



Intracardiac Echocardiography during Invasive Electrophysiological Procedures: a Scientific Statement of the European Heart Rhythm Association of the ESC, and the European Association of Percutaneous Cardiovascular Interventions of the ESC

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Abstract

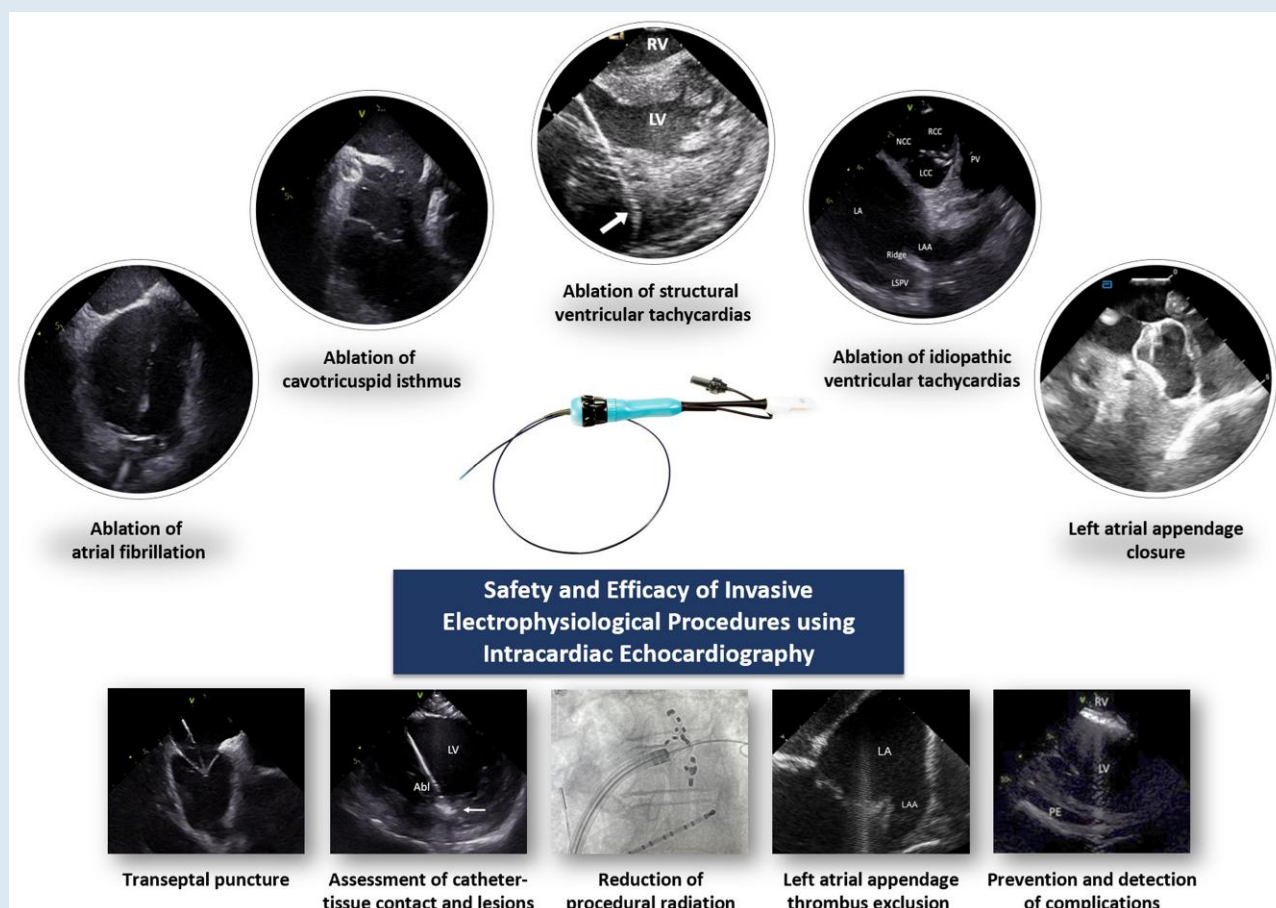
Intracardiac echocardiography (ICE) is an imaging technique that provides real-time, detailed visualization of intracardiac structures during various interventional procedures performed in the electrophysiology laboratory. Over the past decades, ICE has evolved beyond simply assisting with transseptal puncture, becoming an auxiliary tool in numerous aspects of cardiac interventions. This scientific statement offers a comprehensive, systematic overview of current applications of ICE across different clinical scenarios. The existing evidence regarding the benefits of ICE is primarily derived from observational studies, which complicates the formulation of definitive advice for its clinical use. Thus, this document aims to serve as a practical roadmap, emphasizing the key benefits of the technique. The document covers fundamental principles of ICE imaging, standardized views, its role in transseptal puncture, ablation of supraventricular and ventricular arrhythmias, reduction of procedural radiation, early detection and management of periprocedural complications, identification of infective endocarditis, and the role of ICE for endomyocardial biopsy and left atrial appendage occlusion procedures.

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Graphical abstract



Keywords Arrhythmias • Catheter ablation • Intracardiac echocardiography • Left atrial appendage closure • Endomyocardial biopsy • Infective endocarditis

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Intracardiac echocardiography catheter reprocessing in the EU: regulation, cost-effectiveness, and learning curve	29	PVs	pulmonary veins
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		RSPV	right superior pulmonary vein
		RV	right ventricle
		RVOT	right ventricular outflow tract
		SVC	superior vena cava
		SVT	supraventricular tachycardia
		TEE	transoesophageal echocardiography
		TSP	transseptal puncture
		TV	tricuspid valve
		VA	ventricular arrhythmia
		VT	ventricular tachycardia

Abbreviations

2D	two-dimensional
3D	three-dimensional
4D	four-dimensional
AF	atrial fibrillation
ASD	atrial septal defect
AT	atrial tachycardia

Introduction

Recent years have brought a wide variety of improvements in imaging techniques in invasive electrophysiology procedures.¹ One of these is intracardiac echocardiography (ICE), which enables real-time imaging of cardiac structures during procedures. The use of ICE has evolved substantially. It is no longer limited to guiding transseptal puncture (TSP),² but also enables detailed real-time recognition of cardiac anatomy, visualization of ventricular arrhythmogenic substrate, and monitoring of catheter-tissue interface during energy delivery. Furthermore, it enhances procedural safety due to early detection of potential complications, facilitating prompt management and minimizing adverse sequelae.³ Finally, it enables the reduction or elimination of procedural radiation.

General knowledge in imaging techniques (including ICE) is now included in 2024 updated EHRA core curriculum.⁴ Current European Society of Cardiology (ESC) guidelines and

scientific documents do not provide practical advice on the use of ICE in different electrophysiological procedures. This document intends to fill this gap by describing in detail the role of ICE in daily practice.

Aim of the paper

The document aims to propose a practical framework for the use of ICE based on a comprehensive literature review and evaluation of existing evidence. Currently, mainly retrospective studies are available on the use of ICE, making it impossible to issue evidence-based advice. Thus, we created a scientific statement with key messages to guide clinicians across various electrophysiological scenarios in a structured and systematic approach. A total of 18 specific sections cover basic principles of ICE imaging, description of standardized ICE views, utility of ICE for TSP, ablation of supraventricular and ventricular arrhythmias, role of ICE in reduction of procedural radiation, utility of ICE for early detection and management of periprocedural complications, and detection of infective endocarditis, and guidance of other invasive procedures performed in the electrophysiology lab such as endomyocardial biopsy (EMB) and left atrial appendage (LAA) occlusion.

Basic principles and available technology

Key messages:

- Intracardiac echocardiography has evolved from early rotational probes to phased-array systems, which have become the current standard of care.
- By integrating intracardiac echocardiography with electroanatomical mapping and deep learning, detailed three-dimensional left atrial shells can be generated automatically, enhancing both accuracy and efficiency in atrial fibrillation ablation.

Introduced in the early 1980s, ICE provides real-time visualization of cardiac anatomy.¹ Compared with transoesophageal echocardiography (TEE), ICE offers similar image quality, requires only local anaesthesia, and allows for direct operator control.^{5–7} These characteristics have contributed to the increased adoption of ICE in selected interventional cardiology and electrophysiology procedures.

An ICE system consists of a catheter with an ultrasound probe mounted at the tip, along with a compatible ultrasound platform. The catheter is advanced to the cardiac chambers through peripheral venous access.

ICE catheter categories

Three principal categories of ICE catheters are currently available (Table 1):

- Rotational (Radial) ICE uses a single rotating piezoelectric transducer mounted at the tip of a catheter to produce 360° radial images at high frequencies (9–12 MHz). While it provides excellent near-field resolution, it is limited by shallow penetration (6–8 cm) and lacks Doppler capabilities. Today, this technology has largely been replaced by the phased-array type of ICE catheters.
- Phased-array ICE currently represents the mainstream technology.^{2,3} These catheters employ a 64 to 88-element transducer within an 8–10 Fr steerable catheter, producing a 90° sector image perpendicular to the catheter tip. They operate at frequencies of 4–10 MHz and can penetrate depths of up to 15–21 cm. The catheter tip can be deflected in four directions by two rotational control knobs integrated into the handle (Figure 1). A higher tissue

penetration of phased-array catheters allows visualization of left cardiac structures from the right chambers. Additionally, phased-array ICE enables Doppler imaging, enhanced maneuverability, and, in some models, integration with electroanatomical mapping (EAM) systems.

- Volumetric ICE, marketed as either three-dimensional (3D) or four-dimensional (4D) depending on vendor terminology, represents the latest technological advances.⁸ These catheters feature an increased number of piezoelectric elements (128–840) arranged in a helical or matrix-array, allowing for live imaging with multiplanar reconstruction. They can provide 3D volume size up to 90° × 90°. These features come at a price of larger catheter diameters, ranging from 9 Fr to 12.5 Fr. Limitations include catheter stiffness, larger sheath requirements, and a learning curve for image interpretation.

An overview of major commercially available ICE catheters and their characteristics is provided in Table 2.

ICE integration with EAM and 3D imaging

The two-dimensional (2D) ICE systems primarily provide single-plane imaging, which can be challenging for operators unfamiliar with echocardiography. This may make it difficult to interpret and mentally reconstruct these images within a 3D cardiac anatomy (e.g. align the ICE view within 15-segment bi-atrial model recently proposed for EAM).¹⁰ To address these limitations and simplify guidance of electrophysiological procedures, new-generation ICE catheters have adopted two key approaches:

Integration of ICE catheter images with EAM systems

Some ICE catheters are equipped with embedded magnetic sensors that allow the catheter tip to be visualized on the mapping system. The ultrasound sector can thus be represented on the 3D map, creating anatomical shells and correlating images with real-time catheter position.¹¹ In the latest version designed to facilitate AF ablation, a deep learning algorithm automatically constructs detailed 3D left atrial anatomy (Figure 2, Supplementary material online, Video S8.1). This is achieved by processing 2D ultrasound clips acquired with a phased-array catheter rotated in the right atrium (RA) and right ventricular outflow tract (RVOT), and generating a left atrium (LA) shell onto which the ablation catheter is projected in real-time.¹² In a recent observational study, the use of automated algorithm for 3D shell reconstruction was associated with reduced procedural and LA dwelling time, without though significant impact on AF recurrence rate.¹³

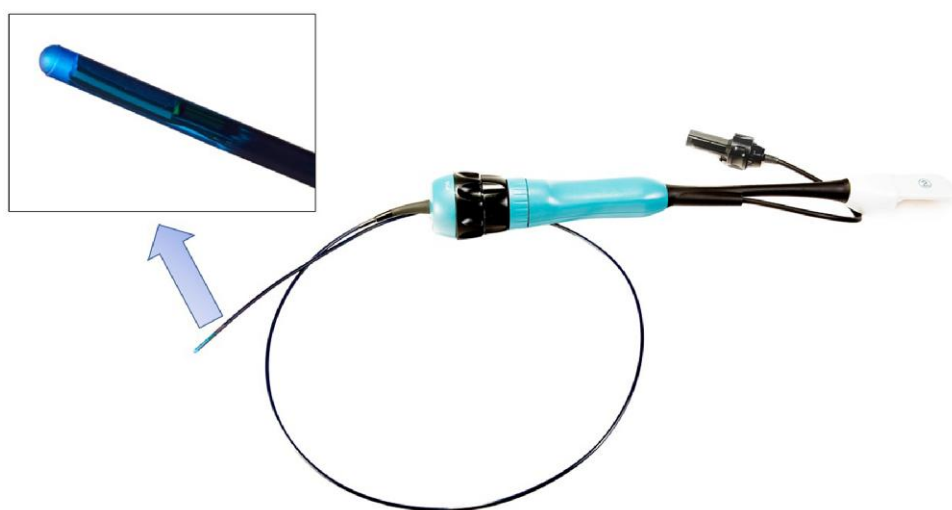
3D/4D ICE

Matrix-array ICE catheters offer several imaging capabilities, including single-plane 2D, biplane, live 3D, and 3D multiplanar reconstruction imaging.⁸ Compared with traditional 2D ICE, their main advantage is the ability to produce high-quality dynamic volumetric images, which enhances the visualization of cardiac structures. This feature has proven particularly valuable in complex procedures such as left atrial appendage closure (LAAC) and structural interventions, where precise anatomical detail is critical.¹⁴ While current clinical experience in electrophysiology is limited, integration of 3D ICE with EAM may broaden its role in catheter ablation in the future.^{15,16}

Despite these advantages, the adoption of volumetric (3D/4D) ICE remains limited by higher system and catheter costs. Whether it will enable easier adoption for users that are not familiar with 2D ICE is to be proven.

Table 1 Comparative features of ICE systems

Category	Feature	Rotational (Radial)	Phased-array	Volumetric (3D/4D)
Technical Specifications	Catheter Size	9 Fr	8–10 Fr	9–12.5 Fr
	Transducer	Single crystal	64-element array	128–840 element matrix
	Frequency	9–12 MHz	4–10 MHz	4–10 MHz
	Imaging Plane	360° radial	90° sector	3D/4D volumetric
	Penetration	6–8 cm	15–21 cm	Up to 21 cm
Functional Characteristics	Manoeuvrability	Only via steerable sheath	High (steerable)	High (steerable)
	Doppler	No	Yes	Yes
	Clinical Role	Niche applications	Standard of care	Emerging, advanced guidance of structural interventions

**Figure 1** Linear phased-array ICE probe with a four-way steerable tip controlled by two rotary knobs. The inset shows a magnified view of the catheter tip with its linear transducer array.

Standard and additional echocardiographic views

ICE images acquired by a phased-array probe are conventionally displayed with the marker positioned commonly on the left side of the image or in the right depending on training institutions. In the orientation with the marker on the left side of the image, the shaft of the probe corresponds to the left side of the image, whereas the distal tip of the probe is projected on the right. In clinical practice, standard positions of the ICE catheter are utilized to ensure consistent and optimal visualization. Knowledge of anatomical correlations is important in obtaining and understanding standard ICE views in the normal heart.

From femoral access to the home view

Basic imaging of intracardiac structures can be obtained from the RA. In most procedures, the ICE catheter is advanced to the RA via a right or left femoral approach, while a superior approach through the internal jugular or subclavian vein may

also be used in special circumstances. The introducer sheath required for ICE catheter insertion generally ranges from 9 French (Fr) to 11 Fr, depending on the specific catheter design. Vascular access and catheter advancement are usually straightforward, if several fundamental principles are followed. It is important to note that the ICE view stems from the side of the catheter tip. Therefore, the primary rule for safe advancement of the ICE catheter within the femoral vein is to ensure that a black, anechoic space, corresponding to the vascular space, is consistently visualized in the proximal sector of the fan view. Advancement should be avoided when a white, echogenic region is present. When an oblique anechoic space is visualized, this indicates that the catheter is being directed against the venous wall. In such circumstances, the catheter should be withdrawn slightly and tilted until a well-defined, anechoic space representing the venous lumen is again observed (see [Supplementary material online, Video S3.1](#)). In cases of extremely tortuous venous anatomy, the use of a longer sheath may overcome this problem. Importantly, fluoroscopy can be used by unexperienced operators at any stage of the procedure.

Table 2 Overview of major commercially available ICE catheters (adapted from ref.^{2,8,9})

Category & device	Company	Catheter size	Transducer	Manoeuvrability	Mapping compatibility	Console
Rotational ICE						
UltralCE Plus	Boston Scientific	9 Fr	A single crystal that physically rotates at high speed	Non-steerable	No	iLab™ Ultrasound
Linear Phased-Array						
Acuson AcuNav	Siemens Healthineers/ Biosense Webster	8 or 10 Fr	64-element phased-array	4-way deflection	No	Siemens ACUSON, GE Vivid
AcuNav Crystal	Siemens Healthineers/ Biosense Webster	9 Fr	88-element phased-array	4-way deflection	No	Siemens ACUSON, GE Vivid
ViewFlex Xtra	Abbott	9 Fr	64-element phased-array	4-way deflection	No	ViewMate Multi, Philips CX50
SoundStar	Siemens Healthineers/ Biosense Webster	8 or 10 Fr	64-element phased-array	4-way deflection	CARTO 3 (via CARTOSound): automated anatomy creation and integration with the SoundFam module	Siemens ACUSON, GE Vivid
SoundStar Crystal	Siemens Healthineers/ Biosense Webster	9 Fr	88-element phased-array	4-way deflection	CARTO 3 (via CARTOSound): automated anatomy creation and integration with the SoundFam module	Siemens ACUSON, GE Vivid
ViewFlex X	Abbott	9 Fr	64-element phased-array	4-way deflection	Ensite X (via Ensite Echo): Automated anatomy with AI assisted contouring	ViewMate Multi
Volumetric (3D/4D) ICE						
Acuson AcuNav Volume	Siemens Healthineers/ Biosense Webster	12.5 Fr	128-element helical-array, 3D (up to 90° × 50°)	4-way deflection	No	Siemens ACUSON SC2000, Origin
NuVision (NAV)	Biosense Webster	10 Fr	840-element matrix-array, 3D (up to 90° × 90°)	2-way deflection plus independent 360° tip rotation	CARTO3 for the NAV version	GE Vivid,
VeriSight Pro	Philips Healthcare	9 Fr	840-element matrix-array, 3D (up to 90° × 90°)	4-way deflection	No	Philips EPIQ CVx, Affiniti, CX50

From the home view to the right ventricle

After advancing the catheter to the mid-RA, the probe is positioned in front of the tricuspid valve (TV) in the so-called *home view* (Figure 3A). From this position, a comprehensive evaluation of the RA and TV can be performed (see [Supplementary material online, Video S3.2](#)). With a gentle clockwise rotation of the probe from the home view, a long-axis view of the aortic root is displayed. In this view, the non-coronary cusp is closest to the probe, overlying the His bundle region. The right coronary cusp is adjacent to the RVOT and the pulmonary valve. With

further clockwise rotation, the right and left ventricular outflow tracts (RVOT/LVOT) are visible. The left ventricle (LV) and the ostium of the coronary sinus are also visualized superior to the TV at the level of the aortic valve. Further clockwise rotation reveals the mitral valve, with the LAA positioned anteriorly (Figure 3B). Continued gentle rotation brings the left pulmonary veins into view, with the superior vein located on the right side of the view and the inferior vein on the left side (Figure 3C). Additional clockwise rotation demonstrates the descending aorta and the posterior wall of the LA (Figure 3D). Behind the posterior wall, the oesophagus is typically visualized. Further

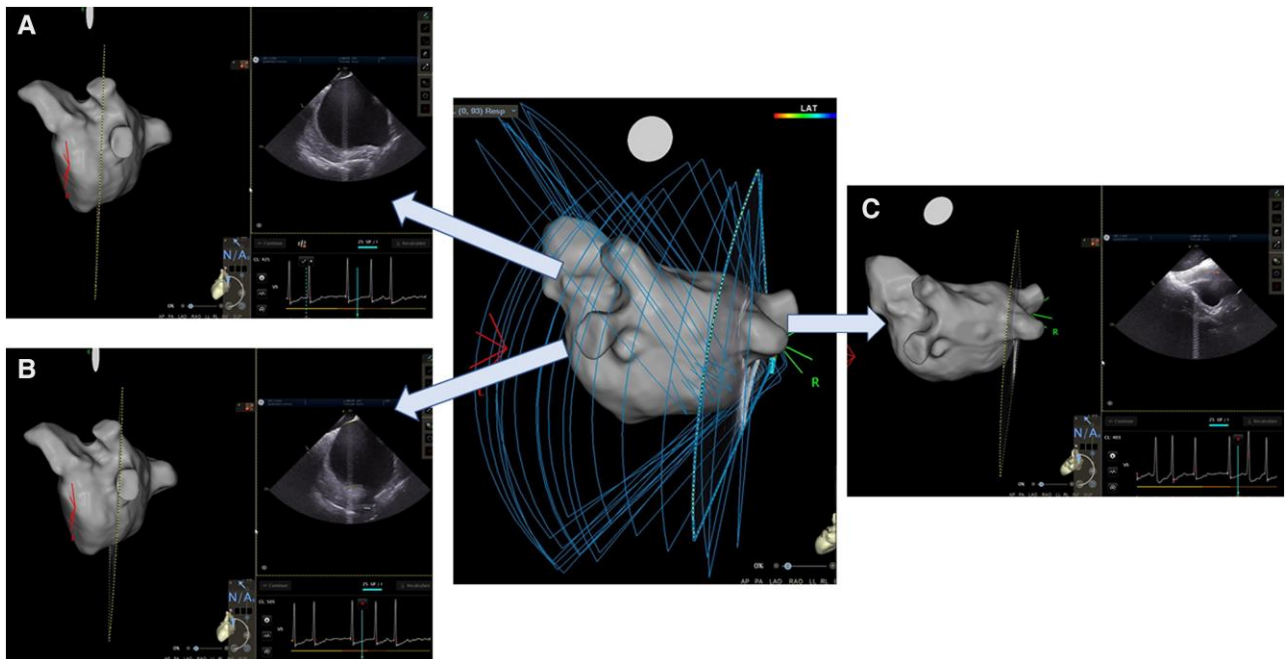


Figure 2 3D reconstruction of the LA generated by a deep learning-based automated algorithm (CARTOSound FAM) from sequential 2D intracardiac echocardiography (ICE) frames acquired by rotating the ICE probe in the RA and base of the RVOT. The displayed 2D plane frames represent the corresponding automatic acquisition planes, from which the algorithm constructs a best-fit anatomical shell (see [Supplementary material online, Video S8.1](#)). Three representative snapshots with their corresponding 2D ICE frames illustrate key anatomical landmarks: (A) LSPV, (B) LIPV and (C) RPV. LSPV, left superior pulmonary vein; LIPV, left inferior pulmonary vein; RA, right atrium; RPV, right pulmonary veins; RVOT, right ventricular outflow tract.

clockwise rotation from this position reveals the right pulmonary veins. The right inferior vein is visualized first (*Figure 3E*), and its longitudinal course can be better displayed by a slight posterior or leftward tilt of the probe. Mild clockwise rotation typically opens the view into the right superior vein with the adjacent pulmonary artery (PA) (*Figure 3F*). Continued clockwise rotation displays the posterior RA, while gentle posterior deflection visualizes the superior vena cava (SVC). Further rotation identifies the crista terminalis, and ultimately, the right atrial appendage and sulcus terminalis appear anteriorly within the RA. Continued rotation returns the probe to the starting orientation, the home view. The views from the RA have also been proposed to facilitate the localization of fat pads containing ganglionated plexi targeted during cardioneuroablation.¹⁷

From the *home* view, a mild counterclockwise rotation and major anterior deflection of the catheter allow advancement into the right ventricle (RV) (see [Supplementary material online, Video S3.3](#)). At this stage, fluoroscopy may be used for less experienced operators—particularly in the right anterior oblique projection—to clearly delineate the RV, RA, and TV. Once positioned within the RV, the initial view displays the inferior RV with the moderator band (*Figure 4A*). Releasing the anterior bend of the catheter and applying gentle clockwise rotation successively displays the interventricular septum, the apex, the posteromedial papillary muscle (PM—*Figure 4B*), and with further rotation, the anterolateral PM (*Figure 4C*), the mitral valve and the lateral LV wall.

Additional clockwise manipulation provides the LVOT view, and further rotation demonstrates the aortic root with all three

cusps (*Figure 4D*). Advancing the catheter through the RVOT brings the ascending aorta into view. From this vantage point, the left superior pulmonary vein (LSPV) and the LAA are identified, while further advancement reveals the pulmonic valve and the PA.

Besides these standard views, additional ones might be required for detailed imaging of specific structures. For visualization of the LAA to rule out presence of thrombus, ICE might be inserted in the PA (see *Intracardiac echocardiography for left atrial appendage thrombus exclusion*). For even more detailed visualization of LAA, ICE probe can be positioned transeptally into the LA and the LSPV (see *Intracardiac echocardiography for left atrial appendage closure* on methods, how to cross interatrial septum with ICE probe). For optimal imaging of the LV structures (e.g. posteromedial PM), ICE catheter can further be advanced across the mitral valve in the superior aspect of the LV (see *Intracardiac echocardiography for ablation of non-outflow tract ventricular arrhythmias* and *Intracardiac echocardiography for ablation of structural ventricular tachycardias*). Finally, the ICE probe can be introduced into the coronary sinus.¹⁸ This allows visualization of the LA roof, LAA, both ventricles, and mitral annulus (see [Supplementary material online, Videos S3.4 and S3.5](#)).

Relevant videos for section standard and additional echocardiographic views

To see the relevant videos for this section, list below, [Supplementary Material](#) is available at [Europace](#) online.

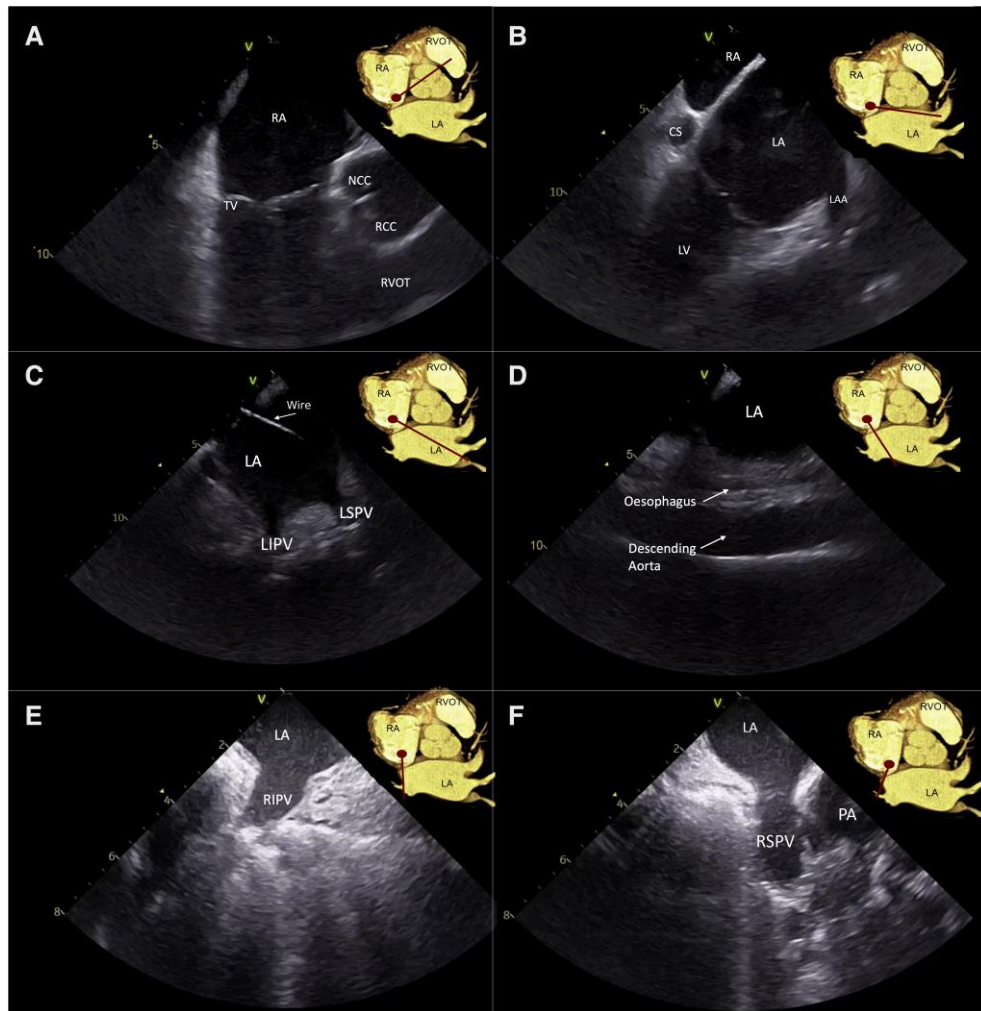


Figure 3 ICE views from the RA showing cardiac structures as they appear during clockwise rotation of the probe. For each of the views, the direction of the imaging beam is shown on the CT heart model in the upper right corner. (Panel A) The home view with the RA, the RVOT, and the aortic valve in long axis view. (Panel B) The LV, the ostium of the coronary sinus, the mitral valve and the LAA. (Panel C) Long axis view of the LPVs. (Panel D) The posterior wall of the LA, the oesophagus and the descending aorta. (Panel E) The RIPV. (Panel F) The RSPV and the pulmonary artery. CS, coronary sinus; LA, left atrium; LAA, left atrial appendage; LIPV, left inferior pulmonary vein; LSPV, left superior pulmonary vein; LPV, left pulmonary veins; LPVLV, left ventricle; NCC, non-coronary cusp; PA, pulmonary artery; RA, right atrium; RCC, right coronary cusp; RIPV, right inferior pulmonary vein; RSPV, right superior pulmonary vein; RVOT, right ventricular outflow tract; TV, tricuspid valve. V, left ventricle; NCC, non-coronary cusp; PA, pulmonary artery; RA, right atrium; RCC, right coronary cusp; RIPV, right inferior pulmonary vein; RSPV, right superior pulmonary vein; RVOT, right ventricular outflow tract; TV, tricuspid valve.

ICE guided transseptal puncture

Key messages:

- Intracardiac echocardiography enhances procedural safety during transseptal puncture and is particularly useful in challenging interatrial septum anatomies.
- The use of intracardiac echocardiography enables site-specific transseptal puncture.
- Intracardiac echocardiography allows fluoroless transseptal puncture.
- Intracardiac echocardiography allows prompt identification of complications related to the transseptal puncture, enabling timely intervention.

TSP is a vital step in many electrophysiological procedures. A thorough understanding of the interatrial septum's anatomy and its relationship with neighbouring structures is essential to avoid procedural complications. The anatomic target for TSP is specifically the fossa ovalis, not the entire right atrial septal wall. The area superior to the fossa ovalis consists of an infolding of the atrial wall filled with extracardiac adipose tissue. An inadvertent puncture of this area may create a communication with the pericardial space. Furthermore, the segment of the right atrial wall that is anterior and superior to the fossa ovalis, known as the aortic mound, overlies the aorta and should be avoided during puncture. Therefore, the safe target area for TSP is limited,

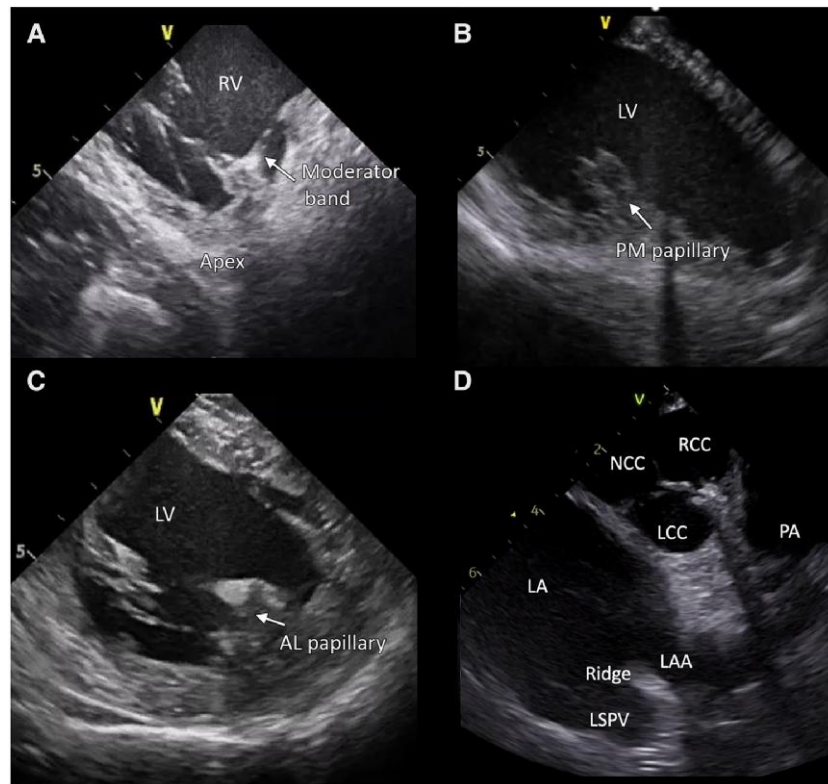


Figure 4 ICE view of ventricular structures from the RVOT. (Panel A) The RV cavity with the moderator band. (Panel B) The LV with the posteromedial PM. (Panel C) The LV with the anterolateral PM. (Panel D) The aortic valve in the short axis with aortic cusps and transverse view of the LA displaying the coumadin ridge between the LAA and LSPV. AL, anterolateral; LAA, left atrial appendage; LCC, left coronary cusp; LSPV, left superior pulmonary vein; LV, left ventricle; NCC, non-coronary cusp; PA, pulmonary artery; PM, posteromedial; RCC, right coronary cusp; RV, right ventricle.

and solely relying on fluoroscopic guidance does not guarantee maximum procedural safety.

ICE offers direct and comprehensive imaging of the fossa ovalis and the neighbouring structures. It allows for assessment of potential anatomic challenges or variations and facilitates accurate identification of the target anatomic site. ICE is also useful for detecting the presence of a patent foramen ovale (PFO) (see [Supplementary material online, Video S4.1](#)), which may be used for gaining direct access to the LA (see [Supplementary material online, Video S4.2](#)). Precise positioning of the sheath-dilator-needle assembly at the desired puncture site can be assessed by visualizing the characteristic tenting of the fossa ovalis on ICE imaging, indicating adequate contact before puncture (see [Supplementary material online, Video S4.3](#)). Familiarity with the typical short- and long-axis views of the fossa ovalis is essential for visualizing needle positioning in the anterior-posterior and cranio-caudal axes, respectively (see [Supplementary material online, Videos S4.4](#) and [S4.5](#)). Combining these perpendicular axial views enables site-specific transseptal crossing, which is crucial for various electrophysiological procedures: central-inferior puncture for pulmonary vein isolation (PVI), posterior-inferior site for LAA closure and anterior-inferior location for antegrade access to the left ventricle (see [Supplementary material online, Video S4.6, Figure 5](#)).

ICE enables the performance of TSP with minimal or even zero use of fluoroscopy. The fluoroless approach relies on

direct visualization and careful execution of each step in the TSP process (guidewire advancement in the SVC—[Supplementary material online, Video S4.7](#), advancement of the sheath over the wire—[Supplementary material online, Video S4.8](#), dragging of the sheath-needle assembly towards the fossa and controlled positioning at the desired puncture location—[Supplementary material online, Video S4.9](#)). Despite its proven feasibility, performing safe fluoroless TSP is dependent on the operator's experience level and requires proficiency in ICE.

ICE also allows for verification of transseptal crossing and safe access to the LA. This is accomplished by directly visualizing the needle crossing through the fossa ovalis, resulting in flattening of the previously tented area (see [Supplementary material online, Video S4.10](#)). Furthermore, saline or contrast injection and visualization of 'microbubbles' in the LA can confirm proper access (see [Supplementary material online, Video S4.11](#)). A major advantage of ICE is that it eliminates the need for injecting contrast media at each stage of the TSP procedure, including verification of correct positioning of the sheath/needle assembly, proper engagement of the fossa ovalis, and left atrial access by fluoroscopically verified staining. This is particularly beneficial for patients with impaired renal function or contraindication to iodinated contrast medium.

The clinical benefits of ICE in transseptal puncture are most pronounced when addressing challenging septum

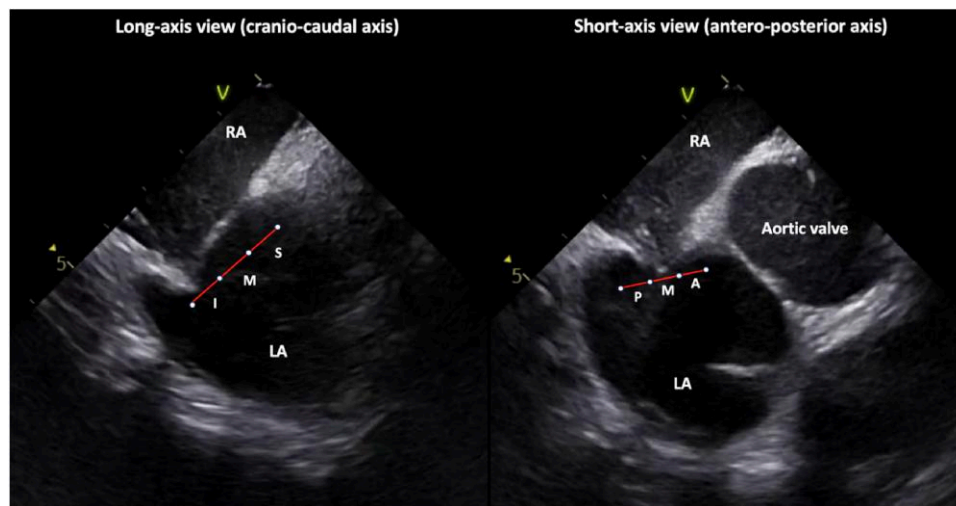


Figure 5 ICE guided site-specific transseptal puncture. Site-specific transseptal puncture guided by ICE. Combined use of long and short axis view enables needle positioning at the mid-inferior fossa. In the left panel, the long axis view guides needle positioning in the cranio-caudal axis, while the short axis view (right panel) enables needle localization in the antero-posterior axis. A, anterior; I, inferior; M, mid; P, posterior S, superior.

Table 3 ICE for transseptal puncture in challenging septal anatomies

Septum variations—challenges	ICE findings	Clinical implications
Aneurysmal septum	- Assessment of the extent of septal aneurysm excursion - Excessive tenting of the FO within the LA by the sheath-needle assembly - Limited distance between the tip of the tenting and the opposite left atrial wall	- Controlled exertion of gentle force during needle advancement - Increased risk of inadvertent LA wall perforation - Potential need for use of radiofrequency needle or transseptal puncture systems
Fibrotic or thickened FO	Thickened FO with increased echo density	- Increased force needed to achieve transseptal crossing - Increased risk of inadvertent LA wall perforation - Potential need for use of radiofrequency needle or transseptal puncture systems
Lipomatous hypertrophy	- Hourglass configuration of the thickened IAS - Narrow, normal thickness FO	- Avoid puncturing the hypertrophied IAS beyond the FO - ICE-facilitated visualization of the sheath dragging process to ensure proper falling within the narrow FO - Limited target site for TSP
Surgical transseptal patch	- Direct imaging of the transseptal patch - Assessment of patch thickness and surrounding native tissue	- ICE-guided attempt to cross patch with mechanical needle - Increased force likely needed to achieve transseptal crossing through the patch - Potential need for use of radiofrequency needle or transseptal puncture systems
Atrial septal occlusion device	- Visualization of the occlusion device - Assessment of remaining native tissue usually inferior-posterior to the device	- ICE-guided positioning of the sheath needle assembly in an accessible rim - ICE-guided puncture through the device with the use of radiofrequency needle in the absence of remaining native tissue

FO, fossa ovalis; IAS, interatrial septum; ICE, intracardiac echocardiography; LA, left atrium; PFO, patent foramen ovale.

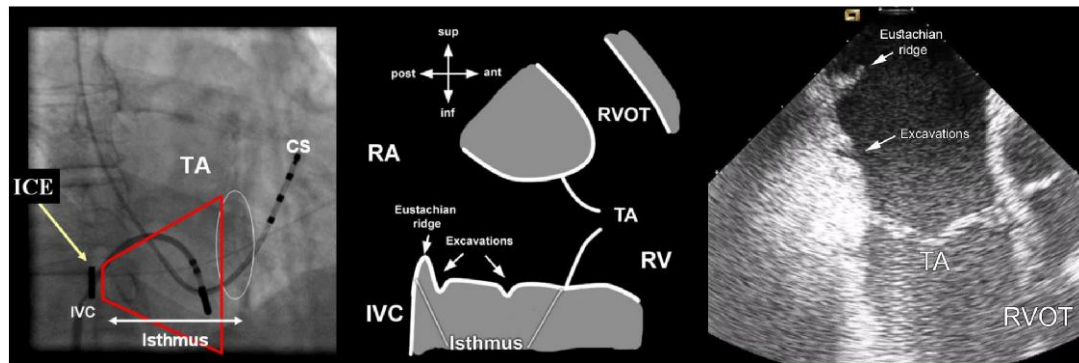


Figure 6 Anatomy of the CTI. Left panel displays fluoroscopic view (RAO) of the ICE catheter position used for CTI visualization and the pertinent ICE fan view (indicated by the rectangle). Middle panel shows schematic depiction of CTI and neighbouring structures. The right panel displays the typical ICE view for CTI visualization. CS, coronary sinus; IVC, inferior vena cava; RA, right atrium; RVOT, right ventricular outflow tract; RV: right ventricle; TA, tricuspid annulus.

anatomies (Table 3, [Supplementary material online, Videos S4.12–S4.14](#)). Such anatomical variations are associated with a higher risk of TSP-related complications, and, in rare cases, failure to access the LA when attempted using fluoroscopy alone. Direct visualization of the interatrial septal anatomy and identification of challenging variations enable the development of a strategy for safe left atrial access (titration of the manual force exerted to cross the septum, assessment of the distance between the tented fossa and the opposing left atrial wall, evaluation of rim presence in patients with occlusion device). Furthermore, ICE findings can be used to determine the need for employing specific tools for transseptal puncture (e.g. RF needles, TSP systems—[Supplementary material online, Video S4.15](#)). A detailed description of the use of these systems is beyond the scope of this document.

Complications during electrophysiological procedures are frequently related to TSP.^{19–24} In the unlikely event of a TSP-related complication, ICE facilitates its prompt identification (e.g. pericardial effusion, atrial dissection), allowing for timely interventions to ensure optimal patient management (see *Intracardiac echocardiography for prevention and detection of procedural complications—complications*).

Relevant videos for section ICE guided transseptal puncture

To see the relevant videos for this section, list below, [Supplementary Material](#) is available at [Europace](#) online.

Intracardiac echocardiography in cavotricuspid isthmus dependent atrial flutter ablation

Key messages:

- Intracardiac echocardiography enables visualization of the anatomy and mobility of the cavotricuspid isthmus (CTI).
- Intracardiac echocardiography allows optimization of catheter-tissue contact on the CTI.

- Intracardiac echocardiography may enhance the efficacy of CTI ablation, especially in complex anatomical situations and redo cases.
- Intracardiac echocardiography reduces fluoroscopy exposure during CTI ablation.

Catheter ablation is a well-established treatment for CTI-dependent typical atrial flutter, offering high success with low complication rates.^{25,26} However, anatomical variations may present challenges for creation of a durable bidirectional block.²⁷ ICE allows for real-time visualization of CTI anatomy, helping to identify key landmarks such as the Eustachian ridge, the inferior vena cava (IVC) junction, and the tricuspid annulus (Figure 6 and [Supplementary material online, Video S5.1](#)). ICE is particularly beneficial for patients with challenging anatomies (see [Supplementary material online, Videos S5.2–S5.5](#)), such as a prominent Eustachian ridge, deep pouches, a hypermobile isthmus, or a sub-Eustachian recess, which can affect both catheter stability and lesion quality. Moreover, ICE provides real-time monitoring of catheter orientation, facilitates optimal catheter positioning, and allows continuous assessment of catheter-tissue contact (see [Supplementary material online, Videos S5.6 and S5.7](#)). ICE may be particularly helpful when non-contact force sensing catheters are used, as tactile feedback and fluoroscopy information are less reliable, e.g. when using a pentapline catheter (see [Supplementary material online, Videos S5.8 and S5.9](#)).

Using ICE is a feasible and safe approach that can minimize or even eliminate radiation exposure, while maintaining procedural efficacy.^{28,29} Compared with CTI ablation procedures performed without ICE, the use of ICE is associated with a higher first-pass success rate, and shorter ablation times.^{30,31} This improved outcome may be due to the ability of ICE to avoid prolonged radiofrequency applications in specific locations (e.g. within pouches), thus reducing the risk of steam pops. ICE may also enhance ablation effectiveness in complex anatomical situations, such as in the presence of a prominent Eustachian ridge or a pouch, where looping the ablation catheter is often necessary (see [Supplementary material online, Videos S5.7 and S5.9](#)) to achieve optimal catheter positioning and lesion quality.^{32–34} ICE also enables visualization of the right coronary artery (RCA) coursing below the CTI (see [Supplementary](#)

[material online, Video S5.10](#)). Extensive CTI ablation using RF or PF carries a potential risk of inadvertent injury or spasm to the neighbouring RCA. However, this risk is mitigated in the clinical setting because the artery acts as a heat sink and cools down the surrounding tissue.³⁵ Finally, ICE can be used to exclude the presence of thrombus in the right and LAA^{36,37} (see Intracardiac echocardiography for left atrial appendage thrombus exclusion).

For CTI ablation, the home view is typically used. By clockwise and counterclockwise rotation of the ICE probe, the septal (where the aorta is also visible) and the lateral (aorta not visible) CTI can be visualized, respectively, while by pulling the ICE probe backwards, the proximal CTI can be visualized.

Relevant videos for section intracardiac echocardiography in cavotricuspid isthmus dependent atrial flutter ablation

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

Intracardiac echocardiography in ablation of supraventricular tachycardias

Key messages:

- Intracardiac echocardiography allows real-time visualization of the Koch's triangle, enabling localization of the slow pathway region during atrioventricular nodal re-entrant tachycardia ablation.
- Intracardiac echocardiography offers real-time visualization of the tricuspid and mitral annuli, facilitating optimal catheter positioning and stability during accessory pathway ablation.
- Intracardiac echocardiography enhances catheter positioning during ablation of atrial tachycardias originating from challenging regions (e.g. atrial appendages or perinodal region).
- Intracardiac echocardiography reduces fluoroscopy exposure in patients undergoing ablation of supraventricular tachycardias.

ICE has emerged as a valuable adjunctive imaging modality in the catheter ablation of supraventricular tachycardias (SVTs). This technique provides high-resolution, real-time visualization of cardiac structures, facilitating procedural guidance. By enabling direct anatomical imaging, ICE aids in accurate mapping and targeted ablation in patients undergoing SVT ablation.

Randomized trials have demonstrated that ICE guidance is a valuable adjunct in patients with atrioventricular nodal re-entrant tachycardia (AVNRT). ICE has been shown to reduce fluoroscopy exposure and the ablation energy required to reach durable endpoints during AVNRT ablation.^{38,39} Observational data further support these findings by showing comparable efficacy and safety to fluoroscopy-guided procedures.⁴⁰ ICE-guided visualization of the Koch's triangle aids in identifying the optimal ablation site and, in the absence of contact force-sensing catheters, assists in achieving and maintaining stable catheter-tissue contact (see [Supplementary material online, Video S6.1](#)).

For ablation of accessory pathways, ICE offers distinct advantages by providing high-resolution imaging of critical intracardiac structures. This capability is particularly beneficial in complex cases, such as Ebstein's anomaly, where multiple or atypically located pathways may coexist^{41–45} (see [Supplementary material online, Video S6.2](#)). ICE enables

accurate localization and positioning of the ablation catheter on the atrioventricular ring, thereby improving mapping accuracy and procedural efficacy. In addition, by delineating nearby anatomical landmarks such as the coronary arteries, ICE improves procedural safety and reduces the risk of complications. In patients undergoing ablation of left-sided accessory pathways, ICE can also facilitate safe and efficient TSP by providing real-time visualization of the interatrial septum and adjacent structures. The integration of ICE with electroanatomic mapping systems has also been demonstrated to minimize or even eliminate fluoroscopy, while maintaining excellent acute and long-term outcomes in patients undergoing accessory pathway ablation⁴⁶ (see [Supplementary material online, Video S6.3](#)).

ICE can also be advantageous in the ablation of atrial tachycardias (ATs), especially in anatomically complex regions such as the atrial appendages or perinodal areas. The intricate morphology of the appendages often hampers stable catheter contact and results in relatively high recurrence rates. ICE supports real-time anatomical visualization, ensures stable catheter positioning, and allows for direct monitoring of lesion formation (see [Supplementary material online, Video S6.4](#)). Moreover, ICE enhances procedural safety by clearly outlining adjacent critical structures, such as the coronary arteries and the aortic root, which is particularly important when ablating perinodal ATs⁴⁷ (see [Supplementary material online, Video S6.5](#)).

To visualize the slow pathway region, the ICE catheter is positioned in the low right atrium and rotated clockwise toward the septum. This imaging plane permits visualization of key anatomical landmarks, including the septal CTI, coronary sinus ostium, TV, RV, and aortic root. His potential is typically recorded septally at the junction of the TV and the aortic root. ICE-guided placement of the ablation catheter inferior to the His bundle area enables the recording of slow pathway potentials and the induction of junctional acceleration during energy delivery ([Figure 7](#)).

During accessory pathway ablation, the visualization of the tricuspid or mitral annulus is crucial for accurate mapping and monitoring of the ablation procedure. This can be readily achieved from the home view. From this orientation, a 10–15° clockwise rotation of the transducer enables visualization of the septal annulus, while an additional 10–15° clockwise adjustment brings the mitral annulus into view. Conversely, rotating counterclockwise from the home view displays the lateral tricuspid annulus, and with a further 10–15° counterclockwise adjustment, the crista terminalis and right atrial appendage can be visualized.

Relevant videos for section intracardiac echocardiography in ablation of supraventricular tachycardias

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

Intracardiac echocardiography for left atrial appendage thrombus exclusion

Key message:

- Intracardiac echocardiography allows visualization of the LAA for exclusion of preexisting or de-novo formed thrombus.

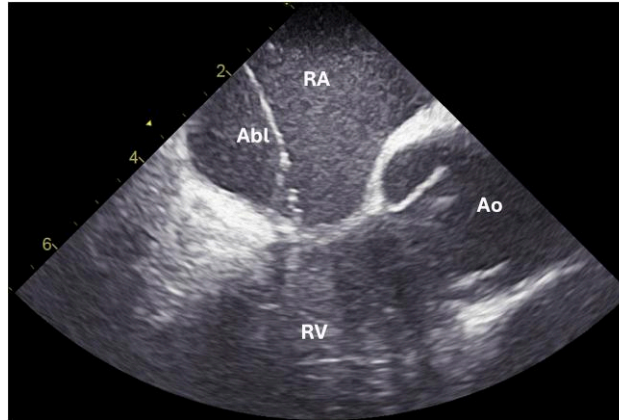


Figure 7 Intracardiac echocardiography visualizing the position of the ablation catheter and relevant surrounding anatomical structures during slow pathway ablation. Abl, ablation catheter; Ao, aortic root; RA, right atrium; RV, right ventricle.

Excluding the presence of thrombus in the LAA is essential before conducting any invasive procedures in the LA. Various imaging methods can be employed for this assessment. Available options include non-invasive techniques like cardiac computed tomography or cardiac magnetic resonance (CMR) imaging, semi-invasive approaches such as TEE—which remains the gold standard—and invasive procedures using ICE.

While ICE requires access through the groin, it serves as a viable alternative when less invasive methods are contraindicated or unavailable. For an accurate assessment of the LAA, the ICE catheter can be positioned in several locations.⁴⁸ In vivo studies have demonstrated that positioning the catheter in the PA provides optimal visualization of the LAA due to its anatomical proximity.⁴⁹ This finding has been confirmed in clinical studies comparing ICE with TEE for thrombus exclusion, showing similar success rates in LAA visualization.^{50–52} While earlier studies were limited by low participant numbers, recent publications offer significantly larger datasets that clearly underscore the importance of ICE for LAA visualization.³⁶ Of note, a recent randomized clinical trial confirmed that ICE imaging, when compared with TEE, is non-inferior in preventing 30-day thromboembolic events in patients undergoing atrial fibrillation (AF) ablation.⁷ Additionally, in cases where TEE results are inconclusive, ICE may be used for thrombus exclusion.⁵³ Although ICE may be an effective alternative to TEE, TEE remains the reference standard in most centres. Finally, continuous ICE monitoring can be beneficial during procedures that carry a very high-risk of periprocedural thrombus formation in the LAA.⁵⁴

The anticipated introduction of 4D ICE may serve to enhance the accuracy of LAA imaging,⁵⁵ although this requires further validation. Its incremental costs compared with 2D ICE may limit its widespread adoption in electrophysiology (see *Future directions*).

The visualization of the LAA typically commences with positioning the ICE catheter in the right atrium, where only the entrance to the LAA is clearly visible (*Figure 8*). The ICE catheter is then advanced to the RV, allowing visualization of the long axis of the LA and the proximal portion of the LAA.

To access the PA, the ICE catheter placed in the RV should be rotated clockwise until both the pulmonary valve and the

PA trunk are visible. To safely advance the ICE catheter in the PA, an anterior deflection should be applied, keeping the PV in constant view. To proceed into the PA, a forward movement of the ICE probe through the PV should be applied, keeping the valve in constant view. For less experienced operators, manoeuvring the ICE probe under fluoroscopic guidance can be beneficial. In this scenario, the right anterior oblique view (20–30°) should be utilized. The ICE probe should be directed toward the posterior part of the RVOT, avoiding its anterior portion, where inattentive manipulation may increase the risk of RV perforation. For challenging cases, placing a flexible decapolar catheter in the RVOT/PA prior to the ICE catheter can act as a roadmap to better illustrate the anatomy.

To achieve the most reliable assessment of the LAA, the ICE probe should be positioned in the left PA due to its proximity to the LAA. By carefully manipulating and rotating the ICE, the LAA can be visualized, starting from its proximal section. By manoeuvring counterclockwise, the more distal parts of the LAA can be displayed until reaching the most distal section. During this process, the operator should assess the contractility of the LAA and check for thrombus presence. To further enhance the assessment of LAA function, continuous flow Doppler measurements may be performed. Thrombi may be visualized as dense, echogenic areas in the LAA (see [Supplementary material online, Video S7.1](#)). In cases of suspected thrombus, colour flow imaging may be utilized. Alternatively, the ICE catheter can be introduced into the coronary sinus and rotated until a longitudinal view of the left ventricle is obtained, also displaying the LAA adjacent to it. Ultimately, the LAA can be visualized from the LSPV (see [Supplementary material online, Video S7.2](#) see *Intracardiac echocardiography for left atrial appendage closure on LAA closure*).

Relevant videos for section intracardiac echocardiography for left atrial appendage thrombus exclusion

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

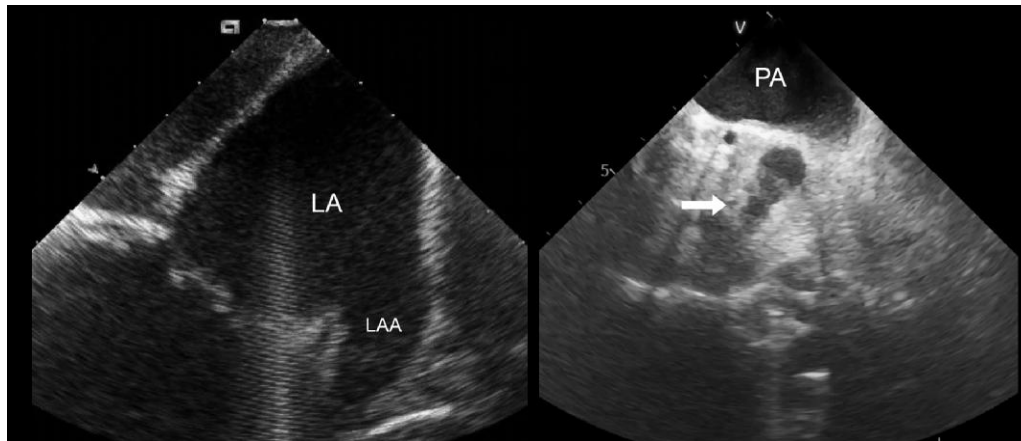


Figure 8 Visualisation of LAA from the RA (left panel) and from the PA (right panel). LA, left atrium; LAA, left atrial appendage; PA, pulmonary artery.

Intracardiac echocardiography for atrial fibrillation ablation

Key messages:

- Intracardiac echocardiography can be used to guide catheter positioning and to optimize catheter contact during pulmonary vein isolation and for ablation of extrapulmonary sites during AF ablation.
- Intracardiac echocardiography allows lesion monitoring and prompt detection of complications, enhancing procedural safety across various AF ablation strategies.
- Intracardiac echocardiography reduces fluoroscopy exposure and contrast media use in various AF ablation settings.

PVI remains the central strategy in AF ablation.⁵⁶ However, the anatomical variability of pulmonary veins may increase procedural complexity justifying the use of advanced imaging tools.⁵⁷ In this context, ICE may prove a useful procedural adjunct, facilitating several stages of the ablation workflow. ICE offers real-time, radiation-free visualization of key anatomical structures, including the LA, the pulmonary veins (PVs), the interatrial septum, the oesophagus, and the phrenic nerve. It facilitates TSP (See ICE guided transseptal puncture), accurate navigation of the mapping and ablation catheters, lesion delivery, and early detection of procedural complications.^{58–61} When integrated with 3D EAM systems, ICE allows for real-time anatomical reconstruction. Recent innovations enable automated LA modelling¹² (Figure 9, [Supplementary material online, Videos S8.1](#) and [S8.2](#)).

During PVI, observational studies have shown that ICE facilitates correct positioning and optimal contact of the ablation catheter at the antral location, reduces fluoroscopy time, and improves catheter stability.⁶² In persistent AF, where ablation often extends beyond the PVs, ICE supports substrate modification by guiding ablation of extrapulmonary regions. Its ability to monitor catheter-tissue contact and lesion formation is particularly valuable in these complex scenarios.

During AF ablation, two main positions for the ICE probe are required for complete LA visualization. The first involves placing the ICE catheter in the RA in the neutral 'home view' position. A clockwise rotation from this position progressively reveals the LAA and the left PVs. In this view, the left PVs are displayed longitudinally. Further clockwise rotation shows the posterior wall

with the neighbouring oesophagus, and subsequently the right PVs. Depending on the position of the heart, the right PVs can be displayed either in cross-sectional view or in a more longitudinal projection. Mild posterior bend of the probe may help to display veins in a longitudinal view. First, the right inferior PV is visible, and with more clockwise rotation, the right superior PV is visualized with the PA adjacent to it. Small adjustments can improve visualization of the roof and the right superior pulmonary vein ostium, such as advancing the probe towards the SVC-RA junction. The second view of the LA involves positioning of the ICE catheter at the base of the RVOT, with the probe oriented upwards. This view can be easily acquired by anterior flexion of the catheter to enter the body of the RV, followed by slow release of the catheter bend with continuous clockwise rotation until the aortic valve is visible in a short axis. Below the aortic valve, the LAA is visualized, separated from the LSPV by the carina or ridge of variable thickness. This view allows for precise placement of the ablation catheter, especially in the LSPV with optimal assessment of its location in the anterior-posterior axis (Figure 10). A third position is direct placement of the ICE catheter into the LA. After transseptal access, the puncture site can be dilated with the transseptal sheath, and then the sheath is withdrawn into the RA over a retained wire. With gentle advancement and anterior deflection to align the tip with the wire, the ICE catheter can be advanced into the LA, and the sheath repositioned over the wire. This technique provides excellent visualization of the PVs and catheter position, especially when thick septal tissue limits ultrasound penetration (see *Intracardiac echocardiography for left atrial appendage closure* on LAA closure).

Using these views, ICE is effective across multiple ablation modalities. In radiofrequency (RF) ablation, ICE can be used to visualize the tip of the ablation catheter and confirm its contact with the tissue throughout the cardiac cycle. Several studies have shown that ICE-guided RF ablation is associated with reduced procedure duration, lower complication rates, and improved lesion durability.^{63–66} Furthermore, it enables precise antral PVI while maintaining a safe distance from the PV ostia to prevent stenosis.⁶⁷ Direct imaging of the oesophagus may improve safety during posterior wall ablation. ICE may also facilitate transmural lesion formation by monitoring contact and guiding energy titration based on wall thickness to avoid tissue overheating.^{65,68} Clinical studies and meta-analyses have shown that ICE use is associated with superior procedural safety, reduced fluoroscopy

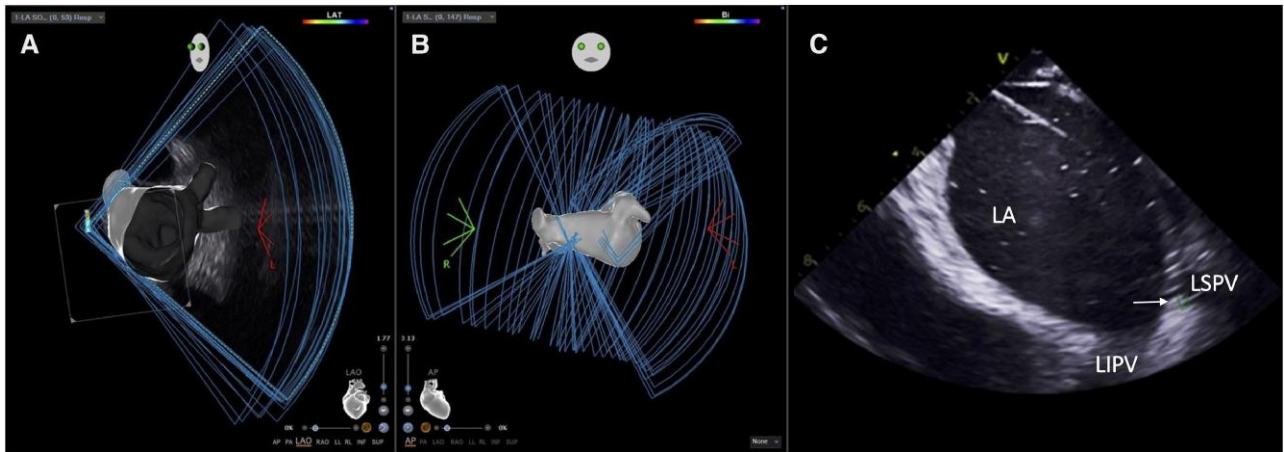


Figure 9 Left atrial reconstruction using the CARTOSOUND™ FAM module. ICE view from the right atrium at the level of the left pulmonary veins (Panel A). Panel B shows the complete reconstruction of the LA, obtained by integrating contours automatically acquired from the 2D ultrasound frames. Panel C shows the position of the ablation catheter, with its tip (arrow) positioned at the carina between the two LPVs (highlighted by the arrow). LA, left atrium; LSPV, left superior pulmonary vein; LIPV, left inferior pulmonary vein; LPVs, left pulmonary veins.

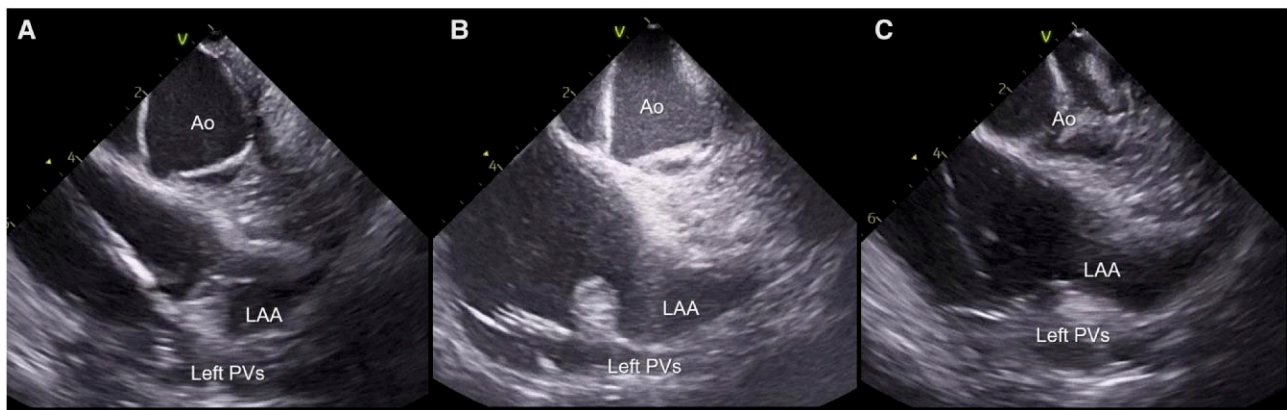


Figure 10 Optimization of the pentaspline catheter positioning using intracardiac echo (ICE) during pulmonary vein isolation. The ICE catheter is positioned in the RVOT and clearly depicts the ridge between the left superior vein and appendage. The first two panels show suboptimal position with too anterior position (Panel A) and too deep position in the left superior vein (Panel B). Panel C shows optimized position with the pentaspline catheter overlying the antral portion of the left superior vein. Ao, aortic root; LAA, left atrial appendage; PVs, pulmonary veins.

use and procedure time, with comparable long-term outcomes as compared to conventional RF ablation.^{69–71} ICE is also beneficial in high-power-short-duration RF protocols.⁷² Examples of mapping and ablation of PVs using RF are shown in [Supplementary material online, Videos S8.3 and S8.4](#).

In cryoballoon ablation, ICE optimizes balloon positioning, confirms PV occlusion, and assesses phrenic nerve proximity. PV occlusion can be verified via Doppler imaging or by assessing for potential 'microbubble' backflow after saline injection. This approach reduces radiation exposure and contrast usage,⁷³ which is particularly beneficial for patients with contraindications to contrast agents or when minimizing radiation exposure is essential. In a prospective randomized trial comparing

ICE-guided fluoroless cryoballoon ablation with conventional fluoroscopic approach, no difference was observed in the risk of complications or recurrences between the two strategies⁷⁴ (see [Supplementary material online, Videos S8.5 and S8.6](#)).

Pulsed field ablation (PFA) is a non-thermal technique that requires optimal contact between the catheter and the tissue.⁷⁵ Several types of PFA catheters are currently available,^{76,77} each with different characteristics and configurations, making real-time visualization essential. In this context, ICE is particularly useful for guiding catheter placement and ensuring adequate contact, especially in anatomically complex cases such as a common left PV ostium. Observational studies have reported high acute success rates and minimal complications with

ICE-guided PFA. Comparative analyses show similar procedural metrics and arrhythmia recurrence rates for ICE-guided and conventional approaches. However, a recent large, multi-centre, observational prospective study demonstrated that ICE-guided PFA with confirmed catheter-tissue contact resulted in a better success rate and a significantly lower reconnection rate in AF patients.^{78–81} [Supplementary material online, Videos S8.7–S8.13](#) provide an overview of AF ablation using various technologies and PFA catheters.

Relevant videos for section intracardiac echocardiography for atrial fibrillation ablation

To see the relevant videos for this section, list below, [Supplementary Material](#) is available at [Europace](#) online.

Intracardiac echocardiography for ablation of idiopathic ventricular arrhythmias from outflow tracts

Key messages:

- Intracardiac echocardiography enables real-time visualization of catheter positioning on various structures within the outflow tract area.
- Intracardiac echocardiography allows for real-time assessment of the distance between the ablation catheter and the coronary arteries, reducing the need for coronary angiography.

The outflow tract area is a complex anatomical region with numerous adjacent structures that can be sources of ventricular arrhythmias (VAs). ICE provides direct visualization of these sites as well as the neighbouring coronary arteries, which must be carefully considered to prevent complications during catheter ablation.

Right-sided structures

ICE is particularly useful for visualizing the RVOT, the pulmonary valve, and the pulmonary trunk. This capability enables the electrophysiologist to accurately determine whether the catheter is positioned within the RVOT or has crossed above the pulmonary valve ([Figure 11](#)). This distinction is crucial when targeting supra-ventricular sites, which more often serve as the origin of idiopathic arrhythmias.⁸² Additionally, ICE offers real-time information on whether the catheter is in contact with the leaflets of the pulmonary valves, the pulmonary sinus cusps, or the tubular component of the pulmonary trunk. This delineation is important for ensuring proper catheter placement and achieving effective lesion application in contact with the pulmonary root wall or sinus cusps, particularly when using a reversed U-curve of the ablation catheter (see [Supplementary material online, Videos S9.1 and S9.2](#)).

ICE enables direct visualization of catheter positioning in this area, thus serving as a critical adjunct to 3D mapping systems, to accurately differentiate among closely related structures. Moreover, ICE potentially enhances safety during energy delivery in the outflow tract area, particularly in thin-walled sections (e.g. the free wall of the RVOT—[Supplementary material online, Video S9.3](#)). Continuous tissue imaging during ablation helps to guide the duration of the lesion application based on changes in tissue echodensity and the local formation of micro-bubbles, which often precede steam pops. ICE-guided timely cessation of energy delivery can prevent steam pops that could

otherwise lead to cardiac perforation in these thin-walled structures.

Left-sided structures

The use of ICE is also extremely beneficial for mapping and ablating arrhythmias originating from the LVOT and the aortic cusps. ICE views from the right atrium (the home view) and the RV (at the level of the supraventricular crest) provide complementary imaging that allows for accurate visualization of these structures. The longitudinal view of the aortic root helps to assess the catheter distance from the valvular level (see [Supplementary material online, Video S9.4](#)). Sequential views at different cross-sections yield 'short axis' images at various levels (annular, subvalvular) and provide clear imaging of the aortic valve, sinuses, and subannular anatomy. Views at the annular level indicate whether the catheter is positioned at the left coronary cusp (LCC), right coronary cusp (RCC), or at the RCC-LCC commissure, which are common ablation targets for idiopathic VAs (see [Supplementary material online, Video S9.5](#)).

Assessment of coronary artery proximity

ICE allows for visualization of all coronary arteries during ablation in the outflow tract area, making it crucial for preventing collateral injury to the coronary arteries and enhancing procedural safety. Visualizing the left main coronary artery (LMCA) ostium, its bifurcation, and the course of the proximal left anterior descending and circumflex arteries is vital when targeting arrhythmias originating either in the RVOT or LVOT areas, especially near the LCC. Visualization of the RCA ostium is also feasible and of clinical utility when mapping and ablating arrhythmias originating in the vicinity of the RCC.

The relative proximity of the catheter to the LMCA is assessed in both the long axis and the short axis views of the aorta. The long axis view, acquired with the ICE catheter in the right atrium, shows the position of the LMCA ostium relative to the sinotubular junction and allows the measurement of the 'vertical distance' between the ablation catheter and the LMCA ostium. The short axis view, obtained with the ICE catheter in the RV, visualizes the annular plane and allows assessment of the 'horizontal' distance from the LMCA ostium. As the ablation catheter moves from the RCC to the RCC/LCC commissure and then to the LCC, its proximity to the LMCA ostium increases, thereby elevating the risk of inadvertent coronary artery injury.

Real-time assessment of the distance between the catheter tip and the coronary artery ostia during energy delivery in the LVOT or supra-ventricular areas reduces the need for coronary angiography.⁸³ This minimizes fluoroscopic exposure and avoids contrast agent use. The continuous monitoring capability of ICE is a significant advantage over the intermittent views provided by coronary angiography, as real-time visualization of catheter positioning throughout the cardiac cycle mitigates the risk of undetected changes in the catheter's location and assures the maintenance of a consistent safety distance from the coronary arteries during lesion delivery.

Left ventricular summit

Ablation of arrhythmias originating from the LV summit is challenging due to their epicardial origin and the proximity of the respective origins to the coronary arteries. In several cases, performing ablation from adjacent, endocardially accessible anatomic structures, either separately or sequentially, may enhance procedural success even in the absence of significant prematurity.^{84,85}

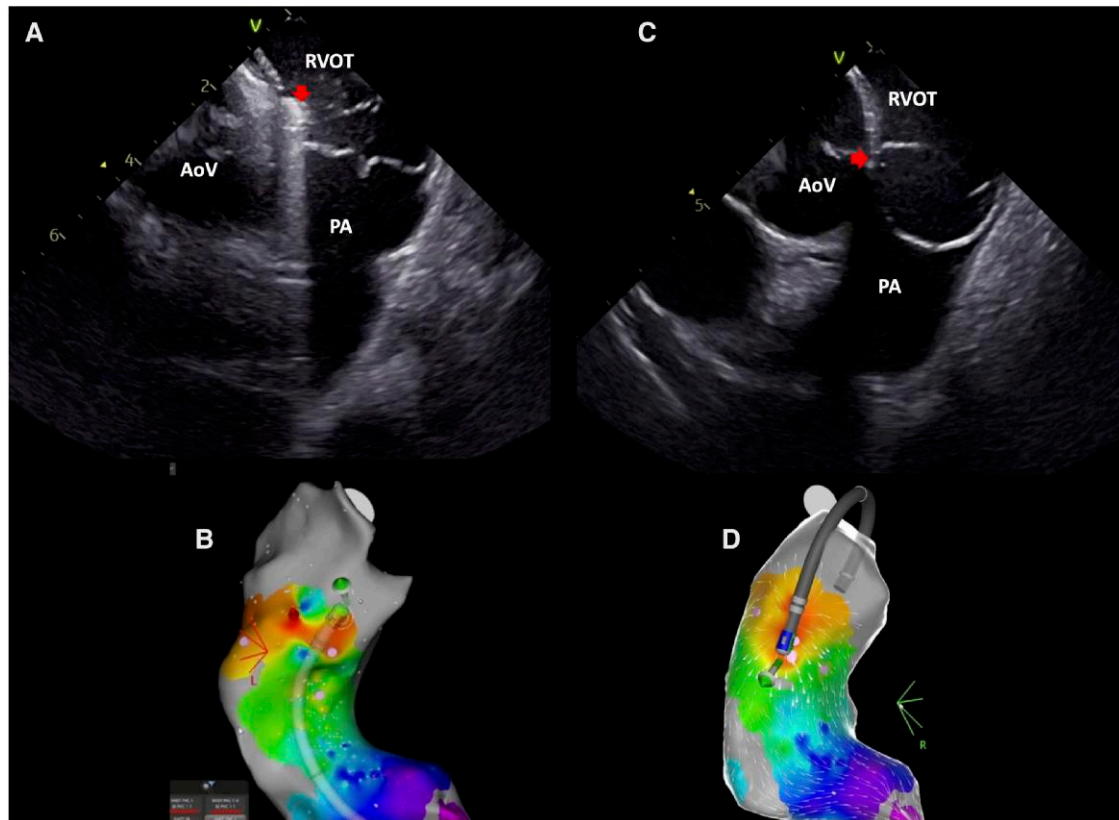


Figure 11 ICE-guided catheter ablation of RVOT idiopathic ventricular arrhythmia below and above the pulmonary valve. (A) ICE-guided ablation at the septal RVOT immediately below the pulmonary valve, (B) visualization of respective subvalvular catheter positioning in 3D mapping (contact vector pointing superiorly and against the RVOT wall), (C) ICE-guided ablation at the respective supra-valvular site (beyond the pulmonary valve) with a reversed U-shaped catheter configuration, (D) visualization of the supra-valvular catheter positioning in 3D mapping (contact vector pointing caudally and against the pulmonary artery wall-pulmonary sinus cusp). AoV, aortic valve; PA, pulmonary artery; RVOT, right ventricular outflow tract.

These structures include the coronary cusps, the endocardial LVOT, the aortomitral continuity, the interleaflet triangle below the right-left coronary junction, and the left pulmonary cusp (see [Supplementary material online, Video S9.6](#)). As mentioned above, ICE is valuable in guiding proper positioning of the ablation catheter within these structures. Real-time assessment of catheter stability helps ensure a safe distance from the LMCA ostium.

Relevant videos for section intracardiac echocardiography for ablation of idiopathic ventricular arrhythmias from outflow tracts

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

Intracardiac echocardiography for ablation of non-outflow tract ventricular arrhythmias

Key messages:

- Intracardiac echocardiography enables real-time monitoring of catheter-tissue contact on mobile intracavitary

structures, such as the papillary muscles and the moderator band.

- Intracardiac echocardiography facilitates catheter positioning and optimizes stability in anatomically challenging regions, such as the tricuspid annulus and the basal inferoseptal left ventricle.

The outflow tract is the most common site of origin of idiopathic VAs. Less commonly, VAs originate from other sites of the right and left ventricles, which present anatomical challenges and prove difficult to manage without ICE guidance.⁸⁶ ICE enhances the safety and effectiveness of ablation by providing real-time imaging of cardiac structures. This allows for precise lesion delivery while minimizing collateral tissue injury.⁸⁷

Left ventricular papillary muscles

LV papillary muscles (PMs) are relatively frequent sites of VAs in structurally normal hearts.⁸⁸ Catheter ablation of LV PMs is particularly challenging due to complex underlying anatomy and is associated with a lower success rate compared with other sites.⁸⁹ The main reason of the suboptimal success rate is the difficulty in maintaining catheter stability, given the high mobility of these intracavitary structures. Additionally, the occasional intramural origin of the VAs requires deeper lesions for successful VA elimination, and there can be diverse exit points of the same VA.

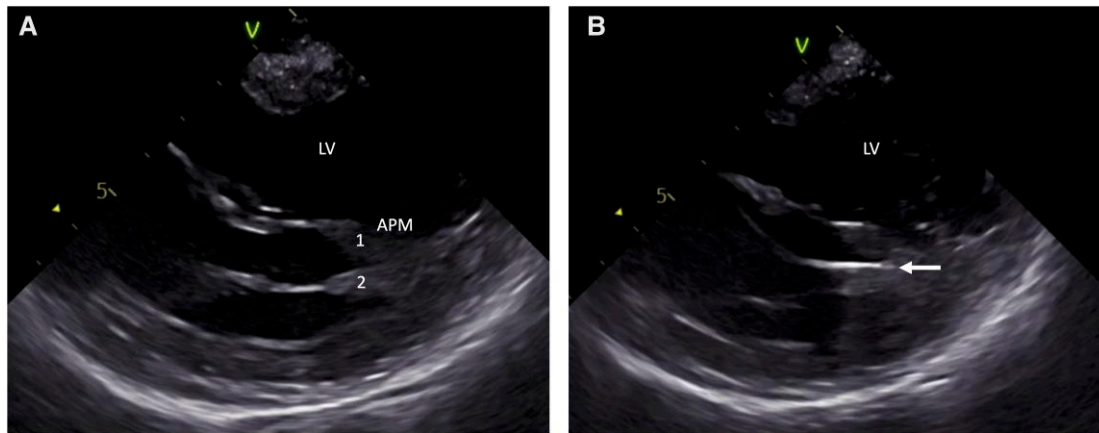


Figure 12 ICE long axis view of the LV showing an anterolateral PM with 2 heads (Panel A) and the ablation catheter tip positioned between them (arrow) (Panel B). APM, anterolateral papillary muscle; LV, left ventricle.

ICE guidance enhances visualization of anatomical landmarks, accurately localizes the LV PMs, and clarifies their anatomy (see [Supplementary material online, Video S10.1](#)). It helps to determine the number and shape of their heads (see [Supplementary material online, Video S10.2](#)), facilitating stable catheter–tissue contact and improving ablation efficacy (Figure 12, [Supplementary material online, Video S10.3](#)).^{90,91} In addition, ICE can identify focal areas of increased echogenicity, which may correspond to the arrhythmogenic site of origin (see [Supplementary material online, Video S10.4](#)).^{92,93} ICE has been reported to identify increased echogenicity in 91% of patients with VAs originating from PM, with 44% of these hyperechoic sites located close to the VA origin.⁹³ However, the association between hyperechogenicity and arrhythmia origin remains challenging to definitively establish and requires further validation. Furthermore, ICE facilitates identification of PM branching sites and myocardial connections, enabling precise catheter positioning to target origins of pleomorphic premature ventricular complexes and thereby improving ablation outcomes for LV PMs VAs.⁹⁴ For visualization of the LVPs, the ICE catheter is typically advanced from the RA into the RV (see *Standard and additional echocardiographic view*).

LV PM ablation can be achieved either via a retrograde-aortic or an antegrade-transseptal approach. When an antegrade approach is chosen, ICE enables a site-specific TSP, typically at the anterior and inferior part of the fossa ovalis to facilitate access to the LV. An alternative approach for visualization of the LV PMs (especially posteromedial PM) involves positioning the ICE catheter within the LV via transseptal access (see [Supplementary material online, Video S10.5](#)), refer to *Intracardiac echocardiography for left atrial appendage closure* on how to cross the interatrial septum with ICE probe.

Furthermore, ICE guidance improves procedural safety during catheter ablation of non-OT sites, providing real-time visualization of tissue imaging characteristics during energy deployment.

Enhanced tissue echogenicity may be used to guide lesion delivery (Figure 13, [Supplementary material online, Video S10.6](#)).⁹⁵ In addition, real-time visualization of ablated tissue is useful to enhance procedural safety by monitoring microbubble formation. The latter imaging finding may be a sign of impending

steam pop and therefore may serve as a safety alarm for lesion termination.⁹⁶

Right ventricular endocavitary structures

Right ventricular endocavitary structures, including the moderator band and the RV PMs, are less common sources of VAs in structurally normal hearts.⁹⁷ Similar to LV PMs, catheter ablation in these areas is challenging due to complex, variable anatomy and high mobility. ICE allows detailed assessment of the number, morphology of the RV PMs, and anatomical relationships of the moderator band and RV PMs (see [Supplementary material online, Video S10.7](#)), enabling safe and effective lesion delivery.⁹⁸

For optimal RV imaging, the ICE probe is advanced from the RA into the RV, offering a detailed view of RV endocavitary structures. Visualization of the moderator band and its connection with the RV PM can be achieved by a slight clockwise rotation of the ICE probe until the interventricular septum is identified.

Other non-outflow tract sites

VAs originating from the tricuspid annulus correspond to 8–9% of idiopathic VAs.⁹⁹ Anatomically, a distinct enfoldment under the valve along the lateral tricuspid annulus impedes catheter contact and stability, reducing the success rate of catheter ablation.¹⁰⁰ A catheter inversion approach, using a deflectable long sheath, is preferred to map and ablate underneath the valve over a purely antegrade technique (see [Supplementary material online, Videos S10.8 and S10.9](#)). When choosing this approach, ICE is useful to confirm optimal catheter position and stability as well as to monitor adequate tissue contact. Visualization of the lateral tricuspid annulus from the home view is achieved by a slight counterclockwise rotation of the ICE catheter, while a gentle clockwise rotation allows visualization of the septal tricuspid annulus.

Among different regions of the tricuspid annulus, the parahisian area is the most common site of origin of premature ventricular complexes.⁹⁹ Ablation in this area is challenging due to the associated risk of atrioventricular block. ICE facilitates the implementation of safer alternative ablation techniques in the parahisian area, such as the ‘reverse S curve,’

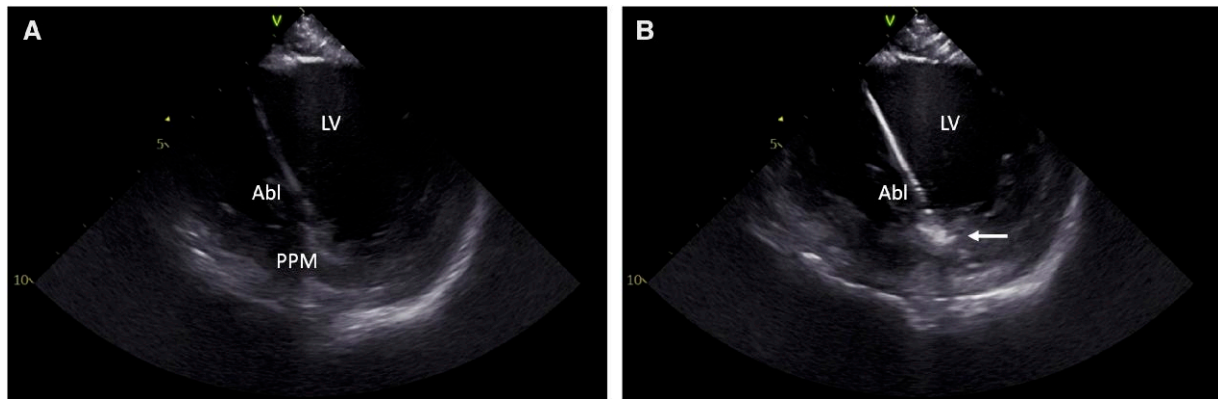


Figure 13 ICE long axis view of the LV showing the ablation catheter positioned at the posteromedial PM before (Panel A) and after (Panel B) RF energy delivery. Please note the increased tissue echogenicity (arrow) at the lesion site during energy application. Abl, ablation catheter; LV, left ventricle; PPM, posteromedial papillary muscle.

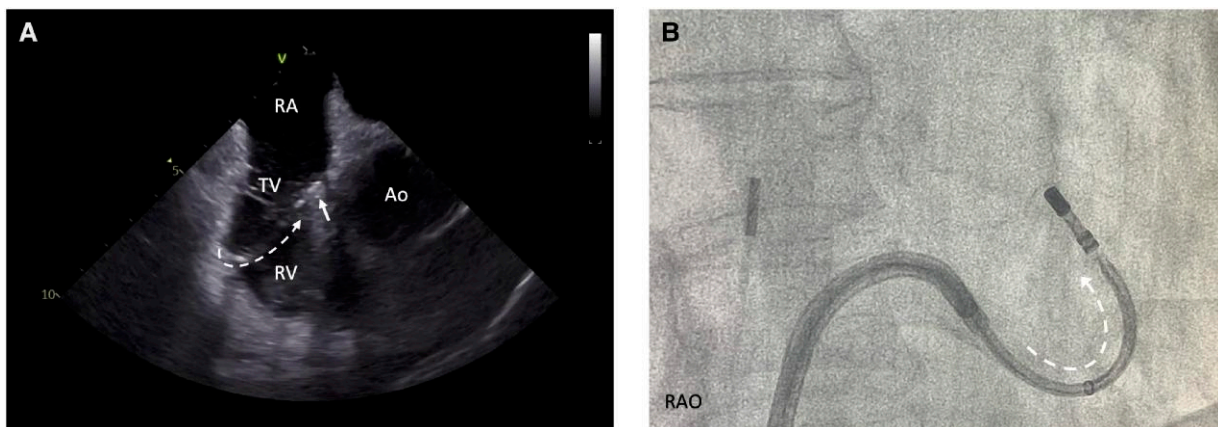


Figure 14 ICE view from the RA (Panel A) and fluoroscopic image in RAO view (Panel B) showing the reversed S-curve technique (dashed arrow) in a patient with premature ventricular complexes originating from the parahisian area. The tip of the ablation catheter is positioned under the tricuspid valve (solid arrow). Ao, aortic root; RA, right atrium; RV, right ventricle; TV, tricuspid valve.

(Figure 14, [Supplementary material online, Video S10.10](#)) and allows targeting of adjacent structures, including the aortic cusps.¹⁰¹

The basal inferoseptal LV and the posterior superior process of the LV (LVPSP) are rare sites of idiopathic VAs. As the tricuspid annulus is positioned more apically than the mitral annulus, the basal inferoseptal LV area is in direct contact with the RA. Therefore, catheter ablation of basal inferoseptal LV sites can be performed from the medial-inferior region of the RA.¹⁰² ICE is essential for precise catheter localization and real-time contact monitoring in these areas (see [Supplementary material online, Video S10.11](#)).¹⁰² The LVPSP can be visualized by positioning the ICE catheter in the home view and applying a slight clockwise rotation and anterior deflection, enabling visualization of the non-coronary cusp–LVPSP junction and the adjacent atrial tissue anterior to the coronary sinus ostium.

Relevant videos for section intracardiac echocardiography for ablation of non-outflow tract ventricular arrhythmias

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

Intracardiac echocardiography for ablation of structural ventricular tachycardias

Key messages:

- Intracardiac echocardiography allows the identification of arrhythmogenic substrate by displaying specific imaging features,

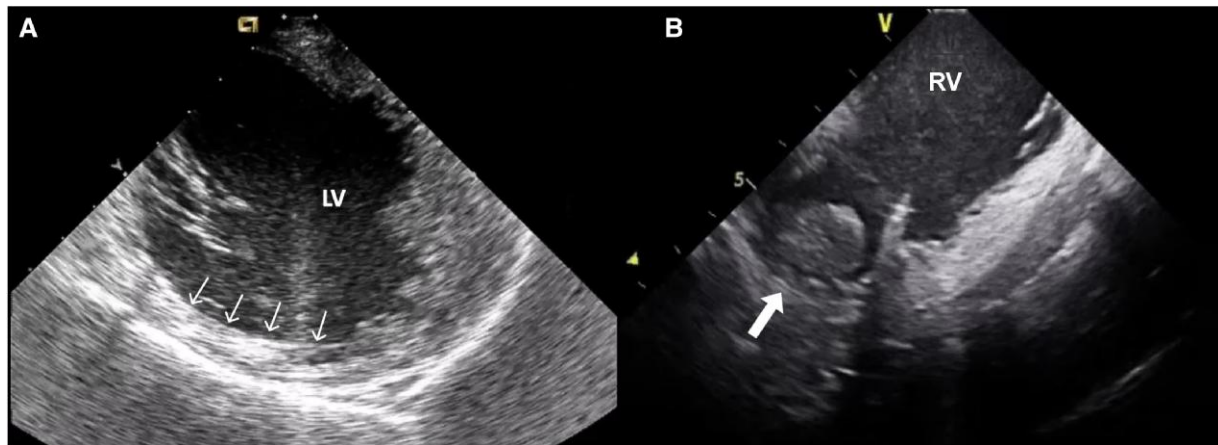


Figure 15 Examples of intracardiac echocardiography use in structural VT ablation. (Panel A) Visualization of arrhythmogenic substrate in a patient with prior lateral myocardial infarction (arrows). Please note the characteristic myocardial wall thinning and the smooth endocardial surface. (Panel B) Rounded thrombus in an aneurysm of the basal lateral right ventricular free wall (arrow) in a patient with arrhythmogenic right ventricular cardiomyopathy. RV, right ventricle; LV, left ventricle.

such as increased echogenicity, wall thinning, or wall motion abnormalities.

- Intracardiac echocardiography facilitates catheter manipulation by visualizing intracavitary structures, like papillary muscles and prominent trabeculae.
- Intracardiac echocardiography enables the detection and imaging characterization of intracavitary thrombus.
- Intracardiac echocardiography helps guide the delivery and titration of radiofrequency energy, optimizing procedural safety.

In patients with structural heart disease, the primary mechanism for ventricular tachycardia (VT) is re-entry, which is often confined to regions of fibrosis or scar tissue. These arrhythmogenic areas can be identified by imaging and/or mapping. While pre-procedural imaging is increasingly utilized for patients with structural heart disease, its applicability is limited in the presence of implantable devices, which may contraindicate the use of CMR imaging. Furthermore, artefacts generated by implanted leads may also impede the interpretation of the septal substrate.

ICE allows for complementary, intraprocedural, real-time assessment of arrhythmogenic substrate for VAs.¹⁰³ Scar regions typically show wall thinning, increased echogenicity, and wall motion abnormalities on ICE (Figure 15A, [Supplementary material online, Videos S11.1](#) and [S11.2](#)).¹⁰⁴ In non-ischaemic cardiomyopathy, ICE can identify epicardial and mid-myocardial arrhythmogenic substrates (see [Supplementary material online, Video S11.3](#)) as well as periaortic substrates.¹⁰⁵ Additionally, ICE optimizes catheter-tissue contact, visualizes uneven endocardial surfaces, and identifies potential barriers to catheter manipulation, such as prominent trabeculae, papillary muscles, or deep recesses (see [Supplementary material online, Videos S11.4](#) and [S11.5](#)). In patients with arrhythmogenic right ventricular cardiomyopathy, ICE can delineate the presence of right ventricular free wall aneurysms (see [Supplementary material online, Video S11.6](#)). During RF ablation, myocardial microbubble formation leads to increased echogenicity, which progressively expands and usually precedes steam pop formation.¹⁰⁶ In one study, when ICE was used for monitoring of prolonged

RF applications (up to 3 min) within the right ventricular aneurysms, no steam pops were observed, and a high long-term success rate (93%) was achieved with endocardial ablation alone.¹⁰⁷ Thus, ICE can effectively guide the titration of delivered energy and enables early detection of complications (see *Intracardiac echocardiography for prevention and detection of procedural complications*).

In patients with structural heart disease undergoing catheter ablation, intracavitary thrombus can be detected in up to 6% of cases.¹⁰⁸ While pre-procedural CMR is the most sensitive modality for thrombus detection, contrast transthoracic echocardiography may be insufficient to rule out thrombus presence.¹⁰⁹ In this context, ICE enables the intraprocedural detection and characterization of intracavitary thrombi. A fresh, protruding thrombus (see [Supplementary material online, Video S11.7](#)) with mobile components may be dislodged by catheter manipulation, leading to severe consequences. Conversely, a laminar and adherent thrombus that covers an old aneurysm protects the arrhythmogenic substrate, creating an impenetrable barrier for endocardial catheter ablation (see [Supplementary material online, Videos S11.8](#) and [S11.9, Figure 15B](#)).

Currently, only retrospective studies have evaluated the use of ICE for VT ablation in patients with structural heart disease. A comparative study including 1324 patients from a large insurance database revealed that ICE guidance was associated with a significantly lower rate of repeat catheter ablation. However, there was no significant difference in VT readmission rates or procedural complications between ICE-guided and non-ICE-guided ablation procedures.⁸⁷ In another study of 5804 patients using a nationwide database from Japan,¹¹⁰ ICE usage was associated with a reduced incidence of cardiac tamponade, but there was no significant difference in procedural effectiveness. Prospective studies are necessary to validate the benefit of ICE guidance in patients with structural heart disease.

Both ventricles can be visualized from the RV position and scanned by slow clock or counter-clockwise rotation of the ICE probe. Some regions in the LV might be difficult to visualize from the RV—e.g. the antero-septal aneurysm. In such cases, the

ICE catheter can be introduced transseptally to the LA and then to the LV to visualize the apex directly (see [Supplementary material online, Video S11.10](#)).

Relevant videos for section intracardiac echocardiography for ablation of structural ventricular tachycardias

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

Intracardiac echocardiography for left atrial appendage closure

Key messages:

- Intracardiac echocardiography is a viable imaging alternative to TEE for procedural guidance of LAA closure.
- Advantages of intracardiac echocardiography over TEE include reduced lab usage time and use of local anaesthesia only, avoiding the risks and discomfort associated with general anaesthesia or deep sedation and TEE.
- Intracardiac echocardiography guided LAA closure does not eliminate the need for pre-procedural planning with cardiac computer tomography or three-dimensional TEE.
- A systematic approach using recommended standard imaging views from the LA should be followed.

Transcatheter left atrial appendage closure (LAAC) is increasingly used to prevent thromboembolism in patients with AF.¹¹¹ Currently, this approach is primarily reserved for patients who are unsuitable for direct oral anticoagulation (DOAC). Recent studies support its use in conjunction with AF catheter ablation.¹¹² Results from ongoing clinical trials comparing LAAC and DOAC therapy across the AF population will be available in the near future.

The anatomy of the LAA is highly variable and often complex, making high-quality imaging essential for optimal device implantation and procedural safety. Pre-procedural imaging, either by cardiac computed tomography or 3D-TEE is essential to assess anatomy, select device type and size, determine TSP location, optimize C-arm positioning, and exclude the presence of LAA thrombus.^{113,114}

Traditionally, LAAC procedures have been guided by TEE, which typically requires general anaesthesia (GA), endotracheal intubation, an anaesthesia team, and a dedicated TEE operator. In some centres, TEE-guided LAAC is performed in deep sedation without intubation. Mini- or micro-TEE probes offer an alternative to conventional TEE but may be limited by suboptimal image quality and patient discomfort. TEE is unsuitable for patients with oesophageal pathology such as varices.

Intracardiac echocardiography (ICE) offers several advantages over TEE for LAAC guidance. The procedure can be performed under local anaesthesia, avoiding the risks and discomfort associated with GA, sparing the personnel required for GA and TEE and allowing the implanting physician direct control of imaging. Several single- and multi-centre studies have demonstrated the efficacy and safety of ICE-guided LAAC, along with reduced in-room time and improved operating room logistics.^{115–119} However, potential limitations include the additional cost of ICE catheters, the learning curve for ICE catheter manipulation, the need for a second operator or multitasking by a single operator, and a minor risk of catheter-related complications.

Intraprocedural use of ICE is essential in several steps of the LAAC procedure, ensuring both safety and efficacy. These steps include: (i) guidance of the TSP at an optimal site as determined based on pre-procedural planning, (usually in the infero-posterior location—*ICE guided transseptal puncture*), (ii) final exclusion of LAA thrombus (*Intracardiac echocardiography for left atrial appendage thrombus exclusion*), (iii) guidance of LAA device implantation to ensure complete sealing without residual leaks, (iv) post-deployment assessment of device stability with the tug testing and (v) early detection of complications such as pericardial tamponade, device malposition or embolization, and formation of thrombus on the device, sheaths, or wires.

Visualization of the LAA can be achieved from various right heart positions, including the RA, coronary sinus, and PA, but imaging of the LAA directly from the LA is superior. Positioning of the ICE catheter inside the LA has become the ICE imaging standard for guiding LAA device implantation. Following ICE-guided TSP (*ICE guided transseptal puncture*), a stiff guide-wire is positioned in the LSPV or a stiff curled wire in the LA. The device delivery sheath is advanced over the wire to dilate the puncture hole and then pulled back into the IVC (see [Supplementary material online, Video S12.1](#)). The ICE catheter is then aligned to the wire by anterior flex and clockwise rotation and carefully advanced under fluoroscopy into the LA using the wire as a roadmap (see [Supplementary material online, Video S12.2](#)). Alternatively, ICE can be used to guide the transseptal crossing by slowly advancing the ICE probe into the LA, while keeping the wire within the ICE field of view (see [Supplementary material online, Video S12.3](#)). There should be no resistance as the catheter crosses the interatrial septum. The same puncture hole is used for both the ICE catheter and delivery sheath. The transseptal crossing of the ICE catheter can be facilitated by biplane or oblique fluoroscopic angles and in difficult cases by insertion of two wires through the TSP hole or using a snaring technique.¹²⁰

The following standard views should be obtained before device release to ensure optimal device position and sealing ([Figure 16](#), [Supplementary material online, Videos S12.4–S12.12](#)):

- **LAA-mitral view:** The ICE catheter tip is positioned at the LSPV ostium (or slightly into the LSPV) or in the mid-LA with slight posterior flex. The LSPV, LSPV ridge, LAA, left circumflex artery (LCx) and mitral valve are visualized. This view resembles the 45–90° TEE views.
- **LAA-aortic view:** The ICE catheter tip is positioned at the mid-LA position with slight posterior and right flex and a slight counter-clockwise rotation of the shaft. This view shows the aorta/aortic valve in a transversal view and the LAA. This view resembles the 0° TEE view.
- **LAA-PA view:** The ICE catheter tip is positioned at the supra-mitral position. From the mid-LA position, the ICE catheter is rotated 180° looking away from the LAA, then posterior flexed and carefully advanced to a position underneath the LAA and on top of the mitral valve. It gives a particularly good view of the infero-posterior part of the LAA, the mitral valve, the LCx (seen in the upper part of the image) and the LSPV and PA (seen in the lower part of the image). This view resembles the 135° TEE view.

The standard ICE views from the LA were initially established with 2D ICE catheters. However, recent advancements have introduced 3D ICE catheters, which offer multiplane, X plane, and 3D imaging similar to TEE technology¹²¹ ([Figure 17](#), [Supplementary material online, Videos S12.13 and S12.14](#)). A recent multicenter study demonstrated a very strong correlation

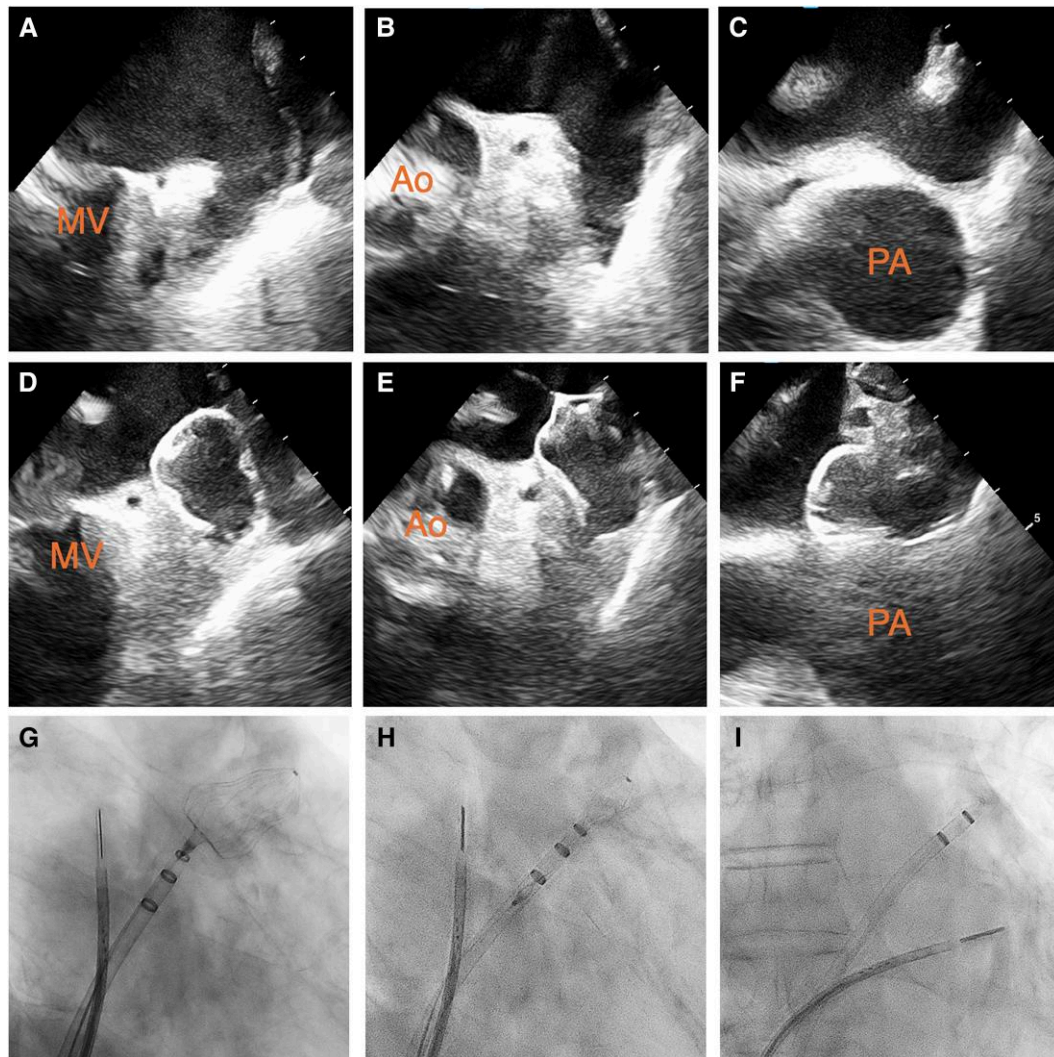


Figure 16 Standard ICE views from the LA. (A, D, and G): LAA-Mitral view before and after deployment of a Watchman FLX device; ICE catheter is in the mid-LA position. (B, E, and H): LAA-Aortic view; ICE catheter is in the mid-LA position with slight posterior and right steer and a minor counter-clock rotation. (C, F, and I): LAA-PA view; ICE catheter is in the supramitral position.

between 3D ICE and TEE measurements of the LAA landing zone, with high agreement between ICE-based device selection and the final implanted device size.¹²² In addition, 3D ICE enables achievement of required LAA views with fewer catheter manipulations inside the LA, potentially improving the evaluation of device positioning and sealing compared with 2D technology. Whether 3D ICE can fully replace the need for pre-procedural imaging remains to be established. Following device release, the pericardial cavity should be checked to rule out bleeding. The tip of the ICE catheter should be placed in the mid-LA with anterior flex aiming downwards to the mitral valve, the LV and pericardium (see [Supplementary material online, Videos S12.15](#) and [S12.16](#)).

It is important to note that there is a learning curve when using ICE to guide LAAC. Simulator-based training,¹²³ proctored

sessions, and prior experience with ICE for TSP, electrophysiology procedures, PFO/atrial septal defect (ASD) closure, or tricuspid interventions can facilitate learning. Conducting LAAC cases using both TEE and ICE is beneficial during the early stages of adoption. Although there are initial concerns about the cost of ICE catheters, these expenses may be offset by the elimination of the need for GA and the reduction in the number of personnel and operating room time required.¹²⁴

Relevant videos for section intracardiac echocardiography for left atrial appendage closure

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

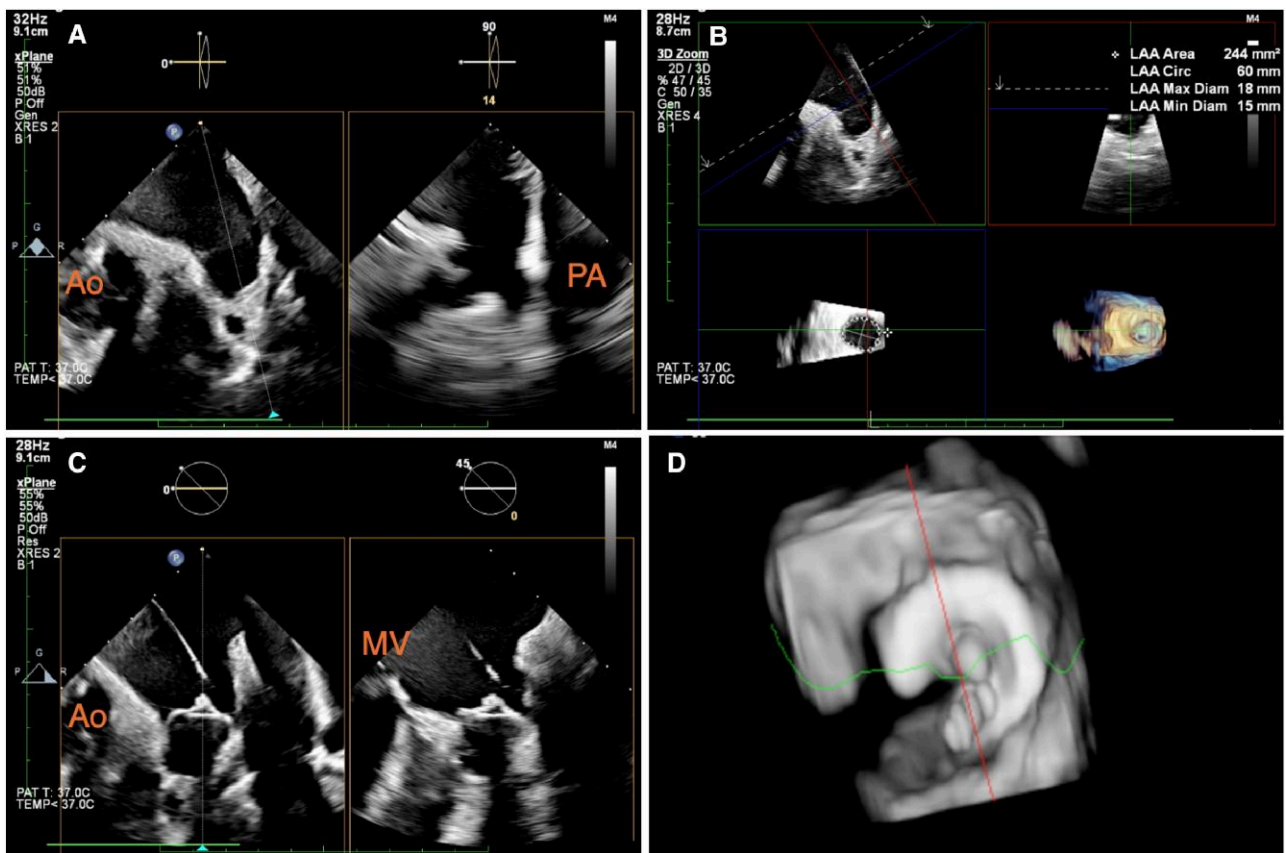


Figure 17 ICE views from the LA obtained by a 3D-ICE catheter (philips VeriSight). All images were acquired with the 3D-ICE catheter in the mid-LA position with slight posterior steer. (A) X-plane images of the LAA in the LAA-aortic and LAA-PA view. (B) Multiplanar reconstruction views of the LAA with auto-tracing of the device landing zone giving maximal diameter, minimal diameter, area, and perimeter. (C) X-plane showing the LAA-aortic and LAA-mitral view after deployment of a Watchman FLX. (D) 3D-view looking en-face onto the atrial surface of the Watchman FLX.

Intracardiac echocardiography for ablation of arrhythmias in congenital heart disease

Key messages:

- Intracardiac echocardiography plays a crucial role in identifying and locating artificial surgical materials, such as patches, artificial valves, and septal closure devices.
- Intracardiac echocardiography facilitates guidance of transbaffle puncture.
- Intracardiac echocardiography facilitates ablation of accessory pathways in patients with Ebstein's anomaly.
- Intracardiac echocardiography enables recognition of anomalous pulmonary venous drainage.

ICE is a valuable adjunctive imaging tool to guide catheter ablation of various tachycardias in patients with congenital heart disease. Its use can potentially shorten procedural duration, reduce fluoroscopy exposure,^{125,126} and enhance both procedural safety and outcomes.¹²⁷ Furthermore, ICE enables visualization of post-operative materials such as patches and artificial valves,^{128,129} highlighting its clinical significance in several procedural contexts.

TSP in the presence of patches, closure devices

Intracardiac echocardiography facilitates safe TSP in challenging situations (*ICE guided transseptal puncture*). In the presence of an ASD closure device (*Figure 18*) or a patch following corrective surgery of ASD, ICE enables visualization and guidance of all necessary steps for achieving safe transseptal access, including tenting, crossing of the needle, wire, and long sheath (see [Supplementary material online, Video S13.1](#)). In the presence of an ASD closure device, ICE allows for identification of a part of the fossa not covered by the device, which is subsequently specifically targeted for transseptal access (see [Supplementary material online, Video S13.2](#)).

Transbaffle puncture

In corrective surgeries for redirection of venous inflow at the atrial level, such as the Senning or Mustard procedure, an atrial baffle is created. This baffle separates the venous and systemic circulations and typically divides the CTI. When ATs originate in the systemic atrium or involve the CTI, a transbaffle puncture is required. ICE is helpful in recognizing the presence of the baffle and in selecting the optimal site for a safe

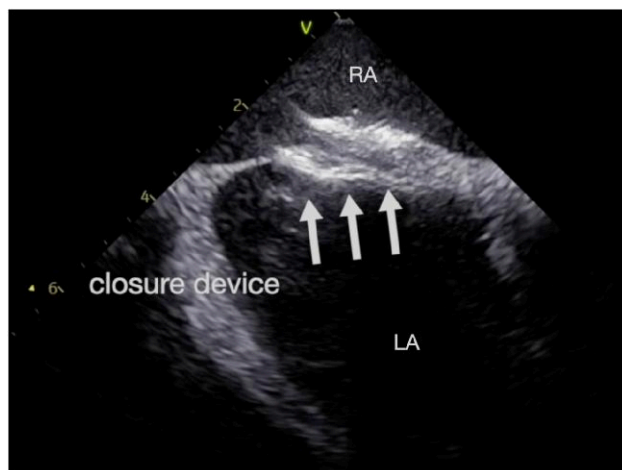


Figure 18 View of the interatrial septum from the right atrium with a closure device consisting of two discs. LA, left atrium; RA, right atrium.

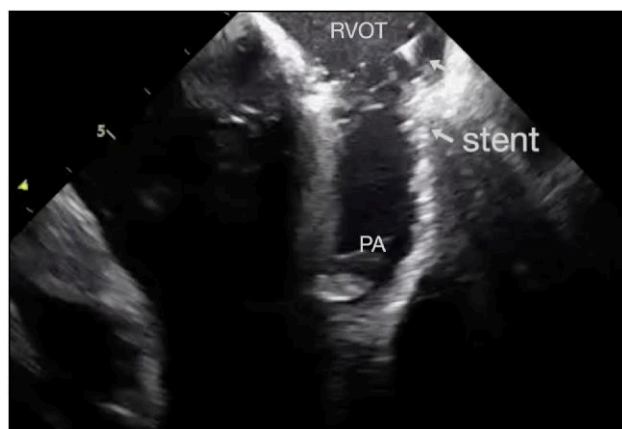


Figure 19 View of the RVOT from the base of the right ventricle showing a stented valve connecting the outflow tract with the pulmonary artery. PA, pulmonary artery; RVOT, right ventricular outflow tract.

transbaffle puncture (see [Supplementary material online, Video S13.3](#)).

Artificial valves and patches in the ventricles

ICE easily identifies the presence of artificial heart valves. In certain conditions, such as tetralogy of Fallot, pulmonary atresia with ventricular septal defect, and pulmonary atresia with an intact ventricular septal defect, valved conduits (see [Supplementary material online, Video S13.4](#)), stented valves (see [Figure 19](#) and [Supplementary material online, Video S13.5](#)) or balloon expandable valves are often used. Additionally, patches (see [Supplementary material online, Video S13.4](#)) may be utilized for enlarging stenosed outflow tracts or for closure of ventricular septum defects (see [Supplementary material](#)

[online, Video S13.6](#)). Recognizing and localizing these structures with ICE is clinically important, as they frequently serve as substrates for re-entry circuits and represent ablation targets during invasive management of VTs.¹³⁰

Catheter ablation in patients with Ebstein's anomaly

ICE is instrumental in understanding the anatomy of patients with Ebstein's anomaly. It enables accurate localization of the anatomical and functional tricuspid annulus and the atrialized ventricular musculature in between. This is relevant for catheter ablation of accessory pathways commonly associated with Ebstein's anomaly (see [Figure 20](#) and [Supplementary material online, Video S6.2](#)).

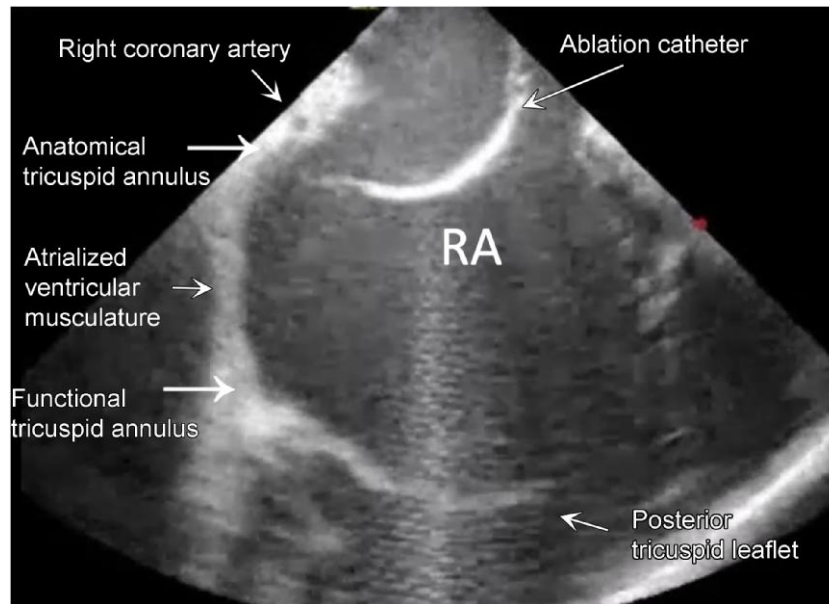


Figure 20 View of the tricuspid annulus in a patient with Ebstein's anomaly (the intracardiac probe is in the right atrium). Please note the apical displacement of the posterior leaflet of the TV (functional annulus). The anatomical annulus is marked by the course of the right coronary artery. In between is the atrialized ventricular myocardium. RA, right atrium.

Anomalous pulmonary vein drainage and coronary artery origin

ICE can also identify anomalous pulmonary vein drainage by advancing the probe into RA and scanning the right PVs (see [Supplementary material online, Video S13.7](#)). Furthermore, it is also valuable in identifying the presence of anomalous coronary artery origin and guiding safe deployment of ablation lesions near the ostia of the coronary arteries (see [Supplementary material online, Video S13.8](#)).

Relevant videos for section intracardiac echocardiography for ablation of arrhythmias in congenital heart disease

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

Intracardiac echocardiography for reduction of procedural radiation and zero-fluoroscopy approach

Key message:

- The use of intracardiac echocardiography in combination with three-dimensional mapping systems can significantly reduce or even eliminate the need for fluoroscopy during catheter ablation procedures.

Traditionally, electrophysiology procedures rely on fluoroscopy for guidance. However, there are compelling reasons to reduce or even eliminate its use during catheter ablation. The primary aim is to prevent the harmful effects of radiation, which

are even more pronounced in vulnerable patient categories such as children, pregnant women, and obese individuals. In addition, eliminating fluoroscopy spares the need for personal protective equipment, thereby increasing comfort and reducing orthopaedic issues for the electrophysiology laboratory staff. By increasing our reliance on ICE as a real-time imaging tool, we can achieve the goal of minimizing fluoroscopy during ablation procedures.

Retrospective, prospective, and randomized studies have shown that near-zero¹³¹ and even zero-fluoroscopy¹³²⁻¹³⁴ catheter ablation for various SVTs is both feasible and safe, with outcomes comparable to fluoroscopy-based approaches. Similar evidence also extends to patients with structural or congenital heart disease¹³⁵ as well as in children^{136,137} and pregnant^{138,139} patients, where the impact of fluoroscopy exposure is of greatest concern, making its elimination critically important.

Zero-fluoroscopy catheter ablation of AF is also feasible, with similar safety and efficacy to fluoroscopy-based approaches. The evidence is strongest for PVI procedures using thermal energy sources.^{74,140-144} Limited data from retrospective analyses suggest similar procedural, safety, and clinical outcomes in zero-fluoroscopy PFA procedures.^{145,146} However, these findings pertain to a specific single-shot PFA platform, and additional data for other platforms and technologies are needed.

The combined use of a 3D mapping system and ICE enables zero-fluoroscopy procedures for the treatment of ventricular ectopy and tachycardias.^{147,148} However, unlike SVT and AF ablation, fluoroscopy cannot always be completely obviated in all cases of ventricular ectopy and tachycardia ablation.¹²⁶ Epicardial procedures or those requiring ablation near coronary arteries still necessitate fluoroscopy for accurate visualization of coronary artery courses.

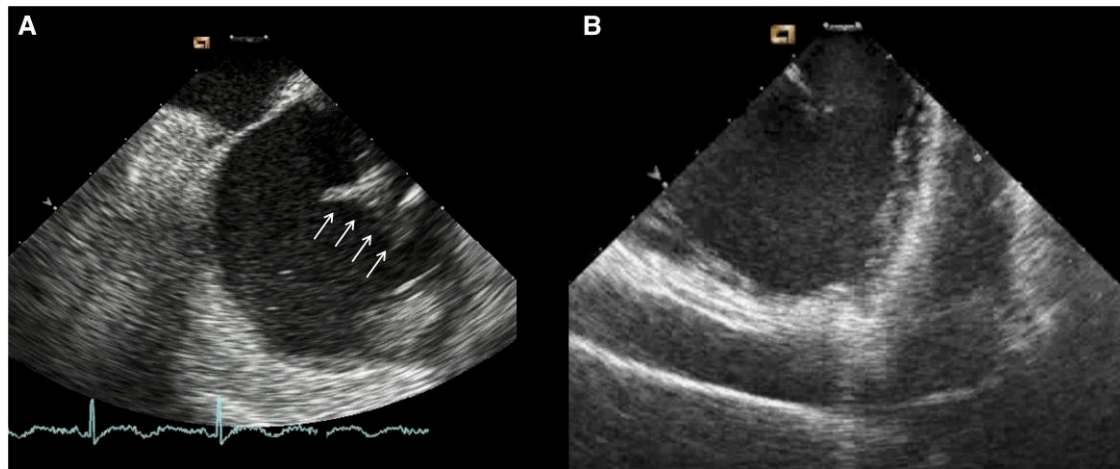


Figure 21 ICE for early detection of complications during electrophysiological procedures. (A) Visualization of a large thrombus (arrows) extending from the tip of the sheath in the LA. (B) Pericardial effusion.

Relevant videos for section intracardiac echocardiography for reduction of procedural radiation and zero-fluoroscopy approach

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

Intracardiac echocardiography for prevention and detection of procedural complications

Key messages:

- Intracardiac echocardiography is essential for the prevention, early detection, and prompt management of procedural complications during catheter ablations.
- Intracardiac echocardiography enables the guidance of radio-frequency energy delivery, ensuring timely cessation of lesion application, reducing the risk of steam pops and cardiac perforation.
- Intracardiac echocardiography has a pivotal role in preventing and detecting procedural complications during various phases of catheter ablation.

Safe transseptal puncture

Fluoroscopy-guided TSP has been associated with a cardiac perforation rate of ~0.09% to 1.3%.^{149,150} Other life-threatening complications may involve perforation of the aortic root¹⁵¹ or damage to the interatrial septum above the fossa ovalis.¹⁵² The use of ICE has been shown to reduce such periprocedural complications, as confirmed by a large observational study¹⁵³ involving 2181 procedures (*ICE guided transseptal puncture*). Additionally, ICE also allows for safe transbaffle puncture in patients who have undergone Senning or Mustard procedures (*Intracardiac echocardiography for ablation of arrhythmias in congenital heart disease*).¹⁵⁴

Detection of intracardiac thrombi

ICE has comparable effectiveness to TEE for detecting thrombi in the LA and LAA.^{7,50,51} For this purpose, the ICE catheter needs to be positioned in the PA, coronary sinus ostium or, if needed, in the LSPV (see *Intracardiac echocardiography for left atrial appendage thrombus exclusion*).

Intracardiac thrombi can form at any time during a left-sided procedure (*Figure 21*). ICE enables real-time observation of blood clot formation on catheters, sheaths, and endocardial lesion sites.¹⁵⁵ Detecting a soft thrombus may prompt attempts to aspirate it into the sheath and adjust heparin levels¹⁵⁶ (see [Supplementary material online, Videos S15.1](#) and [S15.2](#)). Alternatively, ICE can assist in guiding the removal of the thrombus into the RA.

Monitoring of tissue overheating

Tissue overheating, often resulting in steam pops¹⁵⁷ (see [Supplementary material online, Video S15.3](#)), increases the risk of cardiac perforation and tamponade. Sudden whitening of the ablated tissue (see [Supplementary material online, Video S15.4](#)) or a rapid increase in bubble formation on ICE imaging during energy deployment may precede steam pops in nearly 90% of cases.¹⁰⁶ Notably, 39% of pops were acoustically silent and could only be detected using ICE as an explosion of bubbles (see [Supplementary material online, Video S15.5](#)). In a multivariable analysis, tissue whitening and a sudden increase in bubbles were associated with steam pops, independent of impedance fall and the magnitude of power settings.

Prevention of pulmonary vein stenosis

Earlier studies have shown that guiding procedures with ICE aiming to prevent thermal energy delivery inside the PV can avoid severe pulmonary vein stenosis.¹⁵⁸ Subsequent evidence derived from several centres has documented that ICE can effectively prevent this complication.¹⁵⁹

Prevention of phrenic nerve injury

A small study demonstrated that ICE can adequately visualize the right phrenic nerve in most cases, potentially

helping to avoid its injury during thermal ablation in its vicinity.⁶¹

Early recognition of complications

Prevention and rapid detection of procedural complications are the most important benefits of ICE.¹⁵⁶ Major complications include cardiac perforation, left atrial thrombus, oesophageal injury, and PV stenosis.^{160,161} ICE-guidance is considered the best tool for the early detection of growing pericardial effusion (see [Supplementary material online, Video S15.6](#)). This allows for timely reversal of anticoagulation and timely pericardial drainage before the development of cardiac tamponade.¹⁵⁶

Moreover, ICE can assist in differentiating between air embolism (see [Supplementary material online, Videos S15.7 and S15.8](#)) and perforation. In cases of sudden intraprocedural hypotension, ICE can quickly rule out pericardial tamponade. An animal study has shown that small air emboli can be detected by ICE with much greater sensitivity compared with TEE.¹⁶² ICE can also facilitate the recovery of embolized air by aspiration into a multiorifice catheter or sheath.

ICE can be also used to monitor cardiac output. Loss of ventricular contractility (see [Supplementary material online, Video S15.9](#)) and dense spontaneous echo contrast (see [Supplementary material online, Video S15.10](#)) may indicate imminent cardiogenic shock. When observed, avoidance of arrhythmia induction, administration of inotropes, insertion of a haemodynamic support device, or even early procedure termination can prevent catastrophic consequences.

Data supporting the use of ICE to reduce complications

Evidence that the application of ICE during catheter ablation reduces the incidence of perioperative complications in AF ablation,²³ can be derived from large, observational databases and registries.¹⁶⁰ These studies have shown that the use of ICE has shortened the average hospital stay²¹ and decreased the rate of 90-day readmissions.²² Conversely, patients who underwent AF ablation without ICE guidance faced nearly a five-fold higher risk of cardiac perforation compared with those treated with ICE navigation.¹⁶³ The early mortality rate associated with catheter ablation of AF without ICE was reported to be as high as 0.46%.¹⁶⁰ The superior safety of ICE-guided vs. non-ICE-guided AF ablation has been demonstrated in a recent meta-analysis pooling data from nearly half a million patients across 44 studies.⁷¹ However, it must be acknowledged that there are no large prospective randomized trials on the topic.

Relevant videos for section intracardiac echocardiography for prevention and detection of procedural complications

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

Intracardiac echocardiography for guidance of endomyocardial biopsy

Key messages:

- Intracardiac echocardiography enhances the diagnostic accuracy of EMB and allows for targeted biopsies.

- Intracardiac echocardiography improves the safety of EMB and enables real-time monitoring for complications.
- Intracardiac echocardiography facilitates safe selective biopsy of cardiac tumours and masses, offering a minimally invasive alternative to cardiac surgery.

Traditional fluoroscopy-guided EMB is a well-established procedure for diagnosis of cardiomyopathies and myocarditis. However, its diagnostic yield may be limited due to low sensitivity, especially in cases of myocardial disease with focal or patchy involvement.¹⁶⁴ In this respect, ICE provides the opportunity to select tissue for targeted biopsy. Furthermore, ICE can be combined effectively with EAM.^{165–168}

This combined approach is increasingly utilized in patients with non-ischemic cardiomyopathies presenting with arrhythmias, those with suspected or confirmed myocarditis, and competitive athletes.^{169–171} In these cases, a comprehensive evaluation often requires electrophysiological assessment and tissue characterization to guide diagnosis and treatment.^{169–172}

The integration of ICE with EAM, alongside CMR, has proven highly effective for targeted tissue sampling, improving diagnostic sensitivity to 95%. This multi-modality approach identifies pathological areas missed by CMR in 8% of patients and leads to a revised diagnosis in 39% of cases.¹⁶⁵ Furthermore, this combined strategy allows for real-time, high-resolution tissue characterization, including the detection of scarring, oedema, fibro-fatty replacement, and wall motion abnormalities, which are often overlooked by conventional imaging techniques.^{166,167}

Beyond its diagnostic utility, ICE plays a pivotal role in enhancing procedural safety during EMB. EMB-related complications are typically categorized as vascular, electrical, or mechanical. Mechanical complications include inadvertent injury to intracardiac structures such as the papillary muscles, chordae tendineae, or valve leaflets, and even cardiac perforation, with an estimated incidence of ~0.27%.^{173,174} ICE minimizes mechanical risks by providing real-time visualization of cardiac anatomy ([Figure 22](#)). This capability allows for the identification of vulnerable regions and continuous monitoring of catheter-tissue interactions, which significantly reduces the rate of adverse events.¹⁷⁵ [Supplementary material online, Videos S16.1–S16.6](#) demonstrate the use of ICE in RV and LV biopsy procedures.

Furthermore, ICE improves the procedural workflow by replacing TEE, thereby eliminating the need for GA and a second operator. Despite these clear advantages, the use of ICE remains limited to high-volume centres, as highlighted in a recent meta-analysis on EAM-guided EMB.¹⁷⁵

ICE has also demonstrated effectiveness as a stand-alone imaging modality in guiding biopsies of intracardiac masses, facilitating tissue acquisition in anatomically complex or high-risk areas, and offering a minimally invasive alternative to surgical intervention^{176–178} (see [Supplementary material online, Video S16.7](#)).

Relevant videos for section intracardiac echocardiography for guidance of endomyocardial biopsy

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

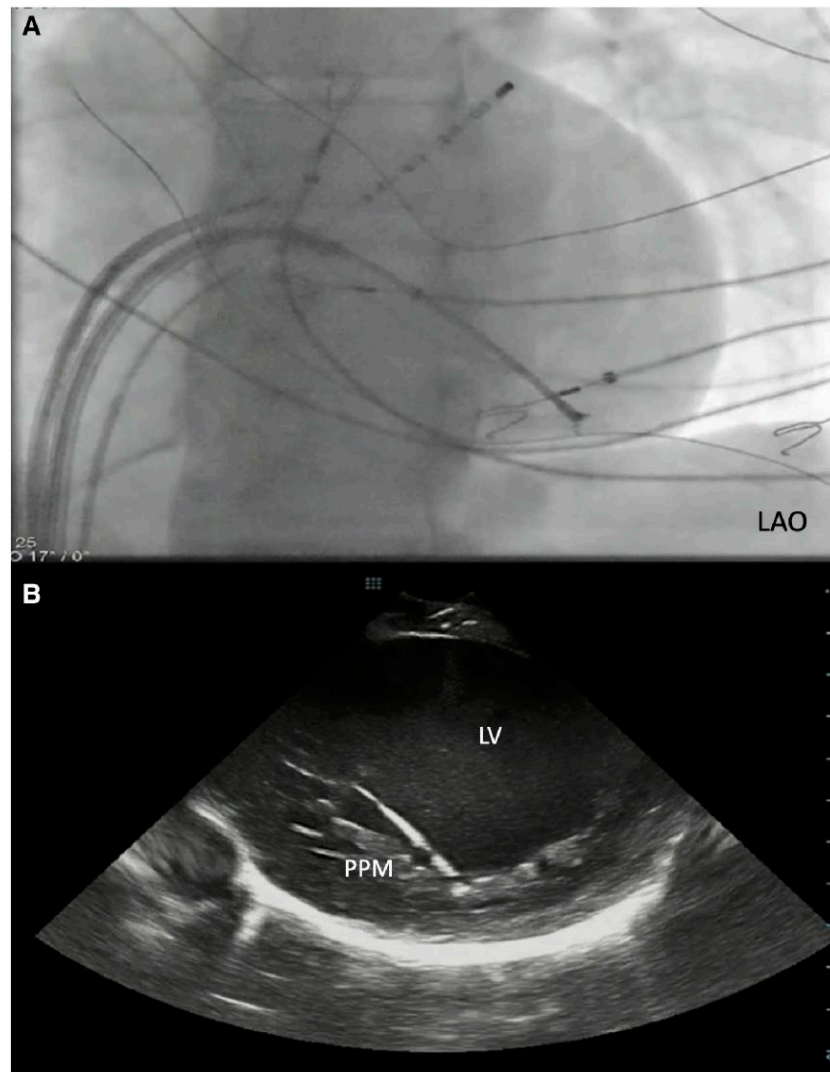


Figure 22 Fluoroscopic image in LAO projection (*Panel A*) and ICE long axis view of the LV (*Panel B*) showing left ventricular EMB. In the ICE view, note the bioprobe positioned near the base of the posteromedial PM, corresponding to a hyperechogenic epicardial/pericardial area. LAO, left anterior oblique; LV, left ventricle; PPM, posterior papillary muscle.

Intracardiac echocardiography for assessment of implantable device-related intracardiac masses and guidance of lead extraction and leadless pacemaker implantation

Key messages:

- Intracardiac echocardiography is a viable option for assessing intracardiac infections, especially when other imaging techniques are inconclusive or not feasible.
- Intracardiac echocardiography is useful for risk-stratification, decision-making, procedural monitoring during transvenous lead extraction, and post-procedural reassessment.

Presence of transvenous intracardiac leads carries a small risk of infective complications.¹⁷⁹ Diagnosing infective endocarditis (IE) can be challenging, particularly in cases of cardiac device-related endocarditis or prosthetic valve endocarditis (PVE). Although echocardiography is a key tool for detecting IE, including PVE and lead-related endocarditis, there are situations where TEE may not provide definitive results or may be difficult to perform. In these cases, ICE serves as an alternative imaging modality.¹⁸⁰

In general, lead-adherent echodensities (LAEs) are masses of various shapes and sizes attached to intracardiac leads that are frequently detected by echocardiography imaging (*Figure 23*). Small LAEs (<1 cm) are a common finding in the RA, typically on the atrial segment of the lead or at the tricuspid annulus (see [Supplementary material online, Video S17.1](#)). These small LAEs

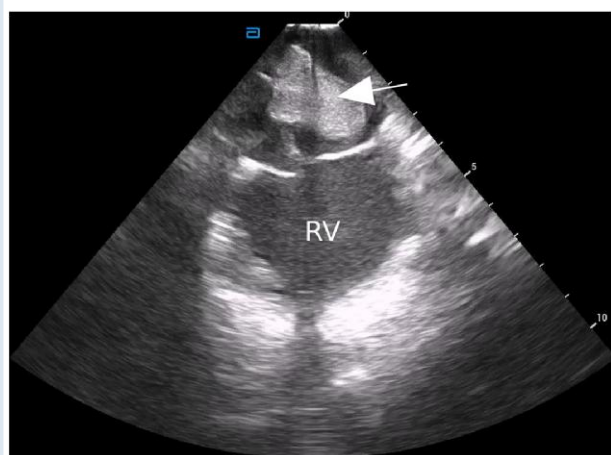


Figure 23 Large mass (lead-adherent echo density) on the defibrillator lead in the right atrium in a patient with sepsis. RV, right ventricle.

are usually clinically insignificant, and stand-alone detection does not constitute a diagnosis of IE. However, in the presence of bacteraemia, LAEs should be regarded as potential vegetation's. When large LAEs are identified (see [Supplementary material online, Videos S17.2](#) and [S17.3](#)), there is concern for clinically significant embolism. In a small series of patients, ICE-guided percutaneous aspiration was performed prior to lead extraction (see [Supplementary material online, Video S17.4](#)).

During transvenous lead extraction, periprocedural ICE guidance enables early detection of potential complications and the identification of lead-tissue bindings. Such bindings can be visualized at the tissue-lead interface during slight lead traction, showing simultaneous movement of both structures.¹⁸¹ The presence of binding sites is associated with increased procedural complexity during lead extraction¹⁸² and aids in planning strategies to reduce procedural risk, such as using simultaneous lead traction from both above and below, vascular occlusion balloon, or specific extraction sheaths. Alternatively, a decision may be made to abandon the lead or refer the case for surgical extraction. Imaging after lead extraction may identify previously unseen LAEs that have been sheared off and remain in the heart, which could potentially require treatment.

Recently, ICE has been proposed as a complementary imaging technique for guiding the implantation of leadless pacemakers.^{183,184} Notably, in the implantation of atrial leadless devices into the right atrial appendage, ICE has been utilized to confirm device-tissue contact, facilitating optimal device placement. Furthermore, this approach has contributed to the reduction of fluoroscopy exposure and the use of contrast media. Additional research is required to ascertain the efficacy and safety of this technique.

Relevant videos for section intracardiac echocardiography for assessment of implantable device-related intracardiac masses and guidance of lead extraction and leadless pacemaker implantation

To see the relevant videos for this section, list below, Supplementary Material is available at [Europace](#) online.

Intracardiac echocardiography catheter reprocessing in the EU: regulation, cost-effectiveness, and learning curve

Key messages:

- The reprocessing of intracardiac echo catheters is a legally and logistically complex topic, with substantial variations among European countries.
- Where permitted and properly regulated, reprocessing of intracardiac echocardiography catheters offers major cost-savings, environmental benefits, and allows for broader use and safer patient care in catheter ablation procedures.

Although incorporating ICE into daily workflows presents many potential benefits, it also comes with considerable costs that differ in affordability in the variable financial context of European countries.¹⁸⁵ One potential solution for reducing these costs is the reuse and reprocessing of medical devices.¹⁸⁶ However, ICE catheters are officially designated as single-use devices by their manufacturers, and as such, are subjected to stringent medical device regulations in the European Union (EU). These regulations, particularly the European Medical Device Regulation (EU MDR 2017/745), place the responsibility for safety and performance on any entity reprocessing a single-use device, effectively treating them as manufacturers. This includes requirements for validation, traceability, and outcome monitoring for each device and reuse cycle. As a result, there are legal barriers and inconsistencies across the EU. In Switzerland, France, Italy, Denmark, and Poland, reprocessing is expressly forbidden. In contrast, other EU countries, including Portugal, Norway, the Netherlands, Belgium, Germany, Croatia, and Bulgaria, permit reprocessing but impose institutional protocols, expiration dates, or limits on the number of reuse cycles.

Multiple studies and practical institutional experiences have shown that reprocessing ICE catheters can yield significant cost-savings and sustainability benefits. A single-centre study reported that each ICE catheter could be safely used for an average of nearly 20 procedures, resulting in a total cost reduction of over 90% (~€2.25 million saved over 8 years) and a 95% reduction in medical waste generation (>600 kg less waste). The authors reused ICE probes consistently and opened new catheters only when acquired images were suboptimal or when the reprocessed catheter exhibited significant visual damage.

By lowering per-procedure costs, reprocessing enables the wider use of ICE, facilitating its broader and safer application, particularly in resource-limited settings. Most surveyed clinicians consider the reuse of ICE and electrophysiology catheters to be safe and cost-effective when conducted according to validated protocols. This practice benefits hospitals and health systems financially while aligning with 'green' healthcare objectives.¹⁸⁷

Concerns about infection risk and device reliability—historically significant barriers—are consistently addressed through real-world data. No increased rate of infections, allergic reactions, or device malfunctions attributable to reprocessing has been observed in large retrospective analyses, provided that visual inspection and functional checks are rigorously performed before each use.¹⁸⁸ However, rare complications, such as device embolization, have been described, underscoring the necessity of stringent reprocessing protocols and controlled limits on the number of safe reuse cycles.²

The successful use of ICE catheters depends on clinical experience and operator skill. ICE use presents a unique learning

curve compared with transthoracic or TEE. Operators must become familiar with various probe manipulations and overcome spatial orientation challenges specific to intracardiac imaging. The complexity of these tasks underscores the need for comprehensive initial and ongoing training, as inexperienced users may encounter difficulties in image acquisition or procedural inefficiencies.¹⁸⁹ Modern advancements, including automated anatomy labelling and artificial intelligence-based navigation assistance, are emerging to help reduce the learning curve for new ICE operators.¹⁹⁰

Future directions

Future technological developments in ICE catheters and their applications are anticipated to further enhance the clinical value of ICE and broaden its use in electrophysiological procedures. The primary areas of innovations include: (i) improvements in image resolution and quality of 2D, 3D, and 4D ICE imaging; (ii) the assessment of tissue and lesion characteristics; (iii) the development of artificial intelligence-based image processing algorithms for ICE images; and (iv) the creation of robot-assisted manipulators for ICE catheters.

Advancements in ultrasound technology, particularly through the integration of next-generation computer micro-machine ultrasound transducers, are expected to improve image resolution without increasing catheter size. Progress in 4D ICE catheters will enable even higher-resolution, real-time volumetric images. Multiplane imaging with 4D ICE allows for continuous visualization of intracardiac structures and ablation catheters, facilitating optimal catheter positioning and efficient lesion deployment.⁵⁵

Advanced ICE catheter features also enable the assessment of tissue properties, which serve as a surrogate for evaluating the size, depth and transmuralty of ablation lesions. Several ICE-based methods have been tested to characterize lesion properties, including shear wave elastography, acoustic radiation force impulse imaging, and myocardial elastography.^{191,192}

Artificial Intelligence is expected to enhance the practical value and clinical applications of ICE. Deep learning auto-contouring algorithms facilitate fast, automated, and more accurate detection of cardiac chamber anatomy.^{12,193–195} These advancements will also expedite the process of 3D volume reconstruction and reduce operator-dependent variability. Deep learning algorithms will be integrated into ICE systems to automatically and dynamically adjust the image gain, depth and focus, maximizing quality and resolution, improving workflow and reducing operator dependency. Furthermore, artificial intelligence-guided continuous image monitoring may also enable prompt identification of early signs of complications, such as pericardial effusion, allowing for timely intervention.

A caveat of ICE use in interventional procedures is the need for a second operator or multitasking by a single operator, which can increase procedural complexity or require high levels of manual dexterity. The development of automatic manipulation systems for ICE catheters aims to overcome this challenge. Enhanced automation in ICE workflows includes catheters equipped with position tracking sensors or robotic manipulators. The latter systems allow for catheter manipulation either with teleoperation of catheter controls (joysticks) or with actuators that automatically steer the catheter handle knobs with four degrees of freedom. These robotic technologies, combined with integrated control algorithms, will enable automatic manipulation and precise navigation of the ICE catheter tip to specific anatomical structures, providing predefined views for the clinician.^{196,197}

Supplementary material

Supplementary material is available at [Europace](#) online.

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Data availability

The data underlying this article are available in the article and in its online supplementary material.

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