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Intracardiac echocardiography in the diagnosis and treatment of atrial fibrillation

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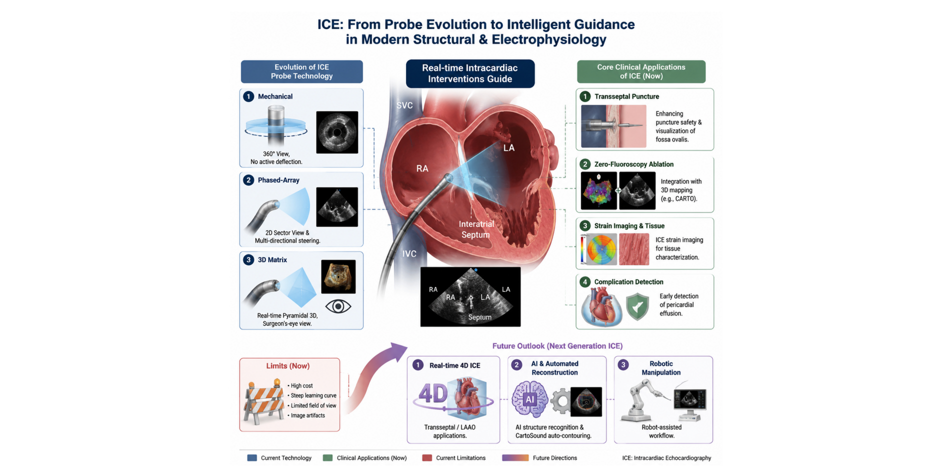

Abstract

Intracardiac echocardiography (ICE) has become an indispensable real-time imaging modality in atrial fibrillation (AF) ablation procedures, offering distinct advantages across multiple domains, including pre-procedural exclusion of left atrial appendage (LAA) thrombus, real-time guidance for transseptal puncture, catheter localization during ablation, anatomical assessment for LAA closure, and monitoring of complications such as pericardial effusion. Recent investigations have further expanded its utility, particularly in pre-ablation LAA thrombus screening and in guiding emerging pulsed-field ablation techniques. Beyond procedural navigation, ICE enables early detection and timely management of potentially serious complications, while also substantially reducing radiation exposure during transseptal puncture. This review provides a comprehensive overview of the broadening applications of ICE in AF catheter ablation and related interventions, with a specific focus on its current roles in AF ablation and LAA occlusion. The synthesized evidence offers a valuable framework for optimizing future clinical strategies that integrate ICE into AF diagnosis and treatment. Given its considerable benefits in enhancing both safety and efficacy, the broader adoption of ICE in these procedures is strongly warranted.

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INTRODUCTION

Currently, catheter ablation and left atrial appendage (LAA) closure represent the two primary interventional strategies for atrial fibrillation (AF). Recent evidence suggests that catheter ablation offers superior clinical outcomes compared with pharmacological therapy in patients with AF[1-3], and current guidelines endorse it as a first-line treatment for those who are drug-refractory[2,3]. For patients at high bleeding risk who are unsuitable for anticoagulation, or those anticipated to respond poorly to ablation, LAA closure provides a safer alternative to long-term anticoagulation[4-7]. As the adoption of these two interventional approaches continues to expand, there is an increasing demand for enhanced procedural safety and efficacy.

Imaging plays an essential role throughout the entire workflow of AF interventional therapy[8,9]. Preoperative transesophageal echocardiography (TEE) remains the standard modality for excluding LAA thrombus prior to ablation; however, it frequently causes patient discomfort, including nausea and vomiting. Conventional fluoroscopy-guided transseptal puncture inevitably exposes both operators and patients to radiation[10]. Preoperative LAA computed tomography angiography (CTA) allows detailed assessment of LAA morphology, facilitating accurate occluder sizing before LAA occlusion and enabling postoperative evaluation of device positioning and endothelialization. Furthermore, integration of CTA data with electroanatomic mapping and fluoroscopic angiography can improve intraoperative ablation targeting. Nevertheless, these modalities primarily provide static anatomical images, which limits their real-time positional accuracy during procedures.

The rapid advancement of intracardiac echocardiography (ICE) has effectively addressed these limitations. ICE offers prominent clinical benefits across multiple key steps, including preoperative exclusion of LAA thrombus, real-time guidance for transseptal puncture, intraoperative positioning of the ablation catheter, anatomical evaluation during LAA closure, and early detection of procedural complications such as pericardial effusion. It enables high-resolution visualization of the left atrium (LA) and LAA fine structures, while also significantly reducing intraoperative fluoroscopy exposure[11,12] [Table 1].

This review aims to summarize the latest clinical applications of ICE in AF interventional therapy, with particular emphasis on its value in improving overall procedural safety and therapeutic efficacy.

ICE probe types

ICE probes can be classified into two main categories. Mechanical probes (e.g., Boston Scientific Ultra ICE) utilize a rotating crystal to generate a 360° radial view but lack active tip deflection. In contrast, electronic phased-array probes (e.g., CartoSound, AcuNav) employ beam-steering technology to produce fan-shaped images and offer multi-directional deflection as well as Doppler functionality[13]. However, 2D imaging still requires mental spatial reconstruction by the operator. 3D matrix probes address this limitation by using a matrix array of crystals to acquire pyramidal volume data in real time, thereby providing intuitive, surgeon's-eye views. Their primary advantage lies in seamless integration with electroanatomical mapping systems (e.g., CARTO), which enhances navigational accuracy[13]. Additionally, ICE enables non-contact 3D reconstruction through catheter rotation. Some ICE catheters can be directly visualized on mapping systems, further clarifying their spatial position. Key anatomical structures can be identified from the right atrium (RA), right ventricle (RV), or LA[14].

CLINICAL INDICATIONS AND SPECIFIC APPLICATIONS

Pre-procedural LAA thrombus evaluation

The presence of LAA thrombus remains an absolute contraindication to AF ablation. TEE has traditionally been the gold standard for thrombus exclusion. Early studies from 2002 demonstrated that ICE could provide image quality comparable to that of TEE[15]. However, initial ICE catheter placement in the RA often

Table 1. Key parameters comparison of ICE, TEE, CTA and fluoroscopy

Key parameters	ICE	TEE	CTA	Fluoroscopy
Sensitivity/specificity	Sensitivity 92%-96%, specificity 90%-95%[17,24]; enables real-time detection of thrombus, pericardial effusion, and catheter malposition	Sensitivity 95%-98%, specificity 93%-96%[19,21]; gold standard for LAA thrombus screening, only for preoperative use	Anatomical evaluation sensitivity > 98%[8]; provides static anatomical images and is poor for dynamic lesion diagnosis	Cannot identify soft tissue lesions or microthrombi; has low diagnostic sensitivity and specificity for indicators related to AF interventions
Patient comfort	High. Vascular access only; no nausea or pharyngeal discomfort	Poor. Esophageal probe placement often causes nausea, vomiting, and throat injury	Moderate. Non-invasive, but requires breath-holding during scanning	High. Fully non-invasive with no physical discomfort
Requirement for general anesthesia	Not required; performed under local anesthesia	Usually required or combined with deep sedation	Not required; mild sedation for agitated patients only	Not required; local anesthesia for routine use
Radiation exposure	No ionizing radiation	No ionizing radiation	Moderate to high ionizing radiation	Continuous low-dose ionizing radiation
Procedural workflow efficiency	High. Integrated with intraoperative procedures, no extra preoperative preparation	Low. Independent preoperative examination, unable to guide real-time operation	Low. Complicated preoperative preparation, only for anatomical reference	Moderate. Easy to operate, single-function, needs combination with other imaging modalities
Core application in AF interventions	Real-time intraoperative guidance for ablation and LAA closure	Preoperative LAA thrombus exclusion	Preoperative anatomical assessment and surgical planning	Basic intraoperative catheter positioning

AF: Atrial fibrillation; ICE: intracardiac echocardiography; TEE: transesophageal echocardiography; CTA: computed tomography angiography; LAA: left atrial appendage.

failed to fully visualize the distal LAA[16]. Subsequent optimization of probe positioning-specifically within the right ventricular outflow tract or the supra-pulmonary valve region-enabled clear, multi-planar LAA views, with thrombus detection rates equivalent to those of TEE[17-20]. In selected patients and experienced centers, ICE may serve as an alternative or complementary imaging modality[21]. Nonetheless, operators using this type of ICE probe typically require additional training to master catheter-handling techniques. Some studies have even suggested that ICE may offer higher sensitivity in patients with negative or equivocal TEE findings[22,23]. A large retrospective study reported that ICE shortened hospital stays and reduced the incidence of post-procedural fever[24]. Most recently, a randomized controlled trial involving 1,810 patients demonstrated that ICE was noninferior to TEE in preventing peri-procedural thromboembolic events, while offering additional advantages in safety, efficiency, and patient comfort[25]. It should be noted that preoperative LAA thrombus assessment via ICE is generally performed during the procedure itself. Therefore, this approach may be more suitable for emergency surgeries or for patients who are unable to undergo CTA or TEE scanning [Table 2].

Transseptal puncture guidance

ICE provides real-time, high-definition visualization of the interatrial septum and fossa ovalis, thereby enhancing puncture safety and substantially reducing radiation exposure compared with conventional fluoroscopy[26-28]. A 15-year multicenter retrospective analysis confirmed that ICE significantly reduced septal-related complications during left atrial procedures[29,30]. ICE is particularly valuable in complex anatomical scenarios, including thickened septum, atrial septal aneurysm, post-closure of atrial septal defect/patent foramen ovale (ASD/PFO), and congenital variants[13,26,27,29-34]. More recently, the integration of ICE with 3D electroanatomical mapping has enabled zero- or near-zero-fluoroscopy ablation, as confirmed by a randomized trial in which over half of 448 patients completely avoided X-ray exposure[35-37] [Table 2, Figure 1].

Catheter visualization and lesion assessment

During AF catheter ablation, ICE enables real-time visualization of catheters and target areas, as well as monitoring of ablation lesions, thereby enhancing both procedural safety and efficacy [Table 2, Figure 1].

Radiofrequency ablation

ICE clearly visualizes the pulmonary vein antrum and ostia to help prevent pulmonary vein stenosis[38], and provides real-time 3D localization of the esophagus to reduce the risk of atrioesophageal fistula[39]. It also assesses catheter-tissue contact to ensure effective lesion formation. Studies have shown that ICE guidance improves energy delivery and linear lesion accuracy, shortening procedure time and increasing acute success rates[40,41]. Additionally, ICE allows energy titration based on atrial wall thickness. An individualized ICE-guided energy strategy has been shown to improve acute success and reduce one-year AF recurrence compared with a fixed protocol[42]. Although long-term success rates may be comparable[43] , multiple analyses confirm that ICE significantly reduces fluoroscopy time, radiation exposure, and procedure duration without increasing complications[44].

Cryoballoon ablation

ICE also plays a significant role in cryoablation. It assists in selecting the appropriate balloon size, facilitates precise positioning at the pulmonary vein antrum, and employs color Doppler to assess complete pulmonary vein occlusion, thereby predicting acute ablation success and ruling out acute venous narrowing[45,46]. Two small randomized studies showed that ICE guidance shortened procedure time and reduced radiation and contrast agent use; although it did not significantly affect long-term recurrence rates, it improved procedural efficiency[47,48]. A large observational study further indicated that ICE-guided cryoablation achieved higher rates of acute pulmonary vein isolation, fewer complications, and lower radiation exposure[49,50]. Additionally, ICE can monitor diaphragmatic movement in real time during right-sided pulmonary vein ablation, providing early warning of phrenic nerve injury[51].

Pulsed field ablation (PFA)

As a novel non-thermal ablation technology, PFA relies heavily on adequate electrode-tissue contact for lesion effectiveness. Preclinical studies have shown that good contact enhances electric field penetration and creates deeper transmural lesions[52-54]. Therefore, for PFA catheters that are not yet fully integrated with 3D electroanatomical systems (e.g., the FARAPULSE™ system), ICE holds significant value for catheter navigation, positioning, and contact assessment. Preliminary clinical experience demonstrates that ICE enables zero-fluoroscopy guidance of PFA procedures, with acute success, safety, and short-term efficacy comparable to those of fluoroscopic guidance[55,56]. Research in this area is still accumulating, and standardized application pathways for ICE in PFA require further establishment.

Left atrial appendage occlusion (LAAO)

LAAO is indicated for AF patients at moderate-to-high stroke risk who are unsuitable for long-term oral anticoagulation[4-6,57]. TEE has been the traditional imaging guide, but ICE may serve as an alternative or complementary modality in selected patients and experienced centers. Studies have shown that ICE-guided LAAO is safe and effective, with comparable peri-device leak rates, shorter procedure times, and reduced radiation and contrast use[58,59]. Although 2D imaging is limited by LAA anatomical variability[60-62], ICE accurately measures LAA dimensions for device sizing[63,64]. Recent studies indicate that 3D ICE outperforms 2D ICE in device sizing and implantation guidance, showing high agreement with pre-procedural TEE[63]. Novel 3D ICE probes (e.g., VeriSight Pro) have been successfully used to guide Watchman FLX implantation[64,65] [Table 2, Figure 1].

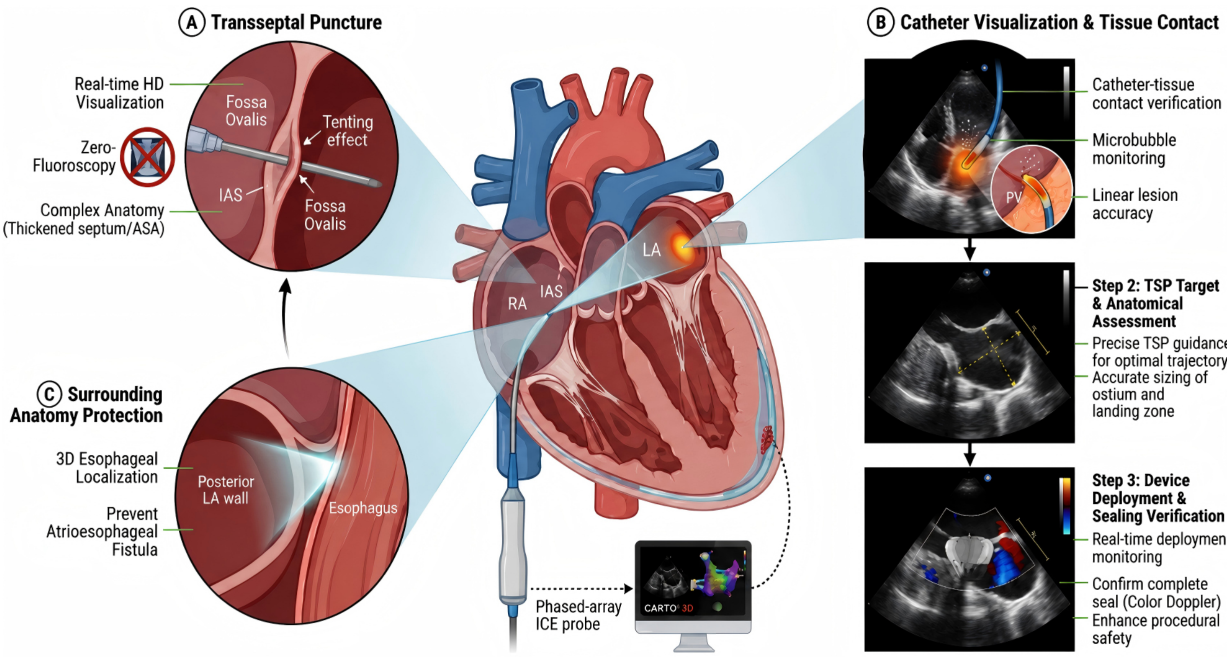

Figure 1. Schematic overview of the core clinical applications of intracardiac echocardiography (ICE) in atrial fibrillation ablation and left atrial appendage closure procedures. (A) Transseptal puncture (TSP) guidance. ICE provides real-time high-definition visualization of the interatrial septum (IAS) and fossa ovalis, enabling safe puncture even in complex anatomies (e.g., thickened septum or atrial septal aneurysm) by clearly visualizing the tenting effect, with the potential to reduce or eliminate fluoroscopy exposure. (B) Stepwise procedural guidance. Top panel: Direct visualization of catheter-tissue contact, microbubble formation, and linear lesion accuracy during pulmonary vein (PV) isolation. Middle panel: Target and anatomical assessment for TSP, including precise trajectory planning and accurate sizing of the left atrial ostium and landing zone. Bottom panel: Real-time monitoring of device deployment and immediate sealing verification using color Doppler, confirming complete occlusion and enhancing procedural safety. (C) Surrounding anatomy protection. ICE enables 3D localization of the esophagus relative to the posterior left atrial (LA) wall, facilitating risk mitigation strategies to prevent atrioesophageal fistula formation. RA: right atrium; LA: left atrium.

Real-time complication detection and immediate management

ICE provides critical support for real-time complication monitoring and immediate management during AF ablation procedures, significantly enhancing overall procedural safety. Data show that the use of ICE can reduce complication rates and the need for repeat ablation by approximately 36% compared with conventional ablation[66]. Its core advantages lie in the early detection of various complications. For example, when the ICE probe is placed in the RV to image the left ventricular (LV) posterior wall and adjacent pericardium, it can detect even a trace amount of pericardial effusion around the LV at an early stage[67]. Simultaneously, ICE can sensitively detect thrombus formation on catheters or sheaths, guiding prompt adjustment of anticoagulation or thrombus removal to reduce embolic risk[68,69]. During right-sided ablation, it can also monitor phrenic nerve function by observing diaphragmatic movement, thereby preventing permanent injury[70]. Furthermore, ICE can visualize tissue microbubbles and spontaneous echo contrast generated during ablation in real time, aiding in the assessment of ablation response and hypercoagulable states to optimize procedural decisions. Thus, ICE facilitates a shift from reactive management to proactive prevention, establishing itself as a crucial imaging tool for ensuring the safety of AF interventions [Table 2, Figure 1].

Myocardial tissue characterization by ICE strain imaging

Beyond anatomical guidance, ICE enables functional assessment of the atrial myocardium. A study using ICE-derived endocardial and myocardial speckle-tracking strain in patients undergoing AF ablation revealed that left atrial tissue characteristics and function were significantly impaired, particularly in those with persistent AF. Although inter-observer variation in strain measurements was minimal, further software refinement is needed to enhance clinical applicability[71] [Table 2].

Table 2. Summary of key representative clinical studies on intracardiac echocardiography-guided atrial fibrillation interventions

References	Study type	Sample size	Main findings	Clinical implications
Hu *et al.*[25]	Prospective randomized controlled trial	1,810 AF ablation patients	ICE was non-inferior to TEE in preventing peri-procedural thromboembolic events. ICE-guided procedures eliminated the need for general anesthesia, significantly improved patient comfort, and shortened total procedural duration without increasing adverse events	ICE can replace routine peri-procedural TEE screening for AF ablation, simplifying the preoperative workflow and reducing anesthesia-related risks
Wang *et al.*[24]	Prospective observational study (ICE-TEE trial)	526 AF ablation patients	Intraoperative ICE exhibited consistent accuracy with TEE in LAA thrombus detection. ICE guidance reduced postoperative fever incidence and shortened hospital stay, with comparable procedural safety profiles	Intraoperative ICE-based LAA thrombus assessment is a reliable alternative to preoperative TEE, optimizing clinical workflow and postoperative recovery
Wang *et al.*[37]	Multicenter prospective trial (PAF-ICE trial)	1,208 paroxysmal AF patients	Systematic ICE guidance enabled standardized minimal/zero-fluoroscopy AF ablation in Chinese multicenter practice. It drastically reduced fluoroscopy time and radiation exposure while maintaining identical acute procedural success and mid-term recurrence rates	ICE is feasible for widespread adoption of zero-fluoroscopy AF ablation in large-volume clinical centers, realizing radiation-free and high-precision intervention
Ahn *et al.*[50]	Prospective randomized controlled trial	328 patients undergoing cryoballoon AF ablation	ICE-guided zero-fluoroscopy cryoablation achieved equivalent acute pulmonary vein isolation (PVI) success and 12-month AF recurrence rates compared with fluoroscopy-guided procedures. It significantly reduced radiation exposure and contrast agent consumption	ICE enables safe and efficient zero-fluoroscopy cryoballoon ablation, which is optimal for radiation-sensitive patients and contrast-intolerant populations
Dello Russo *et al.*[56]	Multicenter propensity-matched analysis	896 AF patients undergoing pulsed field ablation (PFA)	Real-time ICE visualization ensured stable catheter-tissue contact and accurate lesion deployment during PFA. ICE-guided zero-fluoroscopy PFA achieved comparable acute success and short-term safety to conventional imaging-guided procedures	ICE addresses the navigation dilemma of incompletely integrated PFA catheters, promoting the clinical application of zero-fluoroscopy pulsed field ablation technology
Serpa *et al.*[64]	Updated systematic review and meta-analysis	18 eligible studies (n = 2,468) for LAAO	ICE-guided LAAO demonstrated equivalent procedural success rate and peri-device leak rate versus TEE-guided approaches. ICE significantly shortened procedural time and reduced radiation and contrast usage without increasing major complications	ICE is a safe, efficient, and cost-effective alternative to TEE for routine LAAO guidance, optimizing procedural efficiency and reducing procedural trauma
Bottoni *et al.*[31]	Retrospective multicenter analysis	1245 AF patients receiving transseptal puncture	Systematic ICE guidance reduced septum-related complications and accidental pericardial puncture risk during transseptal access. It showed unique advantages in complex anatomical conditions, including thickened interatrial septum and atrial septal malformation	ICE markedly improves the safety of transseptal puncture, especially for high-risk and complex anatomical AF interventional cases
Motoike *et al.*[42]	Prospective single-center study	218 patients undergoing radiofrequency AF ablation	ICE-based real-time atrial wall thickness measurement enabled individualized energy titration. This personalized strategy improved acute PVI success rate and reduced 12-month AF recurrence compared with fixed energy protocols	ICE-mediated tissue characterization facilitates personalized ablation parameter adjustment, improving long-term efficacy of radiofrequency AF ablation
Xu *et al.*[43]	Meta-analysis of RCTs and observational studies	Included 22 studies (n = 3,892)	Compared with non-ICE guidance, ICE-guided AF ablation significantly reduced procedural time, fluoroscopy dosage, and major complication rates, with comparable acute success and long-term sinus rhythm maintenance rates	ICE guidance comprehensively improves the overall safety and efficiency of AF catheter ablation without compromising procedural efficacy
Pongratz *et al.*[49]	Prospective cohort subanalysis (FREEZE trial)	412 cryoballoon ablation patients	Intraoperative ICE monitoring effectively detected early phrenic nerve traction and pericardial effusion during cryoablation, reducing irreversible phrenic nerve injury and severe complication rates	ICE provides real-time functional monitoring during cryoballoon ablation, enabling early intervention and improving procedural safety
Sularz *et al.*[65]	Prospective observational study	196 patients undergoing Watchman FLX LAAO	3D ICE-guided LAAO achieved high consistency with TEE in LAA sizing and occluder positioning. It reduced intraoperative contrast usage and avoided general anesthesia in most patients	Novel 3D ICE is a reliable imaging tool for precise deployment of LAAO devices, further optimizing minimally invasive procedural strategies

Baran *et al*.[19]	Prospective single-center study (Action-Ice I Study)	208 AF ablation patients	ICE exhibited high sensitivity and specificity for LAA thrombus detection, with consistent diagnostic performance compared with TEE. ICE could identify marginal thrombus missed by conventional TEE in partial cases	ICE serves as a valid intraoperative alternative and complementary tool for LAA thrombus screening during AF ablation procedures

AF: Atrial fibrillation; ICE: intracardiac echocardiography; LAA: left atrial appendage; LAAO: left atrial appendage occlusion; TEE: transesophageal echocardiography; PVI: pulmonary vein isolation; PFA: pulsed field ablation.

Table 3. Comparison of ICE and TEE in atrial fibrillation interventions

Parameter	ICE	TEE
Invasiveness	Minimally invasive (intravascular catheter)	Invasive (transesophageal insertion)
Anesthesia requirement	Local anesthesia only; no general anesthesia	Usually requires general anesthesia or deep sedation
Patient comfort	Excellent; no nausea, gagging, or throat injury	Poor; high discomfort, nausea, sore throat, or mucosal injury
Real-time procedural guidance	Excellent; continuous real-time imaging during ablation/LAAO	Limited; mainly for preoperative screening
Transseptal puncture guidance	Superior; direct visualization of fossa ovalis	Limited; cannot provide real-time intraprocedural guidance
Left atrial appendage thrombus detection	High sensitivity/specificity; non-inferior to TEE	Gold standard for LAA thrombus diagnosis
Radiation exposure	No radiation	No radiation
Learning curve	A moderate learning curve for manipulation	Relatively operator-friendly
Cost	Relatively higher (disposable catheter)	Lower
Contraindications	Very few contraindications	Contraindicated in esophageal diseases, strictures, tumors, etc.
Main clinical role	Intraoperative imaging guidance for AF ablation and LAA closure	Preoperative thrombus screening; limited intraoperative use

AF: Atrial fibrillation; ICE: intracardiac echocardiography; LAA: left atrial appendage; LAAO: left atrial appendage occlusion; TEE: transesophageal echocardiography.

Limitations and future developments

Despite its clinical advantages, ICE still faces several practical and technical barriers that limit its widespread adoption. First, the technology is associated with a steep learning curve and substantial operator dependence. Operators require systematic training to master probe positioning, image interpretation, and intraoperative manipulation. Moreover, the assessment of ablation lesions lacks standardized quantitative criteria, remaining largely subjective and variable among different operators. In addition, both 2D and 3D ICE involve inherent trade-offs between imaging field of view and resolution, which further increase the complexity of operation. Second, evidence supporting novel applications remains incomplete. For emerging techniques such as PFA, as well as 3D and 4D ICE, relevant clinical data are still accumulating[72,73]. Standardized procedural protocols, along with robust long-term safety and efficacy data, have yet to be fully established, thereby limiting their routine use on a large scale[74]. Third, cost remains a prominent concern: disposable ICE catheters entail high procurement expenses, which raise overall procedural costs for both hospitals and patients[75,76]. Although catheter reprocessing may partially alleviate the economic burden, such practices have not been universally promoted[77-79] [Table 3].

CONCLUSION

ICE enables real-time, direct intracardiac visualization, shifting practice from indirect imaging to direct guidance. It facilitates transseptal puncture, catheter navigation, tissue contact assessment, and early detection of complications like pericardial effusion. It also supports low-fluoroscopy or zero-fluoroscopy ablation.

However, widespread use is constrained by cost, learning curve, and operator-dependent interpretation. Future advancements toward AI integration, automated reconstruction, and robotic assistance may reduce complexity. In summary, ICE is a critical tool in current AF interventions and is evolving toward greater precision and safety.

DECLARATIONS

Authors' contributions

Conceptualization, literature collation and synthesis, writing-original draft, visualization: Guo J
Writing-review and editing: Liu X
Conceptualization, supervision, project administration: Chen M
Literature retrieval, resource collection, writing-review and editing: Sun Y
Literature analysis and evaluation, writing-review and editing, supervision: Hu X
All authors have read and approved the final manuscript.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool DeepSeek (version V3, released 2024-12-26) and Nano Banana (version 2, released 2026-2-1) were used solely for language and figure editing. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

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Consent for publication

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