

Analysis of Minimally Invasive Robotic-Assisted CABG Procedures Utilizing Intraoperative ICGA and Transit Time Flowmeter Testing

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Abstract

Introduction: Interest in robotic-assisted minimally invasive direct coronary artery bypass (R-MIDCAB) has increased to ensure graft patency, intraoperative techniques utilizing indocyanine green angiography (ICGA) and Transit Time Flowmeter (TTFM) testing have been individually employed. Our study is the first to review the combined use of ICGA and TTFM as a combined intraoperative approach in R-MIDCAB

Methods: This single-surgeon, retrospective study includes 78 patients who underwent robotic-assisted CABG procedures at Reading Hospital between May 2022 and June 2024. ICGA and TTFM testing were utilized intraoperatively to evaluate graft patency. Outcomes were evaluated at 30 days post-operatively, including complications, hospital length of stay (LOS), adverse events, and changes in ejection fraction.

Results: Demographic analysis showed that 67.95% of the cohort was male, with a mean age of 67.3 years (range: 55–78). TTFM confirmed adequate graft flow with a mean flow of 22.5 mL/min and pulsatile index (PI) averaging 2.9. Suboptimal flow and PI values prompted intraoperative revisions in 10% of cases (8 of 78 grafts). Following revision, TTFM flow and PI values were improved (11.4 mL/min, PI: 2.3). At 30 days post-operatively, ejection fraction demonstrated a statistically significant improvement. The mean pre-operative ejection fraction was 52.1% (± 14.3), while the mean post-operative ejection fraction improved to 57.4% (± 13.2) ($p = 0.001$).

Conclusion: The combined use of ICGA and TTFM in R-MIDCAB is safe, reproducible and can provide important insights into LIMA-LAD graft patency.

Introduction

Coronary artery bypass grafting (CABG) remains the most common cardiac surgery procedure performed today. Traditional CABG remains the “gold standard” treatment for multivessel coronary artery disease or left main coronary artery disease¹. In the 1990s, minimally invasive direct coronary artery bypass (MIDCAB) emerged as an alternative approach, utilizing mini thoracotomy to reduce surgical trauma while maintaining durable revascularization². During this period, high resolution Doppler ultrasound techniques were introduced to evaluate graft flow dynamics and patency. Over time, these methods became valuable tools for assessing myocardial reperfusion in both minimally invasive and traditional CABG procedures².

Several intraoperative tools have been developed to evaluate graft patency. Early high-resolution Doppler ultrasound techniques assessed flow dynamics and patency in both traditional and minimally invasive CABG². Transit time flow measurement (TTFM) provides quantitative data by measuring the time required for ultrasound to pass through the blood, enabling calculation of volumetric blood flow⁹. Indocyanine green angiography (ICGA), in contrast, uses a near-infrared fluorescence dye bound to plasma proteins to visualize coronary blood flow in real time^{7–8}. ICGA offers high diagnostic accuracy for detecting occlusions¹⁰, while TTFM provides objective numerical flow data. Notably, there are cases in

which TTFM indicates poor flow, but ICGA confirms adequate perfusion, highlighting their complementary roles¹¹.

Despite their potential, both modalities remain underutilized in current U.S. practice, in part because, unlike European guidelines, U.S. guidelines do not mandate or formally recommend specific intraoperative graft-assessment tools^{3,4} (expanded upon in the Discussion).

Despite their differences, ICGA and TTFM are both increasingly recognized as important tools for assessing graft patency compared to standard Doppler ultrasound, offering high-resolution visualization and quantitative flow measurements, respectively. While TTFM provides quantitative data regarding flow measurements, ICGA can provide visual corroboration and qualitative insight, suggesting a complementary relationship to be explored. This study evaluates the combined use of ICGA and TTFM in a single-surgeon R-MIDCAB series, focusing on their role in optimizing graft patency, minimizing intraoperative revisions, and improving postoperative ejection fraction (EF). We also present institutional cost data to provide insight into the financial implications of implementing these modalities in a community hospital setting.

Methods

Study Design:

This single-surgeon, retrospective study was conducted at Reading Hospital. We aimed to assess the effectiveness of intraoperative indocyanine green angiography (ICGA) and Transit Time Flowmeter (TTFM) testing in evaluating graft patency and their potential impact on post-operative outcomes, including ejection fraction recovery. The study was approved by the institutional review board, and the requirement for individual informed consent was waived due to its retrospective nature.

Patient Population:

The study population consisted of adult patients diagnosed with significant coronary artery disease, indicated for isolated CABG procedures. All procedures were performed using a robotic-assisted technique, involving small thoracic incisions without the need for a full sternotomy. The left internal mammary artery (LIMA) was commonly harvested robotically and grafted to the left anterior descending (LAD) artery. Graft patency was assessed intraoperatively using both ICGA and TTFM. All 78 patients underwent isolated, single-vessel LIMA-to-LAD robotic-assisted MIDCAB; no multi-vessel robotic CABG or hybrid (staged PCI/CABG) revascularization procedures were included in this cohort. All procedures were performed off-pump. No patients required conversion from robotic access to sternotomy or thoracotomy; the small number of intraoperative graft revisions were completed robotically. Target vessel quality was assessed intraoperatively by the operating surgeon on the basis of vessel diameter (size) and the gross appearance of the vessel wall (e.g., absence of diffuse atherosclerotic disease),

consistent with conventional intraoperative grading criteria used to characterize coronary target vessels in the CABG literature.²⁶

Because the cohort was limited to isolated LIMA-to-LAD grafting, a total of 78 grafts were performed (one per patient); the LIMA was the sole conduit used in every case, and bimammary (both internal mammary artery) harvesting was not performed in this series.

Inclusion and Exclusion Criteria:

Inclusion criteria encompassed adults aged 18 years and older with documented coronary artery disease requiring CABG. Exclusion criteria included patients with severe bleeding disorders, known dye allergies to indocyanine green, incomplete intraoperative data, concurrent cardiac procedures beyond CABG, and hemodynamic instability precluding robotic surgery.

Intraoperative Assessment

ICGA was performed in all cases to visualize graft patency after completion of the anastomosis. TTFM was used to obtain quantitative graft flow measurements, including mean flow (mL/min) and pulsatility index (PI). Suboptimal readings (flow < 10 mL/min or PI > 5) prompted immediate revision of the graft. Although this series was limited to LIMA-to-LAD grafting, ICGA is not anatomically restricted to this target and could in principle be applied to other graft-target combinations (e.g., vein or radial artery grafts to the circumflex or posterior descending artery); however, ICGA provides qualitative visualization of flow rather than the quantitative flow and pulsatility data generated by TTFM.

TTFM measurements were obtained using a Transonic Optima® flowmeter (model HT353, single-channel; Transonic Systems Inc., Ithaca, NY) with a 2 mm flow probe positioned on the distal LIMA graft proximal to the anastomosis; mean arterial pressure was maintained above 60 mmHg in all cases at the time of graft assessment. Graft revision was primarily guided by the pulsatility index (PI); flow readings with adequate acoustic signal quality and $PI \leq 5$ were not routinely revised regardless of the absolute flow value. ICGA was administered as a single 1 mL dose of reconstituted indocyanine green via a central venous line and visualized using the near-infrared imaging platform integrated into the da Vinci robotic system; restricted flow on ICGA was defined as absence of visible fluorescence in the graft or target vessel. Consistent with standard intraoperative practice for TTFM timing, measurements were obtained following completion of each anastomosis, before and after protamine administration, and again prior to chest closure.²⁷ The intraoperative decision algorithm proceeded as follows: after completion of the anastomosis, the foot plate was released and graft flow reassessed by TTFM (acoustic signal quality, flow, and PI); ICGA was then performed via the robotic camera to visually confirm perfusion. If TTFM or ICGA findings remained abnormal after foot plate release and reassessment, the graft underwent surgical revision.

Data Collection

Demographic, clinical, and perioperative data were extracted from the electronic health record. EF was assessed preoperatively and at 30 days postoperatively using transthoracic echocardiography.

Cost Analysis

Cost data for robotic CABG procedures and device usage were obtained directly from the Tower Health hospital billing department. Figures represent per-case charges for cardiac robot pack, Flo-thru shunt, IC Green 2.5 mg dose, and other relevant disposables. TTFM cost was limited to the initial acquisition without per-case charges.

Statistical Analysis:

Continuous variables were presented as means $\pm$ standard deviations, and categorical variables as percentages. Paired t-tests were used to compare pre-operative and post-operative ejection fraction data ($n = 78$ paired observations). Formal normality testing was not performed on the pre- to post-operative EF differences; normality was assumed on the basis of sample characteristics and prior literature using paired t-tests for similar EF comparisons, which we acknowledge as a limitation. The significance threshold was set at $p < 0.05$. Additionally, descriptive statistics were utilized to summarize demographic and clinical characteristics.

Complication Definitions

Atrial fibrillation was recorded as new-onset postoperative AF; no patients had pre-existing AF. Wound infection was defined using CDC/NHSN surgical site infection criteria. Stroke was defined as a new focal or global neurological deficit of vascular origin persisting more than 24 hours (or confirmed by neuroimaging if resolving sooner), consistent with STS Adult Cardiac Surgery Database criteria. Acute kidney injury was staged using KDIGO criteria (Stage 1: serum creatinine increase ≥ 0.3 mg/dL within 48 hours or $1.5\text{--}1.9\times$ baseline within 7 days, or urine output < 0.5 mL/kg/h for 6–12 hours; Stage 2: creatinine $2.0\text{--}2.9\times$ baseline or urine output < 0.5 mL/kg/h for ≥ 12 hours; Stage 3: creatinine $\geq 3\times$ baseline, ≥ 4.0 mg/dL, or initiation of renal replacement therapy). Perioperative myocardial infarction was defined per the Universal Definition of Myocardial Infarction (Type 5, CABG-related MI): cardiac biomarker elevation greater than 10 times the 99th percentile upper reference limit within 48 hours of surgery in patients with normal baseline troponin, accompanied by new pathologic Q waves, new left bundle branch block, angiographic evidence of new graft or native-vessel occlusion, or imaging evidence of new loss of viable myocardium. Reoperation for bleeding was defined as unplanned return to the operating room for surgical control of postoperative hemorrhage or cardiac tamponade. Thirty-day mortality was defined as death from any cause within 30 days of the index operation, and 30-day follow-up completeness was assessed for all patients.

Results

Analysis of demographic data revealed a majority of patients were male (67.95%) (53 of 78) and White or Caucasian (87.5%) (68 of 78), with an average age of 67.3 years (range: 55–78). The mean BMI across patients was 29.7 kg/m², with 45.83% of patients having a BMI > 30 kg/m² (36 of 78), indicating obesity as a prevalent risk factor. Pre-operative labs identified elevated troponin levels (mean: 6.45 ng/mL) in 39.74% of patients (31 of 78), consistent with ischemic risk factors. Pre-operative lab values also highlighted elevated hemoglobin A1c (> 6.5%) in 41.7% of patients (33 of 78), elevated cholesterol (> 200 mg/dL) in 23.5% (18 of 78), and reduced kidney function (creatinine > 1.2 mg/dL) in 20.83% (16 of 78).

Intraoperatively, ICGA was performed in all cases, providing high-resolution visualization of graft patency and serving as a critical confirmation tool for graft functionality. TTFM confirmed adequate graft flow with a mean flow of 22.5 mL/min and pulsatile index (PI) averaging 2.9. Suboptimal flow and PI values prompted intraoperative revisions in 10.26% of cases (8 of 78 grafts) (e.g., redo TTFM flow: 11.4 mL/min, PI: 2.3). At 30 days post-operatively, lab values showed normalization trends: mean hemoglobin improved to 12.3 g/dL, hematocrit to 36.4%, and creatinine stabilized at 1.08 mg/dL. Ejection fraction data post-surgery will be included in further analyses to evaluate the impact of optimized graft patency on cardiac function.

Ejection fraction data demonstrated a statistically significant improvement post-operatively. The mean pre-operative ejection fraction was 52.1% ($\pm$ 14.3), while the mean post-operative ejection fraction improved to 57.4% ($\pm$ 13.2) (p = 0.001). Given the retrospective, single-arm design of this study, a causal relationship between intraoperative graft assessment and EF improvement cannot be established from these data; this finding is presented descriptively. Contributing factors may include revascularization itself, postoperative medical optimization, and ventricular remodeling.

The average LOS was 5.6 days (range: 3–12). Complications included pleural effusion (5%, 4 of 78), new-onset atrial fibrillation (10%, 8 of 78; no patients had pre-existing AF), and wound infections meeting CDC/NHSN surgical site infection criteria (3%, 2 of 78). There were no perioperative strokes, episodes of acute kidney injury (KDIGO stage $\geq$ 1), perioperative myocardial infarctions, or reoperations for bleeding in this cohort (0%, 0 of 78 each); 30-day mortality was 0% (0 of 78), and all 78 patients (100%) completed 30-day follow-up. A composite MACCE endpoint (death, myocardial infarction, or stroke) occurred in 0 of 78 patients (0%). Patients with severe aortic stenosis or other comorbid conditions demonstrated longer recovery times and required additional interventions, such as PCI and TAVR. Risk factors such as elevated BMI (> 30 kg/m²), diabetes, and high troponin levels were associated with longer LOS and higher complication rates.

As of 2025, some key costs associated with a Robotic CABG at the Tower Health system per case are as follows: Cardiac Robot Pack- \$1788.32, Flo-thru Shunt- \$426.69, IC Green 2.5mg dose- \$79.61. There is no additional per-case cost for TTFM beyond the initial acquisition cost.

Discussion

This study describes the clinical utility of ICGA and TTFM in robotic-assisted CABG of 78 patients, providing high-resolution intraoperative graft assessments that enhance surgical outcomes.

Mean ejection fraction postoperatively after 30 days improved by 5.3% compared to preoperatively with an average length of stay of 5.6 days. Patients presenting for R-MIDCAB, by definition, present with numerous confounding variables¹⁵ making measuring statistically significant patient outcomes post-CABG intricate. These confounding variables and risk factors can include age, sex, and comorbidities¹⁴ that can prolong the length of stay (LOS). The most prominent risk factors in this study associated with increased LOS were elevated BMI, diabetes, and high troponin levels while the most prominent complications that increased LOS were new-onset atrial fibrillation (10%, 8 of 78), followed by pleural effusion (5%, 4 of 78), and wound infections (3%, 2 of 78).

In 10.26% of patients (8 of 78), grafts were revised intraoperatively based on combined TTFM and ICGA findings that fell outside our predefined adequacy thresholds (mean flow < 10 mL/min and/or PI > 5, or evidence of restricted flow on ICGA visualization). The primary indications for revision were an out-of-range TTFM flow or pulsatility index, or visualized kinking of the graft; TTFM findings drove the majority of revision decisions, with ICGA serving as a confirmatory adjunct rather than the primary trigger, and no revisions in this series were based on ICGA findings alone. Because all grafts in this cohort were LIMA-to-LAD, all revisions occurred within the same (anterior/LAD) target territory. These intraoperative assessments allowed for immediate identification and correction of technical issues, such as anastomotic narrowing or graft kinking, before chest closure. By addressing these abnormalities in the operating room, the surgical team likely reduced the risk of postoperative graft failure, ischemic events, and the need for subsequent reinterventions. This proactive approach aligns with prior studies showing that intraoperative graft verification and timely revision can significantly decrease the incidence of post-surgical redo procedures and associated morbidity^{12,13}.

As mentioned earlier, TTFM has been examined in the context of its impact on myocardial function and clinical outcomes in patients undergoing CABG surgery. Patients with optimal TTFM readings had significantly improved postoperative ejection fraction with lower rates of postoperative complications compared to patients with suboptimal readings¹⁶. Despite limited literature on the direct impact of ICGA on postoperative myocardial function, it was established earlier that ICGA allows recognition of graft abnormalities and is associated with higher levels of accuracy than TTFM¹³. A similar association between graft assessment and postoperative myocardial function is plausible for ICGA, though this remains descriptive and has not been directly demonstrated by the present study.

Positive predictive value (PPV) could not be calculated directly from this cohort, since revision decisions were based on the intraoperative TTFM/ICGA findings themselves rather than an independent reference standard (e.g., routine postoperative angiography) applied uniformly to all grafts, precluding identification of false negatives among grafts that were not revised. Reported PPV from the broader

CABG literature is nonetheless instructive. In a systematic review and meta-analysis of TTFM (66 studies, 15,673 grafts), pooled PPV for detecting an abnormal graft ranged from 0.10 to 0.84 (sensitivity 0.25–0.46, specificity 0.94–0.98), and only 25.1% of grafts flagged as abnormal by TTFM were ultimately revised, reflecting a substantial false-positive burden.²⁸ By contrast, in a randomized comparison of ICGA and TTFM against angiographic reference standard, ICGA demonstrated 83.3% sensitivity and 100% specificity for detecting > 50% stenosis or occlusion (versus 25% sensitivity and 98.4% specificity for TTFM), corresponding to a PPV approaching 100% in that study's population.¹³ Because PPV is prevalence-dependent, these values would be expected to differ in a lower-risk robotic LIMA-LAD population such as ours, and none were derived specifically from robotic or totally endoscopic cohorts. If restricted to a single modality, TTFM would be our preference, given its established evidence base, high negative predictive value, quantitative and objective output, and lower cost and procedural burden relative to ICGA; however, because of TTFM's comparatively limited positive predictive value, an isolated abnormal TTFM reading should prompt confirmatory assessment (repeat measurement or ICGA) before proceeding to graft revision.

In a separate propensity-matched hospital cost analysis, robotic-assisted CABG was associated with substantially lower average cost per patient than traditional sternotomy CABG (\$18,726 vs. \$35,580), an association the authors attributed largely to shortened length of stay in the robotic cohort (5 days) compared to the traditional cohort (7 days)¹⁷. Studies have shown that, on average, patients can resume household activities within 10 days and driving within 2–3 weeks after robotic CABG, compared to 4–6 weeks or more in traditional CABG¹⁸. Patients who have undergone robotic CABG also report better overall health and significantly less postoperative pain due to the minimally invasive nature and sternal preservation. Maintaining the sternum is especially beneficial to those with poor wound healing, like patients with diabetes and renal dysfunction¹⁹; a common characteristic of patients undergoing CABG as displayed in our results.

The costs of advanced techniques extend beyond the patient and are often absorbed by the hospital, including expenses related to acquisition, training, and maintenance. TTFM systems have acquisition costs ranging from \$50,000 to \$100,000 USD, with surgical team training costs estimated between \$10,000 and \$20,000 USD, and annual maintenance ranging from \$5,000 to \$8,000 USD²⁰. To visualize ICGA, there are multiple imaging systems that can be used with high variability in costs. Utilizing the robotic platform, the ICG imaging system is built into the current imaging platform, mitigating additional costs.

As of 2016, the reported acquisition costs and per-case usage costs (USD) for other freestanding imaging systems were as follows: SPY Elite: \$250,000; cost per case: \$650, FLARE (Fluorescence-Assisted Resection and Exploration): \$120,000; cost per case: \$109, PDE-NEO (Photodynamic Eye - Near Infrared): \$75,000; cost per case: \$60, Fluobeam 800: \$40,000; cost per case: \$13²¹.

Despite their high upfront costs, these techniques can be widely considered cost-effective due to preventing graft-related complications post-operatively²⁰. ICGA has applications beyond cardiac surgery,

notably in plastic and reconstructive procedures, where it serves as a cost-effective tool for identifying hypoperfusion and reducing postoperative complications²²—demonstrating its value across multiple surgical disciplines within the hospital.

Limitations

Specific limitations to our study included a relatively small patient population of 78 patients from one institution. Variability in protocols and patient demographics across different centers further complicates generalizing these findings. Differing risk profiles and selection criteria mean one institution may proceed with surgery in cases where another might opt for alternative treatments, introducing potential confounding variables. As a result, future endeavors to improve these factors include doing a multicenter program examining larger, more diverse patient populations to account for said risk factors and confounding variables.

As indicated earlier, TTFM is a class IIa recommendation by the ESC and the EACTS⁶, yet fewer than one-quarter of cardiac surgeons routinely use quantitative graft verification techniques and fewer than 2% employ ICGA intraoperatively, likely reflecting high equipment costs, workflow complexity, and limited standardized protocols³, compared to the United States guidelines, where no specific intraoperative graft assessment techniques are formally recommended by the American Heart Association (AHA) or American College of Cardiology (ACC) as standard practice²³. Instead, the United States guidelines emphasize preoperative risk stratification tools, like STS guidelines, to guide revascularization assessments²⁴. By emphasizing the use of ICGA and TTFM over standard Doppler, this research underscores their potential as a precursor to gold standard coronary angiography, reducing the need for additional imaging and graft revision. These techniques also show promise in improving post-operative ejection fraction recovery and overall patient outcomes.

Conclusion

While many surgeons still rely on standard Doppler, visual inspection, or manual palpation, this study demonstrates that utilizing ICGA and TTFM in tandem provides reliable intraoperative data and reduces reliance on post-operative imaging. The findings contribute novel insights into the combined use of ICGA and TTFM in a community hospital setting.

Declarations

Author Contribution

A.M. wrote the main manuscript text and did the analysis N.M. helped write the main manuscript text U.D. helped make major edits and review the manuscript and data All authors reviewed the manuscript

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