establishing these procedures as commonplace in the future of cardiothoracic surgery.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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