

Comparative Diagnostic Performance and Clinical Effectiveness of Intraoperative Quality Control Modalities in Coronary Revascularization: a Systematic Review and Aggregate Comparative Analysis of Real-World Evidence

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ABSTRACT

Intraoperative graft assessment during coronary artery bypass grafting (CABG) aims to identify technical anastomotic defects before chest closure. Transit-time flow measurement (TTFM) and indocyanine green (ICG) fluorescence imaging represent complementary intraoperative assessment modalities, yet their comparative diagnostic performance against angiographic reference standards remains incompletely defined.

PubMed, Scopus, Web of Science Core Collection, and CENTRAL were searched from January 2000 to February 2026 using terms for CABG, ICG, and TTFM; duplicate screening yielded $\kappa = 0.86\text{--}0.91$. Eligible studies evaluated ICG and/or TTFM against invasive coronary angiography or computed tomography coronary angiography. Methodological quality was appraised using QUADAS-2 for diagnostic cohorts and the Newcastle-Ottawa Scale (NOS) for clinical-utility cohorts. Because only three directly comparable cohorts provided sufficiently reliable paired 2×2 data, formal bivariate random-effects meta-analysis was not performed. Verified 2×2 contingency data were summarised descriptively with exact Clopper–Pearson 95% confidence intervals. Clinical-utility evidence was synthesised narratively.

Eighteen unique primary clinical studies were included. Three studies (Desai et al., 2006; Yamamoto et al., 2015; Hatada et al., 2011), comprising 293 paired bypass grafts, provided directly comparable quantitative evidence. ICG demonstrated an aggregate descriptive sensitivity of 76.0% (95% CI, 54.9%–90.6%) and specificity of 99.3% (95% CI, 97.3%–99.9%). TTFM/flowmetry demonstrated aggregate sensitivity of 24.0% (95% CI, 9.4%–45.1%) and specificity of 96.3% (95% CI, 93.2%–98.2%). Formal between-modality P values were not calculated. The aggregate flowmetry estimate includes one cohort using experimental FFT-based waveform analysis (Hatada et al., 2011) and should be interpreted with caution. NOS assessment of six Tier 3 clinical-utility studies yielded scores of 5–9/9; no study provided a complete two-arm comparison with non-zero revision events in both arms, precluding pooled effect estimation.

ICG fluorescence imaging showed higher descriptive sensitivity than TTFM/flowmetry for detecting structural graft abnormalities. A complementary approach combining quantitative flow assessment with selective fluorescence imaging may be considered in appropriately selected situations. Prospective multicenter studies are required before definitive recommendations can be made.

Keywords: Coronary Artery Bypass; Indocyanine Green; Transit-Time Flow Measurement; Diagnostic Test Accuracy; Real-World Evidence.

Introduction

Chronic coronary syndromes are a major clinical manifestation of coronary artery disease and remain an important cause of morbidity worldwide [1,2]. In patients presenting with left main trunk lesions or extensive multivessel disease, surgical revascularization using CABG functions as a vital treatment pillar, and has been associated with better survival outcomes than percutaneous interventions in these settings [1-3]. Long-term graft performance hinges on both surgical execution and immediate conduit patency at the time of the procedure [2]. Despite careful surgical execution, early graft failure within the first postoperative year occurs in approximately 10%–15% of venous conduits and 3%–5% of arterial grafts [2,4]. Technical problems such as anastomotic narrowing, intimal dissection, suture-related obstruction, and conduit kinking are among the main causes of early graft occlusion [3,5]. Graft dysfunction occurring during this period may subsequently contribute to perioperative myocardial infarction, greater intensive care utilization, and hospital readmission [3,6].

Intraoperative graft assessment is therefore used to identify technical problems before completion of the procedure, with transit-time flow measurement (TTFM) representing one of the established approaches [1,7]. TTFM provides quantitative measurements of graft function, including average conduit flow volume (MGF), waveform pulsatility index (PI), and relative diastolic flow fraction (DF) [7,8]. Its main limitation is that flow measurements do not provide direct information about graft morphology. Consequently, a localized stenosis or conduit kink may remain undetected when overall flow appears satisfactory under otherwise stable systemic hemodynamic conditions [8,9].

Competitive flow from a moderately diseased native coronary artery can further influence TTFM measurements and may result in falsely concerning values, potentially prompting unnecessary re-exploration despite a patent anastomosis [9,10].

Indocyanine green (ICG) fluorescence imaging offers a complementary means of assessing grafts during surgery [11,12]. Upon intravenous injection, ICG rapidly associates with circulating plasma albumin, emitting near-infrared fluorescence (NIR-I spectrum) when stimulated by optical excitation. This permits direct visualization of conduit opacification, anastomotic integrity, and regional myocardial perfusion without exposure to ionizing radiation [12,13]. The technique may also be useful during minimally invasive or robotic procedures, where it can facilitate identification of intramyocardial target vessels before dissection [14].

Despite increasing clinical use, the role of ICG within formal intraoperative graft-assessment algorithms remains incompletely defined, partly as existing clinical data stem primarily from heterogeneous observational cohorts [10,11,15]. Quantitative evidence synthesis based on angiographic reference standards is also limited. We therefore conducted a systematic review and aggregate comparative analysis to examine the diagnostic performance and clinical utility of ICG and TTFM for intraoperative graft assessment.

Methods

Study Design and Protocol Registration

This systematic review was conducted and reported in accordance with PRISMA 2020 and PRISMA-DTA guidelines [35] (Figure 1). Research questions were formulated using

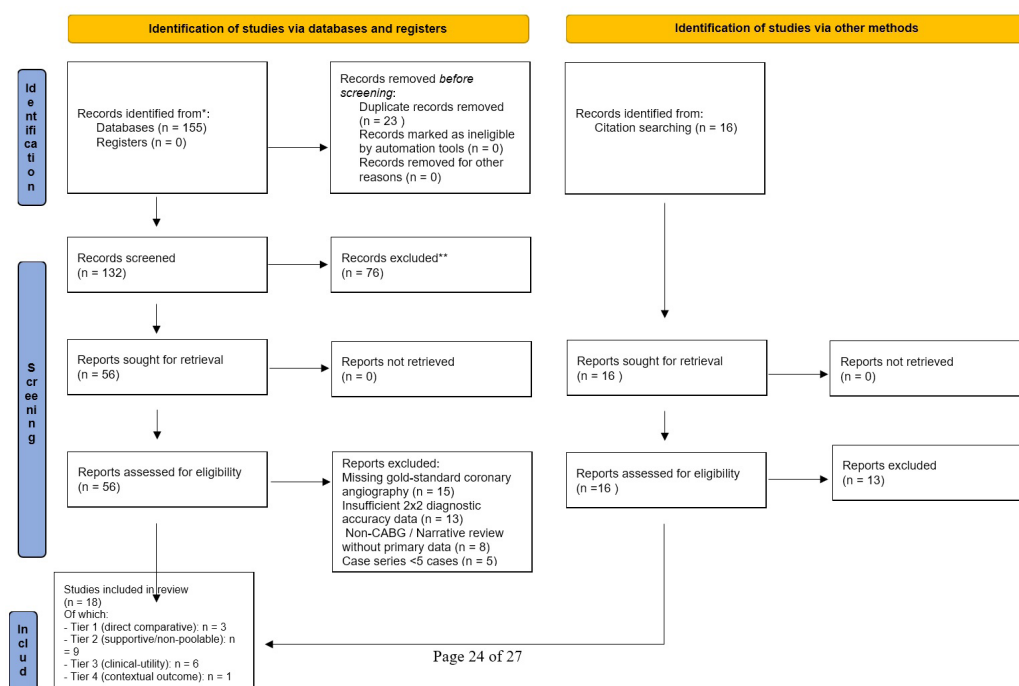


Figure 1 – PRISMA 2020 flow diagram illustrating study identification, screening, eligibility assessment, and inclusion of 18 unique primary clinical studies across four analytical evidence domains

the PICO framework. The study protocol was registered retrospectively with the Open Science Framework (OSF Registries: <https://osf.io/5kbqw/>). Retrospective registration is acknowledged as a methodological limitation (Section 5, item 7).

Eligibility Criteria

Only original primary clinical studies were eligible for inclusion in the evidence synthesis. Systematic reviews, narrative reviews, guidelines, and secondary publications were used exclusively for backward and forward citation searching and were not treated as independent primary studies.

Because included studies differed substantially in methodological structure, evidence was classified into four analytical evidence domains (not mutually exclusive):

(1) Directly comparable diagnostic evidence: studies in which ICG and TTFM/flowmetry were assessed concurrently on the same grafts, an angiographic reference standard was available, and sufficiently reliable 2×2 contingency data could be reconstructed.

(2) Supportive/non-poolable diagnostic evidence: studies evaluating ICG or TTFM against angiographic or other anatomical reference standards but lacking sufficiently reliable paired 2×2 data, involving incomplete or decision-based verification, or evaluating only one modality.

(3) Clinical-utility and decision-making evidence: observational or comparative cohorts evaluating intraoperative revision, revision avoidance, or the role of one modality in resolving discordant findings.

(4) Broader contextual outcome evidence: studies examining patient-level clinical or healthcare-utilisation outcomes not designed to assess graft-level diagnostic accuracy.

Index-test thresholds were retained as reported in primary studies. Common TTFM criteria included MGF <15 mL/min (arterial) or <20 mL/min (venous), PI >5.0, DF <50%, or experimental waveform distortion. ICG abnormalities were defined as anastomotic contrast interruption, visible stenosis ≥50%, or localised epicardial perfusion defect. The reference standard comprised invasive coronary angiography or CT coronary angiography. Structural graft abnormality was defined using angiographic evidence of significant stenosis (≥50% diameter reduction), occlusion, or technically relevant graft abnormality (FitzGibbon Grade B or O where specified [30]).

Exclusion criteria: case reports (<5 cases), editorials, non-human studies, and publications lacking sufficient information to assess diagnostic performance or clinical utility.

Information Sources and Search Strategy

Electronic databases (PubMed/MEDLINE, Scopus, Web of Science Core Collection, and CENTRAL) were searched from 1 January 2000 to 28 February 2026. Search terms combined concepts relating to CABG, ICG/near-infrared fluorescence, TTFM, coronary angiography, graft patency, diagnostic accuracy, and revision. Grey literature (OpenGrey, conference proceedings from EACTS, STS, and AATS) was additionally screened. Citation tracking was performed via Research Rabbit.

Study Selection and Data Extraction

Screening and selection were performed independently in duplicate by two reviewers (I.A. and A.G.) using Rayyan.ai. Inter-rater agreement was excellent: $\kappa = 0.86$ (95% CI: 0.78–0.94) at title/abstract stage and $\kappa = 0.91$ (95% CI: 0.83–0.98)

at full-text stage. Discrepancies were resolved by consensus with a senior adjudicator (O.T.). A standardised data extraction form was used, recording sample size, conduit type, index-test definitions and thresholds, reference-standard characteristics, verification timing, and available diagnostic contingency data. Diagnostic data were re-examined against original primary reports before quantitative synthesis.

Quality Appraisal and Statistical Analysis

Methodological quality of diagnostic accuracy studies was evaluated using the QUADAS-2 tool [36].

Three studies—Desai et al. (2006), Yamamoto et al. (2015), and Hatada et al. (2011) — provided sufficiently reliable paired 2×2 information for direct comparative quantitative synthesis, comprising 293 paired grafts. Because the number of directly comparable studies was small ($k = 3$) and zero cells were present at the study level (Hatada et al.: 0 true positives for ICG), a formal hierarchical bivariate random-effects model (Reitsma approach) was deemed statistically unstable and prone to overparameterisation. Consequently, formal bivariate modelling was not performed. No SROC curve is presented. A Spearman threshold-effect correlation was not calculated as it is not interpretable with three data points.

Instead, study-level TP, FP, FN, and TN counts were summed across the three directly comparable cohorts. Aggregate sensitivity and specificity were calculated from the resulting contingency tables with exact Clopper–Pearson 95% CIs, computed in RStudio (R version 4.6.0). The resulting aggregate proportions are descriptive and should not be interpreted as model-based pooled estimates. No formal between-modality statistical test was performed.

Clinical-utility studies were analysed descriptively. No common risk ratio was calculated. Formal publication-bias funnel-plot testing was not performed ($k = 3$, below any meaningful threshold).

Results

Study Selection and Evidence Stratification

The electronic search identified 155 database records and 16 citation-identified records. After removal of 23 duplicates, 148 records underwent title and abstract screening. Ninety-two records were excluded, and 56 full-text reports were assessed for eligibility. Thirty-eight reports were excluded for predefined reasons, leaving 18 unique primary clinical studies for qualitative synthesis (Figure 2).

The included evidence was organised into four analytical domains (not mutually exclusive, as Waseda et al. contributed both diagnostic and clinical decision-making information). Three studies provided directly comparable paired diagnostic evidence (293 grafts). Nine studies provided supportive or non-poolable diagnostic evidence. Six studies provided clinical-utility evidence. One additional study (Sosa et al., 2023) provided broader patient-level healthcare-utilisation evidence.

Methodological Quality (QUADAS-2)

Methodological quality appraisal using the QUADAS-2 tool revealed nuanced risk-of-bias and applicability profiles across primary diagnostic cohorts (Figure 3 and Supplementary Figure S1).

In the patient selection domain, 83% of cohorts demonstrated low risk, with high risk identified in one study (Hatada et al., 2011) due to enrollment restricted to a small series of vein conduits. For the index test domain, low risk was observed in 67% of cohorts, while unclear (17%) and high risk

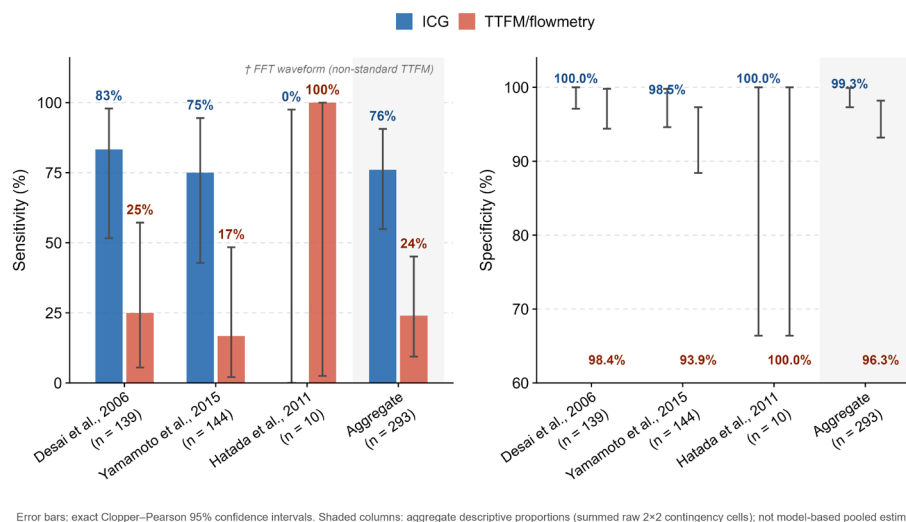


Figure 2 – Study-level descriptive sensitivity and specificity of ICG fluorescence imaging and TTFM/flowmetry across the three directly comparable cohorts (Desai et al., 2006; Yamamoto et al., 2015; Hatada et al., 2011; 293 paired grafts) and aggregate data. Error bars represent exact Clopper–Pearson 95% confidence intervals. No model-based summary estimate is displayed

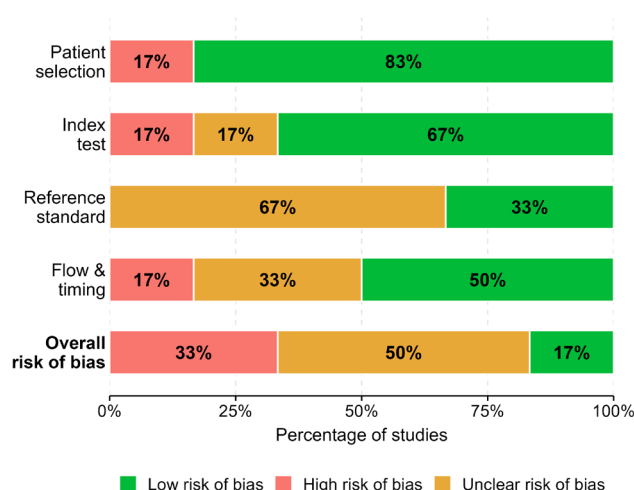


Figure 3 – QUADAS-2 risk-of-bias and applicability summary plot across included diagnostic studies. High risk of patient selection bias documented for Hatada et al. (2011); applicability concerns for Yamamoto et al. (2015) due to delayed one-year angiographic verification.

(17%) reflected non-standard waveform distortion analysis or qualitative threshold subjectivity.

Importantly, in the reference standard domain, low risk was established in only 33% of cohorts (on-table intraoperative angiography), whereas 67% were classified as unclear risk due to post-discharge verification or hybrid imaging protocols. Flow and timing demonstrated high risk in 17% of studies, directly driven by protocolized 1-year follow-up intervals (Yamamoto et al., 2015), where late conduit remodeling cannot be differentiated from acute technical error. Overall, only one cohort (Desai et al., 2006, 17%) demonstrated a low overall risk of bias across all domains, while 50% exhibited unclear risk and 33% high risk of bias.

NOS assessment of six Tier 3 clinical-utility studies yielded scores ranging from 5/9 (Balacumaraswami et al. 2005; Kuroyanagi et al. 2012) to 9/9 (Usta et al. 2025); full domain breakdown is provided in Supplementary Table S1.

Direct Comparative Diagnostic Evidence (Tier 1)

Three studies provided directly comparable paired data (Table 1). Desai et al. (2006) included 139 grafts with

postoperative angiography on day 4. ICG detected 10/12 defects (sensitivity 83.3%, specificity 100.0%); TTFM detected 3/12 (sensitivity 25.0%, specificity 98.4%). Yamamoto et al. (2015) evaluated 144 grafts at approximately one-year follow-up. Reconstructed 2×2 data yielded ICG sensitivity 75.0% and specificity 98.5%; TTFM sensitivity 16.7% and specificity 93.9%. Hatada et al. (2011) evaluated 10 saphenous vein grafts using experimental FFT-based waveform analysis; ICG did not identify the single stenosed graft (sensitivity 0.0%, specificity 100.0%), whereas the FFT analysis detected it (sensitivity 100.0%, specificity 100.0%).

Aggregate descriptive synthesis: Summing raw 2×2 cells across 293 paired grafts yielded — ICG: TP=19, FP=2, FN=6, TN=266; sensitivity 76.0% (95% CI, 54.9%–90.6%) and specificity 99.3% (95% CI, 97.3%–99.9%). TTFM/flowmetry: TP=6, FP=10, FN=19, TN=258; sensitivity 24.0% (95% CI, 9.4%–45.1%) and specificity 96.3% (95% CI, 93.2%–98.2%). These values are descriptive aggregate proportions and should not be interpreted as model-based pooled estimates or evidence of statistically tested superiority. The aggregate flowmetry estimate includes the experimental FFT-based Hatada cohort.

Table 1 Comparable Head-to-Head Diagnostic Cohorts (Tier 1)

Study	N grafts	Reference standard & timing	ICG TP/FP/FN/TN	ICG Se (95% CI)	ICG Sp (95% CI)	TTFM/flowmetry TP/FP/FN/TN	TTFM/flowmetry Se (95% CI)	TTFM/flowmetry Sp (95% CI)	Key note
Desai et al., 2006	139	Postoperative angiography, day 4	10/0/2/127	83.3% (51.6–97.9%)	100.0% (97.1–100.0%)	3/2/9/125	25.0% (5.5–57.2%)	98.4% (94.4–99.8%)	Direct paired comparison; on-pump and off-pump CABG
Yamamoto et al., 2015	144	Fluoroscopic angiography, ~1 year	9/2/3/130	75.0% (42.8–94.5%)	98.5% (94.6–99.8%)	2/8/10/124	16.7% (2.1–48.4%)	93.9% (88.4–97.3%)	Delayed verification; 2×2 reconstructed from primary data
Hatada et al., 2011	10	Postoperative angiography (<30 days)	0/0/1/9	0.0% (0.0–97.5%)	100.0% (66.4–100.0%)	1/0/0/9	100.0% (2.5–100.0%)	100.0% (66.4–100.0%)	Experimental FFT waveform analysis; 10 SVGs only
Aggregate	293 paired grafts	Angiographic reference standards	19/2/6/266	76.0% (54.9–90.6%)	99.3% (97.3–99.9%)	6/10/19/258	24.0% (9.4–45.1%)	96.3% (93.2–98.2%)	Descriptive aggregate; not model-based. Flowmetry estimate includes FFT cohort — interpret cautiously

Note: TP = true positive; FP = false positive; FN = false negative; TN = true negative; Se = sensitivity; Sp = specificity; CI = confidence interval; SVG = saphenous vein graft; FFT = fast Fourier transformation. Aggregate proportions calculated from summed raw 2×2 cells with exact Clopper–Pearson 95% CIs. The aggregate flowmetry estimate includes the experimental FFT-based Hatada cohort and should not be interpreted as a homogeneous estimate of conventional MGF/PI-based TTFM.

Table 2 Supportive and Non-Poolable Diagnostic Evidence (Tier 2)

Study	Sample	Modality	Reference standard	Reason for non-pooling
Waseda et al., 2009	116 pts / 289 analyzed grafts (507 screened)	ICG + TTFM	Postoperative angiography (~13.5 days)	Decision-dependent verification prevented independent 2×2 reconstruction
Handa et al., 2009	39 pts / 116 grafts	CCD-ICG + TTFM	Follow-up angiography (subgroup)	Complete paired cell-level data against a common reference standard unavailable for the full cohort
Di Giammarco et al., 2014	333 pts / 717 grafts	TTFM + HR-ECUS	HR-ECUS with selective angiography	No ICG index test; retained as evidence for multimodal morphological assessment
Tokuda et al., 2007	123 pts / 261 grafts	TTFM alone	Postoperative angiography (<3 months)	TTFM-only threshold-derivation study; no ICG comparator
Walker et al., 2013	160 pts / 160 grafts	TTFM alone	Angiographic assessment	TTFM-only; no ICG comparator
Jokinen et al., 2011	75 pts / 204 grafts	TTFM alone	Early postoperative angiography	TTFM-only; no ICG
Lehnert et al., 2015	CABG cohort / coronary anastomoses	TTFM alone	1-year follow-up angiography	TTFM-only; delayed reference standard; no ICG
Taggart et al., 2003	84 pts / 213 conduits	ICG (SPY) alone	Clinical/selective angiography	ICG-only feasibility cohort; no paired TTFM
Reuthebuch et al., 2004	38 pts / 107 grafts	ICG (SPY) alone	Clinical inspection/ selective revision	ICG-only observational series; no systematic TTFM

Table 3 Clinical-Utility and Surgical Decision-Making Evidence (Tier 3)

Study	Cohort	Main observation	Interpretation
Balacumaraswami et al., 2005	100 pts / 266 grafts	18 grafts had persistently unfavorable TTFM; 10 had satisfactory ICG and were not revised	ICG provided additional information in flowmetry-discordant cases
Waseda et al., 2009	116 pts / 289 analyzed grafts	ICG identified 6 failures missed by TTFM; 20/21 grafts with poor TTFM but satisfactory ICG were patent on follow-up	Supports complementary use; not an independent diagnostic 2×2 estimate
Kuroyanagi et al., 2012	159 pts / 435 grafts	12 grafts revised after abnormal TTFM; ICG used for post-revision patency assessment	Sequential single-arm workflow; no TTFM-only control group
Usta et al., 2025	70 pts; 35 TTFM-only vs 35 TTFM+ICG	Zero graft revisions in either group	Comparative study; zero-event outcome prevents RR estimation
Hol et al., 2004	186 pts / 427 grafts	18 grafts (4.2%) revised following intraoperative angiography	Contextual benchmark for angiography-directed revision rate
Becit et al., 2007	200 pts; 100 control vs 100 TTFM group; 303 grafts assessed by TTFM	9 grafts (2.97%) revised based on unsatisfactory TTFM; no ICG used	TTFM-only study; contextual evidence for flowmetry-directed revision in on-pump CABG

Note: TTFM = transit-time flow measurement; ICG = indocyanine green; MGF = mean graft flow; PI = pulsatility index. Becit et al. (2007): TTFM-only study; ICG not used; DOI corrected to <https://doi.org/10.1016/j.ejcts.2007.04.037>. No pooled risk ratio was calculated across Tier 3 studies.

Note on reference-standard timing heterogeneity: The three contributing cohorts differ substantially in verification timing. Desai et al. (2006) and Hatada et al. (2011) employed early perioperative angiography (postoperative day 4 and <30 days, respectively), enabling direct attribution of graft abnormalities to intraoperative technical events. Yamamoto et al. (2015) used angiography at approximately one year, a timepoint at which biological processes — including intimal hyperplasia and competitive-flow remodelling — contribute to graft status independently of acute surgical error. These studies therefore do not measure exactly the same clinical construct, and the aggregate estimates should be interpreted with this heterogeneity explicitly in mind. The Yamamoto cohort's contribution is flagged as high risk of bias in the flow and timing domain of the QUADAS-2 assessment (Figure 3 and Supplementary Figure S1).

Supportive and Non-Poolable Diagnostic Evidence (Tier 2)

Nine studies provided supportive or non-poolable diagnostic evidence (Table 2). Waseda et al. (2009) assessed 289 grafts from 116 patients; decision-dependent verification prevented independent 2×2 reconstruction. Handa et al. (2009) evaluated 116 grafts in 39 patients; complete paired cell-level data against a common reference standard were unavailable for the full cohort. Di Giammarco et al. (2014) evaluated 717 grafts using TTFM and HR-ECUS without ICG. TTFM-only studies (Tokuda et al. 2007; Walker et al. 2013; Jokinen et al. 2011; Lehnert et al. 2015) and ICG-only feasibility cohorts (Taggart et al. 2003; Reuthebuch et al. 2004) are retained as supportive evidence.

Clinical Utility and Surgical Decision-Making Evidence (Tier 3)

Important note on evidence type: The studies presented in this section constitute clinical decision-making evidence (Tier 3) and should be interpreted entirely separately from the diagnostic accuracy findings reported in the Tier 1 section above. These cohorts were not designed to establish diagnostic sensitivity or specificity, and no 2×2 contingency data from Tier 3 studies contribute to the aggregate diagnostic estimates. The outcomes described here reflect intraoperative surgical decision-making rather than index-test performance against an independent reference standard.

Six studies reported decision-making data (Table 3). Balacumaraswami et al. (2005) evaluated 266 grafts; ICG demonstrated satisfactory opacification in 10 of 18 grafts with unfavorable TTFM, and revision was withheld. Waseda et al. (2009) demonstrated discordance between TTFM and ICG, with angiographic verification supporting fluorescence-guided decisions. Kuroyanagi et al. (2012) used ICG for post-revision patency confirmation in a sequential workflow. Usta et al. (2025) reported zero revisions in both arms (TTFM-only vs TTFM+ICG), precluding risk ratio estimation. Hol et al. (2004) reported 18/427 grafts (4.2%) revised following intraoperative angiography [28]. Becit et al. (2007) assessed 303 grafts by TTFM (Group B, 100 patients); 9 grafts (2.97%) required revision; ICG was not used [29].

No pooled risk ratio was calculated. Descriptively, adjunctive ICG imaging provided visual reassurance when TTFM findings were ambiguous. These observations reflect surgical decision-making patterns, not proven causal treatment effects. Formal risk-of-bias assessment of Tier 3 studies using ROBINS-I was not performed; this is acknowledged as a limitation.

Broader Healthcare-Utilisation Evidence (Tier 4)

Sosa et al. (2023) examined 230,506 adult CABG patients (treatment group n=1,965 NIRF with ICG). After 1:3 propensity score matching, NIRF imaging was associated with lower odds of 90-day all-cause emergency department use (adjusted OR 0.84; 95% CI, 0.73–0.96; P=0.009) [34]. These are patient-level healthcare-utilisation data, not directly comparable with graft-level diagnostic accuracy. Importantly, this study was funded by Stryker Corporation, a manufacturer of NIRF imaging systems, and several authors disclosed employment or consultancy relationships with the sponsor. This conflict of interest should be considered when interpreting the reported association.

Discussion

Principal Findings

This systematic review provides a source-verified synthesis of intraoperative ICG fluorescence imaging and TTFM/flowmetry for CABG graft assessment. Only three primary studies provided sufficiently comparable paired diagnostic data comprising 293 grafts. In this limited evidence base, the descriptive aggregate sensitivity of ICG was higher than that of TTFM/flowmetry (76.0% vs. 24.0%), while both modalities demonstrated high descriptive specificity. These findings should not be interpreted as formal statistical evidence of superiority. No bivariate random-effects model, SROC curve, or pooled risk ratio was calculated.

Diagnostic Interpretation and Verification Timing

TTFM measures volumetric blood flow and may be influenced by systemic haemodynamics, distal resistance, and competitive native coronary flow. ICG provides optical visualisation of contrast passage and distal perfusion. Reference-standard timing represents an important source of heterogeneity: Desai et al. used early postoperative angiography (day 4); Yamamoto et al. used angiography at approximately one year, which may capture biological processes including graft remodelling and intimal hyperplasia in addition to intraoperative technical flaws. Diagnostic performance estimates from these studies should not be regarded as measuring exactly the same clinical construct [12].

Resolving the competitive flow dilemma

Regarding competitive flow, native circulation in moderately stenosed coronary arteries frequently depresses TTFM flow values [9,10]. By confirming unimpeded graft opacification and downstream tissue perfusion, ICG may serve as a complementary anatomical assessment when quantitative flowmetry produces an equivocal result, potentially supporting decisions to withhold revision in the absence of morphological abnormality [10,15]. Preventing unnecessary high-risk surgical revisions or early graft occlusions may be associated with reduction in perioperative myocardial injury and postoperative resource utilisation [3,6]. In minimally invasive and robotic CABG, pre-anastomotic ICG imaging may facilitate localisation of intramural coronary arteries, potentially reducing the risk of inadvertent right ventricular injury during myotomy [14]. More broadly, routinely integrating multimodal verification technologies into surgical workflows requires overcoming institutional inertia, equipment availability barriers, and standardized interpretation challenges [27].

Limitations

1. Limited directly comparable evidence: Only three studies provided sufficiently reliable paired diagnostic data, comprising 293 grafts.

2. Heterogeneity of flowmetry methods: One of the three directly comparable studies used experimental FFT-based waveform analysis rather than conventional MGF/PI-based TTFM. The aggregate comparator estimate should not be interpreted as a homogeneous standard-TTFM estimate.

3. Reference-standard heterogeneity: Verification ranged from early postoperative angiography to approximately one-year follow-up, capturing different biological processes.

4. Graft-level analysis and within-patient clustering: The quantitative synthesis was performed at the graft level; adjustment for within-patient clustering was not possible. Precision estimates should be interpreted cautiously.

5. Reconstruction of published data: Some diagnostic cells were reconstructed from published numerical information; reconstructions were included only when the underlying data permitted sufficiently reliable derivation.

6. Non-poolable clinical-utility evidence: Clinical-utility studies differed in design, decision pathways, denominators, revision criteria, and follow-up, precluding a common causal effect estimate. Formal risk-of-bias assessment of Tier 3 studies using ROBINS-I was not performed.

7. Retrospective protocol registration: The review protocol was registered retrospectively with OSF.

8. Limited assessment of small-study effects: Formal funnel-plot testing was not undertaken ($k = 3$).

Conclusion

In the limited directly comparable evidence base, indocyanine green fluorescence imaging demonstrated higher descriptive sensitivity than TTFM/flowmetry for detecting structural graft abnormalities, while both modalities demonstrated high descriptive specificity. The available clinical-utility literature suggests that ICG may provide complementary anatomical information when TTFM findings are ambiguous.

A complementary approach combining quantitative flow assessment with selective anatomical fluorescence imaging may be considered in appropriately selected intraoperative situations. Prospective multicenter studies using standardised index-test thresholds, prespecified reference standards, patient-level analysis, and clinically meaningful outcomes are required to determine the incremental value of multimodal graft assessment.

The complementary approach described here represents a conceptual framework informed by expert synthesis of the available literature; it is not an evidence-based clinical guideline and has not been validated in prospective outcome studies. Formal guideline recommendations await prospective multicenter data with standardised protocols, patient-level analysis, and clinically meaningful endpoints.

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Supplementary materials

The Supplementary information includes:

- Supplementary Figure S1. Study-level QUADAS-2 traffic-light plot showing domain-specific risk-of-bias and applicability judgements. Waseda et al., Handa et al., and Di Giammarco et al. contributed to Tier 2 (supportive/non-poolable) evidence only;

- Supplementary Table S1. Newcastle-Ottawa Scale (NOS) Risk-of-Bias Assessment for Tier 3 Clinical-Utility Studies.

These supplementary materials have been provided by the authors to give readers additional information about their work.

The files can be accessed using links: <https://www.editorialpark.com/download/article-supp/796/SupplementaryFigureS1.png> and <https://www.editorialpark.com/download/article-supp/797/SupplementaryTableS1.docx>.

Author Contributions: Conceptualization, A.Yel. and A.T. (Almas Tolegenuly); methodology, A.Yel. and A.T.; validation, A.T.; formal analysis, A.Yel. and A.Yer.; investigation, A.Yel.; resources, A.T.; data curation, A.Yel.; writing – original draft preparation, A.Yel. A.A.; writing – review and editing, A.Yel. and A.C.; visualization, A.Yel.; supervision, A.T. and S.L.; project administration, A.T. and A.Abdr.; funding acquisition – not applicable. All authors have read and agreed to the published version of the manuscript.

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Data availability statement: All quantitative data extracted and analyzed during this study, as well as the RStudio statistical scripts, are included within the published manuscript and its supplementary information files.

Artificial Intelligence (AI) Disclosure Statement: During manuscript preparation, artificial intelligence technologies were limited strictly to linguistic editing and proofreading. AI systems were not applied for data analysis, statistical modeling, or creating scientific statements. All text and findings were critically evaluated and verified by the authors.

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