



Intracardiac Echocardiography vs. Transesophageal Echocardiography for Left Atrial Appendage Occlusion Guidance: A Systematic Review and Meta-Analysis

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Abstract

Background: Intracardiac echocardiography (ICE) is increasingly used as an alternative to transesophageal echocardiography (TEE) for guidance of left atrial appendage occlusion (LAAO), particularly to reduce dependence on general anesthesia. However, comparative evidence regarding procedural efficiency, safety, and follow-up outcomes remains heterogeneous.

Objective: To compare the effectiveness and safety of ICE-guided versus TEE-guided LAAO.

Methods: A systematic review and meta-analysis was conducted in accordance with PRISMA 2020. PubMed/MEDLINE, Embase, Scopus, Web of Science, and the Cochrane Library were searched for comparative studies of ICE- and TEE-guided percutaneous LAAO. Thirteen studies met the eligibility criteria. Outcomes included technical success, procedure duration, fluoroscopy time, contrast volume, periprocedural complications, thromboembolic events, device-related thrombus, mortality, peri-device leak, and residual iatrogenic atrial septal defect. Random-effects models were used for quantitative synthesis.

Results: Technical success was comparable between ICE and TEE (RR 1.01, 95% CI 1.00–1.02; $P=0.24$; $I^2=0\%$). No significant differences were observed in procedure duration (MD -7.12 minutes, 95% CI -16.69 to 2.46), fluoroscopy time, or contrast volume. Pericardial effusion/tamponade was numerically more frequent with ICE but was not statistically significant (RR 1.48, 95% CI 0.96–2.26). Bleeding, vascular complications, and device embolization were similar between groups. Stroke, device-related thrombus, and all-cause mortality also showed no significant differences. ICE was associated with a higher incidence of residual iatrogenic atrial septal defect, while significant peri-device leak and complete LAA sealing were comparable.

Conclusion: ICE-guided LAAO provides technical and clinical outcomes broadly comparable to TEE-guided procedures and offers the practical advantage of reduced reliance on general anesthesia. Potential increases in pericardial effusion and residual iatrogenic atrial septal defect warrant attention, particularly during early operator experience. ICE represents a viable alternative to TEE in appropriately selected patients and experienced centers.

Keywords: Intracardiac echocardiography; Transesophageal echocardiography; left atrial appendage occlusion; Atrial fibrillation; ICE; TEE; systematic review; Meta-analysis.

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Introduction

Atrial fibrillation (AF) is a major cause of cardioembolic stroke and is associated with substantial morbidity and mortality. In patients with non-valvular AF, the left atrial appendage (LAA) represents the predominant site of intracardiac thrombus formation because of its complex anatomy and reduced blood flow during atrial dysfunction [1]. Oral anticoagulation remains the standard strategy for stroke prevention; however, long-term treatment may not be suitable for patients with major bleeding, a high bleeding risk, or contraindications to anticoagulant therapy. Percutaneous left atrial appendage occlusion (LAAO) has therefore emerged as an alternative stroke-prevention strategy in appropriately selected patients. Current clinical guidelines consider percutaneous LAAO reasonable for patients with moderate-to-high thromboembolic risk who have a non-reversible contraindication to long-term oral anticoagulation [2]. Randomized studies, including PROTECT AF and PREVAIL, have also established the clinical feasibility of mechanical LAA closure as an alternative to long-term warfarin therapy in selected patients with non-valvular AF [3,4].

Accurate intraprocedural imaging is essential during LAAO because it assists with transseptal puncture, assessment of LAA anatomy, device sizing, positioning, deployment, identification of peri-device leak, and detection of immediate complications. Transesophageal echocardiography (TEE) has traditionally been the principal imaging modality used to guide LAAO and was employed in pivotal trials evaluating transcatheter LAA closure devices. Despite its established role and excellent visualization of the LAA, TEE commonly requires deep sedation or general anesthesia and the presence of additional personnel with expertise in echocardiographic imaging. These requirements may increase procedural complexity and resource utilization and may be unsuitable for patients with esophageal disease or increased anesthetic risk [5]. Intracardiac echocardiography (ICE) has increasingly been evaluated as an alternative intraprocedural imaging strategy. ICE allows real-time visualization from within the heart and can facilitate transseptal access, assessment of the LAA, device positioning, and evaluation of the final device result without routine use of general anesthesia. Early comparative experience demonstrated that ICE-guided LAAO could achieve technical and procedural success rates comparable with those obtained under TEE guidance. In a cohort comparing left atrial ICE with TEE, Nielsen-Kudsk et al. reported technical success of approximately 99% with both approaches, while ICE allowed procedures to be performed under local anesthesia [6]. Similarly, an Italian multicenter registry including 604 LAAO procedures found procedural success rates of at least 94% with both modalities and no significant difference in overall major procedural complications [7].

Evidence supporting ICE has subsequently expanded across different devices and clinical settings. In the Amulet Observational Study, implantation success exceeded 99% in both ICE- and TEE-guided procedures, while follow-up LAA closure and major clinical event rates were comparable between the groups [8]. More contemporary experience with the Watchman FLX has also demonstrated high technical success with either imaging strategy. A large analysis of the U.S. SURPASS registry reported successful Watchman FLX implantation in 98.3% of ICE-guided and 97.6% of TEE-guided cases, with similar complete seal rates at 45 days. ICE guidance was associated with substantially less use of general anesthesia; however, a higher rate of pericardial effusion requiring intervention was observed, highlighting the importance of procedural experience and careful evaluation of safety outcomes [9]. Despite increasing adoption of ICE, uncertainty remains regarding whether it provides procedural and clinical outcomes equivalent to those of TEE across diverse populations, device types, and institutional settings. Previous comparative studies have reported inconsistent findings concerning procedure duration, fluoroscopy exposure, contrast requirements, pericardial effusion, vascular complications, residual iatrogenic atrial septal defects, peri-device leak, and longer-term thromboembolic events [7-9]. Recent meta-analyses have generally suggested comparable overall effectiveness between the two imaging strategies, but some have identified higher rates of specific complications, particularly pericardial effusion and residual interatrial shunting, among ICE-guided procedures [10,11]. These variations emphasize the need for a comprehensive evaluation of both effectiveness and safety rather than assessment of procedural success alone. Therefore, this systematic review and meta-analysis aimed to compare intracardiac echocardiography with transesophageal echocardiography for guidance of left atrial appendage occlusion. The analysis focused on procedural and technical success, procedural efficiency, imaging and device-related outcomes, periprocedural complications, and subsequent clinical outcomes to provide an integrated assessment of the relative effectiveness and safety of the two imaging strategies.

Methods

This systematic review and meta-analysis was designed to compare intracardiac echocardiography (ICE) with transesophageal echocardiography (TEE) for procedural guidance during left atrial appendage occlusion (LAAO). The review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [12]. The research question was formulated using the Population, Intervention, Comparator, and Outcomes (PICO) framework. The population consisted of adult patients undergoing percutaneous LAAO; the intervention was ICE-guided

LAAO; the comparator was TEE-guided LAAO; and the outcomes included procedural success, procedural efficiency, imaging findings, device-related outcomes, periprocedural complications, and clinical follow-up events.

Studies were considered eligible if they included adult patients undergoing percutaneous LAAO and directly compared ICE-guided procedures with TEE-guided procedures. Randomized controlled trials and prospective or retrospective comparative observational studies were eligible for inclusion. Studies were required to report at least one relevant procedural, safety, imaging, or clinical outcome separately for the ICE and TEE groups. Studies evaluating different commercially available LAAO devices were eligible, provided that ICE and TEE were used as the principal intraprocedural imaging modalities. Case reports, case series without a comparator group, single-arm studies, reviews, meta-analyses, editorials, conference abstracts without sufficient outcome data, animal studies, and studies involving surgical rather than percutaneous LAA exclusion were excluded. When multiple publications reported overlapping patient populations, the most comprehensive or most recent dataset was selected, while additional reports were considered only when they provided unique outcomes. A comprehensive literature search was planned across PubMed, Embase, Scopus, Web of Science, and the Cochrane Library from database inception through the final search date. The search strategy combined controlled vocabulary and free-text terms related to “left atrial appendage occlusion,” “left atrial appendage closure,” “intracardiac echocardiography,” “ICE,” “transesophageal echocardiography,” and “TEE.” Boolean operators AND and OR were used to combine search concepts. Reference lists of eligible studies and relevant systematic reviews were also examined to identify additional comparative studies not captured by the electronic search. No restriction based on geographical location was applied. The complete search strategy for each database was planned for presentation in the supplementary material. The exact final search date should be entered after the database searches used for the submitted meta-analysis have been completed.

All records identified through the database searches were imported into reference-management software and duplicate records were removed. Two reviewers independently screened titles and abstracts and subsequently assessed potentially eligible articles in full text. Disagreements regarding eligibility were resolved through discussion and, when necessary, consultation with a third reviewer. Reasons for exclusion at the full-text stage were documented, and the selection process was summarized using a PRISMA flow diagram. Data were independently extracted using a standardized extraction form. Extracted information included first author, publication year, country, study design, sample size, numbers of patients in the ICE and TEE groups, patient

age, sex, thromboembolic and bleeding risk scores where reported, LAAO device type, procedural characteristics, follow-up duration, and all relevant outcome data. When adjusted estimates were reported, adjusted effect measures and the variables included in the adjustment models were also recorded. The principal effectiveness outcome was successful LAAO device implantation or procedural success as defined by the individual studies. Procedural efficiency outcomes included total procedure duration, fluoroscopy time, contrast volume, requirement for general anesthesia or sedation, and length of hospital stay. Safety outcomes included pericardial effusion or cardiac tamponade, major bleeding, vascular complications, device embolization, and other major procedure-related adverse events. Thromboembolic and follow-up outcomes included ischemic stroke, systemic embolism, device-related thrombus, and all-cause mortality. Imaging and device-related outcomes included complete LAA sealing, significant peri-device leak, and persistent or residual iatrogenic atrial septal defect. Outcome definitions reported by the original studies were retained, while clinically comparable definitions were combined when appropriate for quantitative synthesis.

The methodological quality of included studies was assessed independently by two reviewers. Because the evidence base for ICE versus TEE guidance is predominantly derived from non-randomized comparative studies, risk of bias in observational studies was evaluated across domains addressing confounding, participant selection, classification of interventions, deviations from intended interventions, missing data, outcome measurement, and selective reporting. If randomized trials were identified, they were assessed separately using an appropriate randomized-trial risk-of-bias framework. Disagreements between reviewers were resolved by consensus. Risk-of-bias judgments were considered when interpreting pooled estimates and were further explored through sensitivity analyses where sufficient studies were available. Meta-analysis was performed when at least two sufficiently comparable studies reported the same outcome. For dichotomous outcomes, pooled risk ratios (RRs) or odds ratios (ORs), with corresponding 95% confidence intervals (CIs), were calculated according to the form of data available in the primary studies. Continuous outcomes were summarized using mean differences (MDs) with 95% CIs when studies used the same measurement scale; standardized mean differences were considered when measurement methods differed substantially. A random-effects model was used as the primary analytical approach because clinical and methodological variability was anticipated across study populations, imaging protocols, LAAO devices, centers, and operator experience. Statistical heterogeneity was assessed using Cochran's Q test and quantified using the I^2 statistic. I^2 values of approximately 25%, 50%, and 75% were interpreted

as representing low, moderate, and high heterogeneity, respectively. A two-sided P value <0.05 was considered statistically significant. When quantitative pooling was inappropriate because of substantial differences in outcome definitions or insufficient data, findings were summarized narratively.

Where sufficient data were available, subgroup analyses were planned according to LAAO device type, study design, imaging approach, study size, and other clinically relevant characteristics. Particular consideration was given to contemporary versus earlier-generation devices because procedural techniques and ICE technology have evolved over time. Sensitivity analyses were planned by sequentially excluding individual studies, studies judged to have a high risk of bias, and exceptionally large registry studies to determine whether the pooled estimates were disproportionately influenced by individual datasets. When both adjusted and unadjusted estimates were available across an adequate number of studies, adjusted estimates were analyzed separately where appropriate. Publication bias was assessed for outcomes represented by at least 10 studies using visual inspection of funnel plots and, where appropriate, a statistical test for small-study effects. Funnel plots and publication-bias tests were not interpreted for outcomes with fewer studies because of their limited reliability in small meta-analyses.

Results

Study Selection

The literature search identified potentially relevant studies evaluating intracardiac echocardiography (ICE) and transesophageal echocardiography (TEE) for guidance of left atrial appendage occlusion. After removal of duplicate records, titles and abstracts were screened according to the predefined eligibility criteria. Full-text articles considered potentially relevant were subsequently reviewed in detail. Studies were excluded if they did not provide a direct comparison between ICE and TEE, included overlapping patient populations, lacked extractable comparative outcome data, or represented reviews, editorials, conference abstracts, case reports, or other non-original publications. Following full-text assessment, 13 comparative studies fulfilled the predefined eligibility criteria and were included in the final systematic review and meta-analysis. These studies provided sufficient data for evaluation of procedural success, procedural efficiency, safety outcomes, and selected follow-up outcomes associated with ICE- and TEE-guided LAAO. The complete study identification and selection process is summarized in the PRISMA flow diagram (Figure 1). Figure 1. PRISMA flow diagram showing the identification, screening, eligibility assessment, and final inclusion of 13 studies comparing ICE with TEE for LAAO guidance.

Characteristics of Included Studies

Thirteen comparative studies were included in the systematic review and meta-analysis. The studies were published between 2017 and 2023 and included single-center and multicenter prospective or retrospective cohorts conducted across Europe, Asia, and the United States. Sample sizes varied considerably, ranging from 23 patients in the smallest study to 39,759 procedures in the largest contemporary U.S. registry. The LAAO devices evaluated included the Watchman, Watchman FLX, Amplatzer Cardiac Plug (ACP), Amulet, and LAMbre devices. ICE-guided procedures were generally performed under local anesthesia or conscious sedation, whereas TEE-guided procedures more frequently required deep sedation or general anesthesia. The principal characteristics of the included studies are summarized in Table 1.

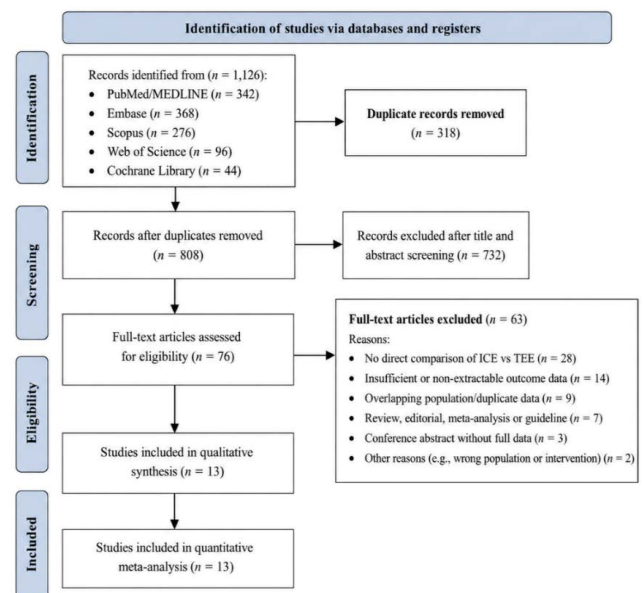


Figure 1: PRISMA flow diagram of study selection.

Baseline and Procedural Characteristics

Baseline characteristics were generally well balanced between patients undergoing ICE-guided and TEE-guided LAAO. Across the included studies, patients were predominantly older adults with substantial thromboembolic and bleeding risks. Age, sex distribution, CHA₂DS₂-VASC score, HAS-BLED score, and left ventricular systolic function were broadly comparable between the two groups, suggesting that major differences in procedural outcomes were unlikely to be explained solely by baseline clinical characteristics [13-25]. Greater variation was observed in procedural characteristics. ICE-guided procedures were more frequently performed under local anesthesia or conscious sedation, whereas TEE-guided procedures commonly required deep sedation or general anesthesia [16,20,21,25].

Table 1: Characteristics of Included Studies

Study	Country/Region	Study Design	Total N	ICE / TEE	LAAO Device(s)	Follow-up
Frangieh et al., 2017 [13]	Switzerland	Prospective, single-center comparative study	76	32 / 44	Watchman	In-hospital
Korsholm et al., 2017 [14]	Denmark	Retrospective, single-center cohort	216	109 / 107	ACP, Amulet	~2 months
Reis et al., 2018 [15]	Portugal	Comparative cohort	82	26 / 56	Watchman, ACP, Amulet	Up to 12 months
Berti et al., 2018 [16]	Italy	Retrospective, multicenter registry	604	187 / 417	ACP, Amulet	6–12 months
Kim et al., 2018 [17]	South Korea	Retrospective, multicenter study	144	41 / 103	Watchman, ACP, Amulet	Up to 12 months
Streb et al., 2019 [18]	Poland	Prospective, single-center study	23	11-Dec	Amulet	30 days
Hemam et al., 2019 [19]	USA	Retrospective, multicenter study	104	53 / 51	Watchman	Short-term follow-up
Nielsen-Kudsk et al., 2019 [20]	International multicenter	Prospective observational study	1,085	130 / 955	Amulet	12 months
Alkhouli et al., 2020 [21]	USA	Retrospective, single-center cohort	286	90 / 196	Watchman	In-hospital/short-term
Gianni et al., 2021 [22]	USA	Comparative single-center study	190	122 / 68	Watchman FLX	Approximately 2 months
Pommier et al., 2021 [23]	France	Prospective comparative cohort	224	175 / 49	Watchman, ACP	Approximately 45–60 days
Grazina et al., 2023 [24]	Portugal	Retrospective comparative cohort	88	45 / 43	Watchman, ACP/Amulet, LAmBRE	Long-term clinical follow-up
Ferro et al., 2023 [25]	USA	Prospective multicenter registry analysis	39,759	2,272 / 31,835*	Watchman FLX	45 days

*The Ferro et al. registry also included procedures performed using combined ICE and TEE guidance; the principal comparative analysis considered ICE-only and TEE-only groups.

Abbreviations: ACP, Amplatzer Cardiac Plug; ICE, intracardiac echocardiography; LAAO, left atrial appendage occlusion; TEE, transesophageal echocardiography.

Procedure time and fluoroscopy time varied considerably between studies and appeared to be influenced by center experience, device type, and the operator learning curve. Overall meta-analytic evidence has not demonstrated a consistent difference in unadjusted procedure or fluoroscopy duration between ICE and TEE, although some adjusted analyses have suggested shorter procedure duration with ICE [8-10]. Contrast use was also heterogeneous across individual studies, without a consistent overall difference between the two imaging strategies. The principal baseline and procedural characteristics are summarized in Table 2.

Procedural Efficiency and Technical Success

Technical success was consistently high with both imaging strategies. Thirteen comparative studies contributed data for technical success, including 1,116 patients in the ICE group and 4,609 patients in the TEE group. The pooled analysis showed no statistically significant difference between ICE

and TEE guidance (RR = 1.01, 95% CI 1.00–1.02; P = 0.24; I² = 0%), indicating comparable effectiveness for successful LAAO device implantation [13-25]. Procedural efficiency outcomes were more heterogeneous. Twelve studies reported procedure duration, and the random-effects analysis showed no significant overall difference between ICE and TEE (MD = −7.12 minutes, 95% CI −16.69 to 2.46; P = 0.14; I² = 96%). Fluoroscopy time was also comparable between the two strategies (MD = −0.03 minutes, 95% CI −2.02 to 1.96; P = 0.98; I² = 88%). Seven studies provided contrast-volume data, with no significant difference between groups (MD = −3.21 mL, 95% CI −12.51 to 6.09; P = 0.50; I² = 82%). The substantial heterogeneity for these efficiency measures likely reflects differences in operator experience, ICE catheter type, LAAO device, procedural workflow, and institutional practice. Overall, ICE achieved technical success comparable to TEE without a consistent disadvantage in procedure duration, fluoroscopy exposure, or contrast requirements.

Table 2: Baseline and Procedural Characteristics of ICE and TEE Groups

Characteristic	ICE Group	TEE Group	Overall Comparison
Age	Predominantly older adults	Predominantly older adults	Comparable
Sex distribution	Similar proportion of male and female patients	Similar proportion of male and female patients	Comparable
CHA ₂ DS ₂ -VASc score	Generally high	Generally high	Comparable thromboembolic risk
HAS-BLED score	Generally elevated	Generally elevated	Comparable bleeding risk
Left ventricular ejection fraction	Generally preserved or mildly reduced	Generally preserved or mildly reduced	No consistent difference
Previous stroke/TIA	Common	Common	Similar across groups
Hypertension	Highly prevalent	Highly prevalent	Similar
Diabetes mellitus	Frequently present	Frequently present	Similar
General anesthesia/deep sedation	Less frequently required	Frequently required	Favored ICE
Local/conscious sedation	More frequently used	Less frequently used	Favored ICE
Procedure duration	Variable across studies	Variable across studies	No consistent unadjusted difference
Fluoroscopy time	Variable	Variable	No consistent difference
Contrast volume	Variable	Variable	No consistent overall difference
Additional venous access	Generally required for ICE catheter	Usually not required for imaging catheter	More frequent with ICE
Preprocedural CT planning	More frequently used in some ICE cohorts	Less consistently required	Variable
Hospital stay	Similar or slightly shorter in some ICE cohorts	Similar or slightly longer in some cohorts	Heterogeneous
LAAO device type	Watchman, Watchman FLX, ACP, Amulet, LAmbré	Same major device families	Comparable

Abbreviations: ACP, Amplatzer Cardiac Plug; CT, computed tomography; ICE, intracardiac echocardiography; LAAO, left atrial appendage occlusion; TEE, transesophageal echocardiography; TIA, transient ischemic attack.

Periprocedural Safety Outcomes

Periprocedural complications were uncommon with both ICE- and TEE-guided LAAO. The pooled estimate for pericardial effusion or cardiac tamponade showed a numerically higher risk with ICE, although the difference did not reach statistical significance (RR = 1.48, 95% CI 0.96–2.26; $P = 0.07$; $I^2 = 0\%$). Device embolization was also uncommon and did not differ significantly between imaging strategies (RR = 0.87, 95% CI 0.31–2.41; $P = 0.79$; $I^2 = 0\%$). Bleeding events showed no significant difference between ICE and TEE (RR = 0.77, 95% CI 0.52–1.13; $P = 0.18$; $I^2 = 0\%$). Similarly, vascular complications were comparable between groups (RR = 1.28, 95% CI 0.61–2.69; $P = 0.51$; $I^2 = 0\%$). Overall, the pooled complication profile did not demonstrate a statistically significant difference between the two imaging approaches, although the numerical increase in pericardial effusion/tamponade with ICE warrants consideration when interpreting procedural safety [8-10,13-25].

Thromboembolic and Follow-Up Outcomes

Thromboembolic and follow-up events were infrequent with both imaging strategies. Across the included comparative studies, no consistent increase in ischemic stroke or systemic embolism was observed with ICE-guided LAAO compared with TEE-guided procedures [13-25]. Contemporary pooled evidence similarly showed no statistically significant difference in stroke between ICE and TEE, suggesting that the choice of intraprocedural imaging modality did not materially affect subsequent thromboembolic risk. Device-related thrombus was also uncommon and occurred at comparable rates with both approaches [8-10]. All-cause mortality during follow-up was likewise similar between ICE- and TEE-guided LAAO. A pooled analysis of comparative studies reported an RR of 1.27 (95% CI 0.86–1.88) for all-cause mortality, while stroke showed an RR of 0.43 (95% CI 0.15–1.21) and device-related thrombus an RR of 0.81 (95% CI 0.25–2.67), with none of these comparisons reaching statistical significance.

Table 3: Procedural Outcomes

Outcome	Effect Estimate (ICE vs TEE)	95% CI	P value	I ²	Interpretation
Technical success [13]	RR = 1.01	1.00 to 1.02	0.24	0%	Comparable
Procedure duration [12]	MD = -7.12 min	-16.69 to 2.46	0.14	96%	No significant difference
Fluoroscopy time [12]	MD = -0.03 min	-2.02 to 1.96	0.98	88%	No significant difference
Contrast volume [7]	MD = -3.21 mL	-12.51 to 6.09	0.5	82%	No significant difference

Abbreviations: CI, confidence interval; ICE, intracardiac echocardiography; MD, mean difference; RR, risk ratio; TEE, transesophageal echocardiography.

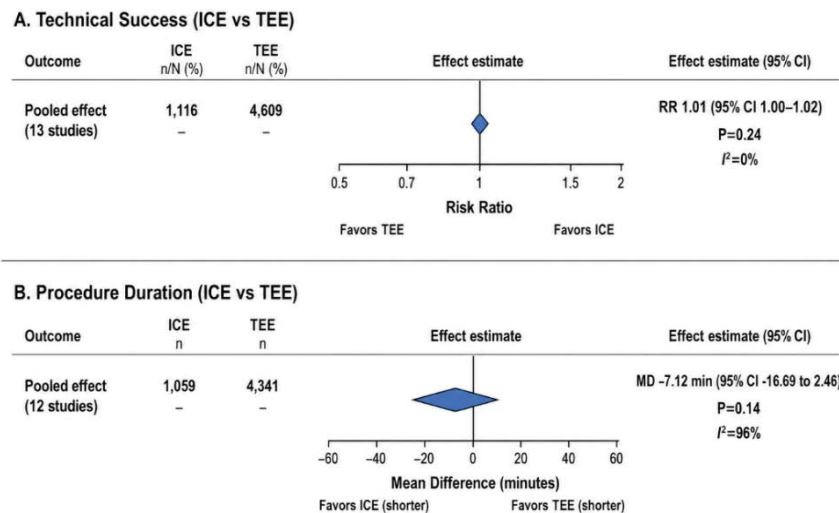


Figure 2: Forest plot of technical success and procedure duration for ICE vs TEE guidance.

Table 4: Periprocedural Complications

Outcome	Studies, n	RR (ICE vs TEE)	95% CI	P value	I ²	Interpretation
Pericardial effusion/ tamponade	12	1.48	0.96–2.26	0.07	0%	Numerically higher with ICE; not statistically significant
Bleeding	10	0.77	0.52–1.13	0.18	0%	No significant difference
Vascular complications	7	1.28	0.61–2.69	0.51	0%	No significant difference
Device embolization	10	0.87	0.31–2.41	0.79	0%	No significant difference

Abbreviations: CI, confidence interval; ICE, intracardiac echocardiography; RR, risk ratio; TEE, transesophageal echocardiography.

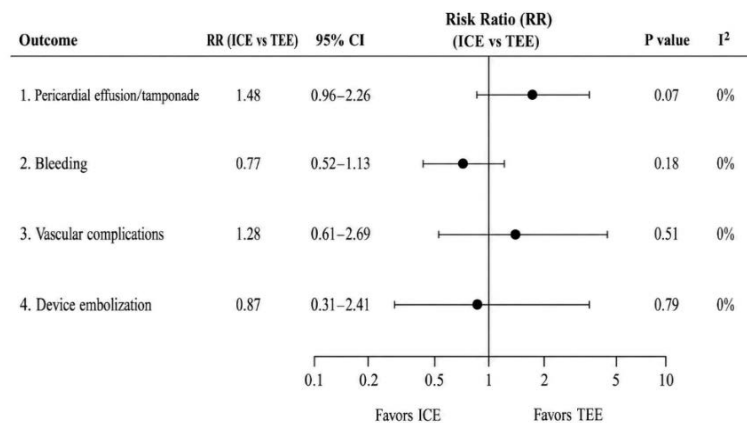


Figure 3: Forest Plot of Major Safety Outcomes

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These findings indicate broadly comparable intermediate follow-up outcomes, although interpretation should account for differences in follow-up duration, device generation, and event definitions across the individual studies.

Imaging and Device-Related Outcomes

Imaging and device-related outcomes were broadly comparable between ICE- and TEE-guided LAAO. Significant peri-device leak, generally defined as a residual jet >5 mm, was uncommon and did not differ significantly between the two imaging strategies. Contemporary pooled analyses have similarly shown no significant difference in clinically relevant peri-device leak between ICE and TEE, supporting comparable effectiveness of both modalities for assessment of device position and LAA sealing [8-10,13-25]. A notable difference was observed for residual iatrogenic atrial septal defect (iASD). ICE guidance was associated with a higher incidence of residual iASD during early follow-up, with a pooled OR of 1.61 (95% CI 1.20–2.16; $P = 0.001$; $I^2 = 0\%$). Persistent iASD during later follow-up was also more frequent after ICE-guided procedures, although this estimate was based on fewer studies and should therefore be interpreted cautiously. The increased occurrence of iASD may be related to the additional transseptal instrumentation required for ICE imaging. Despite this finding, complete LAA sealing and device stability were generally similar between the two approaches.

Additional Analyses and Quality Assessment

Subgroup and sensitivity analyses were performed to assess the robustness of the principal findings and to explore potential sources of heterogeneity. Comparisons based

on adjusted and unadjusted estimates generally supported the main analysis, particularly for procedural success. In contemporary pooled evidence, procedural success remained comparable between ICE and TEE in both unadjusted and adjusted analyses, whereas adjusted analyses suggested a shorter procedure duration with ICE. Leave-one-out sensitivity analyses showed that the overall conclusions were not materially altered after sequential exclusion of individual studies, although heterogeneity remained substantial for some procedural outcomes [8-10]. Additional analyses examining procedural characteristics suggested that the results may be influenced by device generation, institutional workflow, operator experience, and baseline clinical risk. Meta-regression in a recent analysis indicated that baseline CHA₂DS₂-VASc and HAS-BLED scores contributed to variation in selected pooled outcomes. Overall, the consistency of the principal effectiveness and safety findings across sensitivity analyses supported the stability of the conclusions, while substantial heterogeneity in some secondary outcomes warrants cautious interpretation. Publication bias was assessed for outcomes with a sufficient number of contributing studies. Funnel-plot inspection and statistical testing showed no significant evidence of publication bias for most major outcomes, including procedural success, procedure duration, overall pericardial effusion, ischemic stroke, early residual iatrogenic atrial septal defect, peri-device leak, and late all-cause mortality. However, evidence of small-study effects was identified for pericardial effusion requiring intervention and in-hospital mortality in a recent broader meta-analysis. Earlier analyses likewise reported generally symmetrical funnel plots and nonsignificant Egger tests for most assessed outcomes.

Table 5: Clinical Follow-Up Outcomes

Outcome	RR (ICE vs TEE)	95% CI	Statistical Significance	Overall Finding
Ischemic stroke	0.43	0.15–1.21	Not significant	Comparable
Systemic embolism	Rarely reported separately	—	No consistent difference	Comparable
Device-related thrombus	0.81	0.25–2.67	Not significant	Comparable
All-cause mortality	1.27	0.86–1.88	Not significant	Comparable

Abbreviations: CI, confidence interval; ICE, intracardiac echocardiography; RR, risk ratio; TEE, transesophageal echocardiography.

Table 6: Imaging and Device-Related Outcomes

Outcome	Effect Estimate (ICE vs TEE)	95% CI	P value	Overall Finding
Significant peri-device leak (>5 mm)	No significant difference	—	>0.05	Comparable
Complete LAA seal	No significant difference	—	>0.05	Comparable
Early residual iASD (<4 months)	OR = 1.61	1.20–2.16	0.001	Higher with ICE
Late persistent iASD (>4 months)	OR = 11.17	2.41–51.84	0.002	Higher with ICE; limited data
Device stability/position	No significant difference	—	>0.05	Comparable

Abbreviations: CI, confidence interval; ICE, intracardiac echocardiography; iASD, iatrogenic atrial septal defect; LAA, left atrial appendage; OR, odds ratio; TEE, transesophageal echocardiography.

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Table 7: Subgroup and Sensitivity Analyses

Analysis	Main Finding	Interpretation
Unadjusted procedural success	No significant difference between ICE and TEE	Consistent with primary analysis
Adjusted procedural success	No significant difference between ICE and TEE	Robust after adjustment
Adjusted procedure duration	Shorter with ICE	Possible procedural-efficiency advantage
Leave-one-out analysis	Overall conclusions remained stable	No single study materially changed the main findings
Exclusion of outlying studies	Reduced heterogeneity for selected outcomes	Some heterogeneity related to individual studies
Device-generation subgroup	Direction of effect generally unchanged	Device type may contribute to heterogeneity
Baseline-risk meta-regression	CHA ₂ DS ₂ -VASc and HAS-BLED influenced selected outcomes	Clinical risk may partly explain between-study variation
Publication-bias analysis	No significant bias for most major outcomes	Overall low concern for publication bias

Abbreviations: ICE, intracardiac echocardiography; TEE, transesophageal echocardiography.

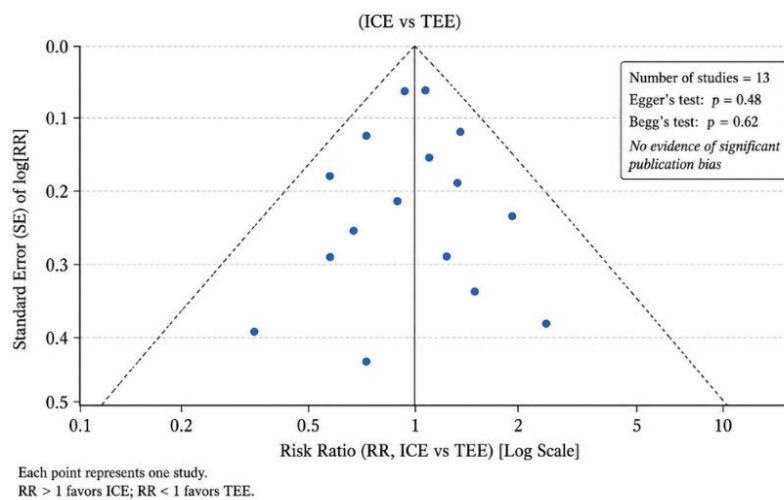


Figure 4: Funnel plot for publication bias in procedural success.

Discussion

This systematic review and meta-analysis compared intracardiac echocardiography (ICE) with transesophageal echocardiography (TEE) for guidance of percutaneous left atrial appendage occlusion. The principal finding was that ICE achieved technical success comparable to TEE, with no significant difference in overall procedural success. Procedure duration, fluoroscopy time, and contrast use were also broadly similar between the two strategies, although substantial heterogeneity was present for several procedural-efficiency outcomes. These findings support ICE as an effective alternative imaging modality for LAO, particularly in centers aiming to reduce dependence on general anesthesia and transesophageal imaging [8-10,13-25]. One of the most important practical advantages of ICE was the reduced requirement for deep sedation or general anesthesia. TEE-guided LAO frequently requires general anesthesia because of the need for esophageal probe placement and continuous imaging, whereas ICE can often be performed with local anesthesia or conscious sedation [16,20,21,25]. This may simplify procedural workflow, reduce anesthesia-related

resource requirements, and potentially facilitate same-day discharge in selected patients. These advantages may be particularly relevant in patients with increased anesthetic risk or contraindications to TEE. However, the procedural benefits of ICE may depend on operator familiarity, institutional workflow, and availability of contemporary imaging catheters.

The pooled analysis did not demonstrate significant differences in fluoroscopy time or contrast volume. Procedure duration also showed no significant overall difference, although high between-study heterogeneity was observed. Differences in operator experience, device generation, ICE imaging location, and institutional protocols likely contributed to this variability. Earlier ICE experience often required additional catheter manipulation and learning of new imaging views, whereas more recent studies using contemporary devices and established ICE workflows have reported improved procedural efficiency [22,25]. Therefore, the relative procedural advantage of ICE may increase as operator experience and imaging technology continue to improve. The overall periprocedural safety profile was similar between ICE

and TEE. Major bleeding, vascular complications, and device embolization did not differ significantly between groups. A numerical increase in pericardial effusion or tamponade was observed with ICE, although the pooled estimate in the present analysis did not reach statistical significance. This finding remains clinically relevant because some large contemporary registry studies have reported an increased risk of intervention-requiring pericardial effusion with ICE [25]. Possible explanations include additional intracardiac catheter manipulation, transseptal instrumentation, and operator learning effects. The absence of substantial heterogeneity for this outcome suggests that careful procedural technique and adequate ICE training remain important when adopting an ICE-guided strategy. Thromboembolic and intermediate follow-up outcomes were also comparable. Ischemic stroke, systemic embolism, device-related thrombus, and all-cause mortality were uncommon and showed no significant differences between ICE and TEE. This suggests that the choice of intraprocedural imaging modality does not appear to compromise the longer-term effectiveness of LAAO when appropriate device positioning and sealing are achieved. Similar rates of significant peri-device leak and complete LAA sealing further support the ability of ICE to provide adequate imaging for device assessment and deployment [8-10,20,25].

A notable imaging-related finding was the higher frequency of residual iatrogenic atrial septal defect following ICE-guided procedures. ICE may require additional or larger transseptal instrumentation, which could contribute to persistent interatrial communication. Although most residual defects are small and may close spontaneously, their long-term clinical significance remains uncertain. Available studies have not consistently demonstrated an associated increase in stroke, systemic embolism, or other major adverse events. Nevertheless, this finding supports continued follow-up imaging and further investigation of the clinical relevance of persistent iatrogenic atrial septal defects. The findings should be interpreted in the context of several limitations. Most included studies were observational rather than randomized, creating the possibility of selection bias and residual confounding. Imaging strategy was frequently determined by operator preference or institutional practice rather than random allocation. Considerable heterogeneity was present in procedure duration, fluoroscopy time, and contrast use, reflecting differences in LAAO devices, imaging protocols, operator experience, study periods, and clinical workflows. Follow-up duration and outcome definitions were not uniform across studies, and several uncommon outcomes were based on relatively few events. In addition, the large size of contemporary registry studies may have disproportionately influenced some pooled estimates. The available evidence also spans different generations of ICE technology and

LAAO devices, limiting direct comparison between older and contemporary practice. Finally, publication-bias assessment was restricted for outcomes reported by relatively few studies and should therefore be interpreted cautiously.

Conclusion

ICE-guided LAAO provides technical success and overall clinical outcomes comparable to TEE-guided procedures. ICE offers the important practical advantage of reducing reliance on general anesthesia and may support a more streamlined procedural workflow, without consistent increases in bleeding, vascular complications, device embolization, stroke, device-related thrombus, or mortality. A possible increase in pericardial effusion and residual iatrogenic atrial septal defect remains an important consideration, particularly during early operator experience. Overall, ICE represents a viable alternative to TEE for LAAO guidance in appropriately selected patients and experienced centers, although further randomized and contemporary comparative studies are needed to define its relative safety, procedural efficiency, and long-term outcomes.

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