Current perspective

Intracardiac echocardiography: from electroanatomic correlation to clinical application in interventional electrophysiology

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Intracardiac echocardiography (ICE), using an ultrasound transducer at the tip of a percutaneously placed catheter, has recently been introduced for the visualization of the intracardiac anatomy and in order to reduce the fluoroscopy time. This review focuses predominantly on the current use of ICE in interventional electrophysiology.

ICE has been shown to facilitate the targeting of specific anatomic landmarks, such as the crista terminalis, the Eustachian ridge, the tricuspid annulus, the coronary sinus ostium, and the pulmonary veins that cannot be adequately visualized at fluoroscopy. Direct imaging of these sites can be advantageous in that it facilitates the accurate guidance of the ablative procedure and shortens the fluoroscopy time. ICE has been demonstrated to be useful in the positioning and stabilization of the imaging ablation catheter, the evaluation of the lesion size and continuity and in the immediate identification of complications. Furthermore, in the last few years there has been a revival in the use of transseptal catheterization due to a larger development of radiofrequency catheter ablation in the left atrium. ICE, providing excellent views of the fossa ovalis and of the transseptal apparatus, can be safely used to prevent life-threatening complications following inadvertent puncture of anatomic structures such as the lateral wall of the left atrium or the aortic root. Moreover, ICE appears to be very useful in combining true anatomical features with electrical activation in an attempt to construct realistic electrical-anatomical maps. Finally, the three-dimensional tomographic reconstruction of intracardiac images and the phased array ICE catheter with Doppler capabilities seem to be promising tools both for the guidance of ablation procedures as well as in leading experimental studies.

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Introduction

In recent years the ever increasing acceptance of radiofrequency (RF) catheter ablation as the standard therapy for various arrhythmias has significantly increased the importance of direct imaging of the intracardiac anatomy. During the ablation procedures, the catheter is usually positioned on the basis of fluoroscopic intracardiac electrogram analysis. While this technique has proved to be satisfactory for the majority of procedures, it does not allow for accurate targeting of specific anatomic sites (i.e. the crista terminalis, the Eustachian ridge, the tricuspid annulus, the coronary sinus ostium, and the pulmonary veins) that play a critical role in a variety of cardiac arrhythmias. In fact, in a large number of arrhythmias there appears to be a strong relationship between the endocardial anatomy and the arrhythmia substrate and mechanism. Moreover, fluoroscopy is associated with significant radiation exposure[1-3] to the patient as well as to the operator. This is particularly true for most complex procedures.

Intracardiac echocardiography (ICE), using an ultrasound transducer at the tip of a percutaneously placed catheter, has recently been introduced for the visualization of the intracardiac anatomy[4-7] and in order to reduce the fluoroscopy time[8]. ICE has been found to be useful for the positioning and stabilization of the imaging ablation catheter, for the evaluation of the lesion size and continuity and for the immediate identification of complications[9]. Furthermore, ICE has proved to be very useful in defining the relationship between the electrophysiological characteristics of the arrhythmia and anatomic landmarks[10-12]. Finally, in the last few years there has been a revival in the use of transseptal catheterization[13] due to a more widespread development of left atrial RF catheter ablation procedures[14-22]. Transseptal puncture, performed under fluoroscopic guidance, is burdened by rare but serious complications. ICE, providing excellent views of the fossa ovalis and of the transseptal apparatus, can be safely used for the prevention of life-threatening complications following inadvertent puncture of anatomic structures such as the lateral wall of the left atrium or the aortic root.

This review predominantly focuses on the current use of ICE in interventional electrophysiology. Moreover, in view of the rapid technological advances, we address some of the experimental areas in which ICE seems to be promising.

Imaging system

Currently, the intravascular ultrasound system[23-25] is commonly used by interventional cardiologists to evaluate the coronary anatomy before and after intervention. This system uses high-frequency ultrasound (20 to 35 MHz), yielding excellent resolution but very limited penetration (millimeters). The development of lower-frequency (6 to 15 MHz) catheter-based ultrasound transducers has allowed for an increased field of view, intracardiac imaging and the visualization of intracardiac structures. When ultrasound technology was introduced, individual investigators had to adapt the imaging system because clinical systems specifically designed for intracardiac imaging had not been fully developed yet. A dilator with a long vascular sheath similar to that used for transseptal catheterization can be used to place the ICE transducer in the right atrium.

ICE was first used in 1994 by Chu et al.[26] to guide RF catheter ablation of cardiac arrhythmias in humans. Later, different types of intracardiac echo transducers have been evaluated both in animals and humans for various clinical and experimental purposes[21,27,28]. Recently[6,13,29], a 9F/9-MHz imaging catheter that provides improved depth penetration and resolution and prevents imaging deterioration after a certain period of time has been developed. However, the catheter no longer has a guide wire and is not steerable. This limits its utility when obtaining a variety of intracardiac views. More recently, a new application which allows the construction of three-dimensional real size and real gating heart images using as a source a conventional 9F/9-MHz catheter (Boston Scientific Corporation, San José, CA, USA)[30,31] has been used. The system loads the images and constructs a "cube" containing all the planes. In the post-processing phase it allows the user to have all the images in a three-dimensional tomographic reconstruction visualizing different sections and with a dynamic three-dimensional view. Figure 1 shows an example of the three-dimensional reconstruction of the right atrium.

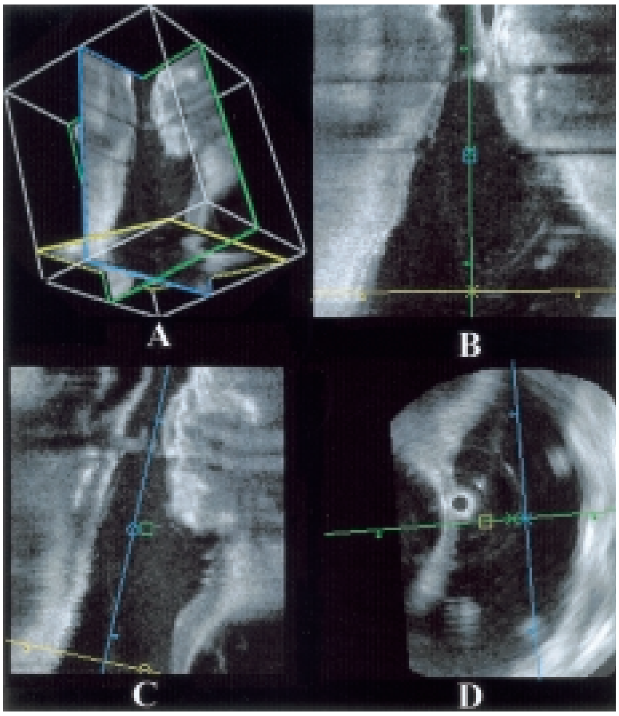


Figure 1. *Three-dimensional reconstruction of the right atrium. This new application allows the operator to build three-dimensional heart images. The system allows visualization of a two-dimensional cut plane of the three-dimensional tomographic reconstruction at any time. Moreover, the orientation of cut planes can be determined with different angles.* Panel A *shows the three-dimensional view of the right atrium.* Panel B *shows the plane of section indicated by the* blue line. Panel C *shows the plane of section corresponding to the* green dashed line. *In* panel D *the* yellow dashed line *corresponds to the plane of section.*

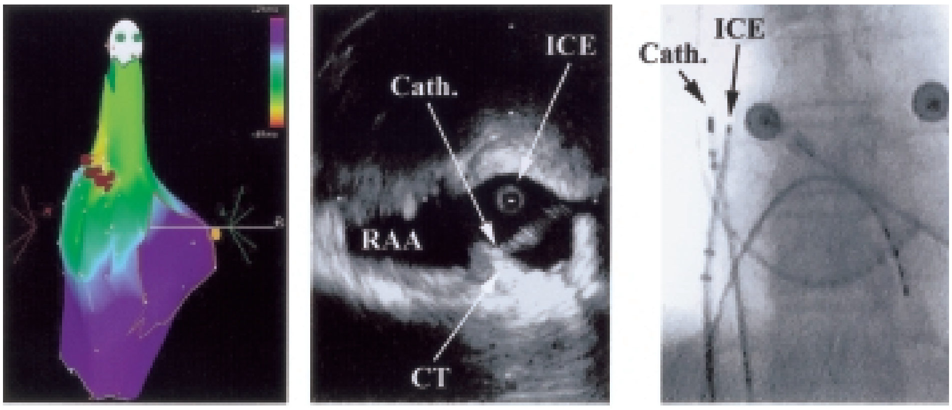
Finally, the use of a phased array ICE catheter (Acunav, Acuson, Mountain View, CA, USA) with Doppler capabilities has been proposed. This 10F/7-MHz imaging catheter has a single-plane 64-element phased array ultrasound transducer mounted along the long axis of the catheter immediately proximal to the catheter tip. In addition to two-dimensional imaging, the catheter has full pulsed wave, continuous wave, tissue and color flow Doppler capabilities. The catheter tip can be deflected by 160° in two planes (antero-posterior and sagittal). In an animal model Morton et al.[32] demonstrated the utility of this phased array ICE catheter for the imaging of the left atrial and pulmonary vein anatomies from the right atrium. Moreover, they showed that this catheter is a useful tool for the accurate guidance of RF ablation of the pulmonary vein ostia and for the evaluation of the pulmonary vein blood flow before and after ablation using Doppler parameters.

Utility of intracardiac echocardiography in specific arrhythmias or interventional procedures

Inappropriate sinus tachycardia. The syndrome of inappropriate sinus tachycardia is characterized by an elevated resting heart rate and by an excessive heart rate increase following minor exertion or stress. Patients with refractory symptoms despite medical therapy may be treated by means of RF modulation of the sinus node function. The sinus node pacemaker complex is distributed over an area lying between the junction of the superior vena cava and the right atrial appendage and extending inferiorly and laterally along the sulcus terminalis almost to the inferior vena cava[33,34]. The crista terminalis is an endocardial marker for this pacemaker complex[35,36]. Some authors[37-39] observed that the vagal tone increases the cycle length shifting the location of the dominant pacemaker to a lower atrial site, whereas sympathetic activation decreases the cycle length resulting in a more cranial and anterior pacemaker site.

On the basis of these observations, RF catheter ablation of the superior portion of the sinus node may be used to eliminate the highest rates and thus modify the sinus node function. In 1995 Kalman et al.[40] demonstrated the feasibility of modifying the sinus node pacemaker function by means of catheter-based delivery of RF energy in 11 dogs. ICE was used to identify the crista terminalis as an anatomic marker of the sinus node location and to facilitate activation mapping in relation to endocardial structures. At intracardiac ultrasound imaging, the crista terminalis appeared as a prominent, irregularly shaped endocardial ridge and its visualization facilitated catheter placement. In this study, modification of the sinus pacemaker resulted in a significant decrease in the intrinsic heart rate, in the heart responsiveness to isoproterenol and in the average and maximal heart rates during 24-hour Holter monitoring. These effects were maintained in the long-term follow-up. The authors concluded that ICE accurately defined the crista terminalis and provided a reliable means of anatomically localizing the catheter position as related to that of the sinus node. In the same year, Lee et al.[41] studied 16 patients with disabling episodes of inappropriate sinus tachycardia refractory to drug therapy. They identified the region of earliest atrial activation in sinus rhythm at electrophysiological evaluation of the patients. This region was further defined by means of ICE in 9 patients in whom it was found that an ablation catheter could be reliably guided and maintained on the crista terminalis. Total sinus node ablation was successfully performed in all 4 patients in whom it was attempted and was characterized by a junctional escape rhythm; sinus node modification was successfully achieved in the remaining 12 patients and characterized by a 25% reduction in the sinus heart rate. In this study there was a significant decrease in the number of deliveries of RF energy required in patients undergoing ICE-guided procedures compared with that observed when fluoroscopy alone was performed. The fluoroscopy time was also decreased. Callans et al.[42] used ICE to guide the positioning of the ablation catheter and for continuous monitoring during RF application in 13 ablation procedures performed for inappropriate sinus tachycardia. The superior vena cava-right atrial junction was measured before and after energy delivery. They observed a local and circumferential swelling, causing a progressive and statistically significant reduction in the diameter of the superior vena cava-right atrial junction (> 30% in 5 patients). An increase in the crista terminalis wall thickness and wall swelling extending to the adjacent superior vena cava was also described by Ren et al.[43] but the degree of thickening was not specific for the effective RF lesions. Importantly, the authors noted that effective RF applications resulting in a heart rate reduction were characterized by echo density changes of the atrial wall, with the development of a linear low echo-density or echo-free space, extending directly to the epicardium. This particular echocardiographic feature suggesting transmural epicardial damage may be an appropriate guide for RF ablation of inappropriate sinus tachycardia when using an approach based on the cardiac anatomy as visualized at echocardiography. They concluded that the delivery of multiple RF ablation lesions for the therapy of inappropriate sinus tachycardia could cause considerable atrial swelling and a resultant narrowing of the superior vena cava-right atrial junction. In our experience, we successfully modified the sinus node function in 6 patients with inappropriate sinus tachycardia. No complications were observed. We used a nonfluoroscopic mapping system (Carto, Biosense-Webster, Diamond Bar, CA, USA) to determine the area of earliest atrial activation during sinus rhythm and ICE to visualize the crista terminalis and to assess the tissue-tip contact and the stability of the ablation catheter (Fig. 2).

Atrioventricular nodal reentrant tachycardia. In case of atrioventricular nodal reentrant tachycardia, the positioning of the ablation catheter is based on fluoroscopy and on the morphology of the intracardiac electrograms. The anatomical location of the posterior slow pathway[44,45], that is the target of the RF ablation procedure, is defined in relation to the position of the catheters placed in the coronary sinus and in the His bundle region. In addition, an annular location is inferred from the electrogram atrioventricular ratio. Although the traditional RF ablation technique is highly effective in atrioventricular nodal reentrant tachycardia, the use of ICE for investigational purposes could provide additional information on the atrioventricular node physiology and on the atrioventricular nodal reentrant tachycardia mechanisms in relation to anatomical structures such as the triangle of Koch, the coronary sinus, the tendon of Todaro and the tricuspid annulus. Fisher et al.[46] studied 25 patients with atrioventricular nodal reentrant tachycardia using a 6.2F/12.5-MHz ICE catheter positioned adjacent to the triangle of Koch. As revealed by ICE, anterograde slow pathway ablation was achieved between 2 and 7 mm from the tricuspid valve in imaging planes containing the atrioventricular muscular septum in all cases. RF energy application at other sites within the triangle of Koch failed



A B C

Figure 2. *Electroanatomic mapping and intracardiac echocardiography (ICE) imaging used to guide radiofrequency ablation of inappropriate sinus tachycardia in a 24-year-old woman.* Panel A *shows the activation map of the right atrium during sinus tachycardia. The color-coded activation sequence is shown with* red *identifying the earliest and* purple *the latest excitation. The* red dots *represent the sites of radiofrequency delivery.* Panel B *shows an echographic view of the site of radiofrequency ablation. The ICE transducer is positioned in the superior portion of the right atrium. The crista terminalis (CT) and the right atrial appendage (RAA) may be clearly seen. The ablation catheter (Cath) tip is identified by its characteristic fan-shaped acoustic shadow. An excellent tip-tissue contact on the CT is visible*. Panel C *shows the fluoroscopic view (antero-posterior) of the Cath positioned at the ablation site. The ICE transducer is positioned in the superior portion of the right atrium.*

to interrupt the slow pathway conduction. They concluded that ICE contributes to the identification of the effective anatomic ablation site in typical atrioventricular nodal reentrant tachycardia. Actually, the authors observed that the site of attachment of the septal leaflet of the tricuspid valve to the atrioventricular muscular septum was invariably also the site of successful ablation, supporting the hypothesis that slow pathways consistently traverse this anatomic location.

Ectopic atrial tachycardia. Ectopic or focal atrial tachycardia is a reversible cause of cardiomyopathy but may be quite difficult to control with conventional therapy. The mechanisms of ectopic atrial tachycardia are heterogeneous and may include enhanced automaticity, triggered activity and microreentry. However, characteristic of all the arrhythmias appertaining to this group is their origin from a single discrete focus. In case of atrial tachycardia, three-dimensional mapping of the atria is required. The difficult catheter orientation and navigation associated with conventional technology and with mono or multiplane fluoroscopy may complicate the ablation therapy of atrial tachycardias. Different methods have been proposed for the mapping of ectopic atrial tachycardia[47-49]. A large number of studies demonstrated a typical anatomical distribution of ectopic atrial tachycardia sites[49-51]. Right atrial tachycardias involve a clustering along the long axis of the crista terminalis originating within the body of the right atrial appendage, from the region of the coronary sinus ostium and around the atrioventricular node. In the left atrium, common sites of ectopic foci include the region of the pulmonary venous ostia and the left atrial appendage. Lesh et al.[28] assume that, if the site of the earliest P wave lies high and posteriorly within the right atrium, an origin in the right upper pulmonary vein is likely and the operator can proceed to a transseptal catheterization. The possibility of visualizing the intracardiac anatomy, as well as the position of the mapping and ablation catheters, may greatly enhance the safety and efficacy of RF ablation procedures in ectopic atrial tachycardia. Appropriate placement of a multipolar catheter along the crista terminalis, the left or right appendages, or pulmonary venous mouth facilitate the mapping and the ablative procedures. Using ICE, Kalman et al.[35] studied "cristal tachycardias" in order to facilitate activation mapping as related to endocardial structures. A 20-pole catheter was positioned along the crista terminalis under ICE guidance. Of 27 focal right atrial tachycardias, the origin of 18 (67%) was localized on the crista terminalis. ICE identified the location of the tip of the ablation catheter immediately adjacent to the crista terminalis in all 18 cases. The 20-pole mapping catheter together with echocardiographic visualization of the crista terminalis provided a guide to the sites of origin of the tachycardia along this structure. RF ablation was successful in 26 (96%) of 27 right atrial tachycardias. They concluded that two thirds of focal right atrial tachycardias occurring in the absence of structural heart disease will arise along the crista terminalis and the recognition of this common origin, as confirmed by ICE guidance, may facilitate the mapping and ablation of these tachycardias. Thus, when a multipolar catheter is placed on the crista terminalis under ICE guidance and no site is found to be particularly early relative to onset of the surface P wave, the operator can quickly conclude that the tachycardia does not originate on the crista terminalis thus saving time and proceeding with the mapping of regions away from it[28,35]. Figure 3 shows the ICE-guided positioning of an ablation catheter along the crista terminalis and the monitoring of its stability during RF delivery.

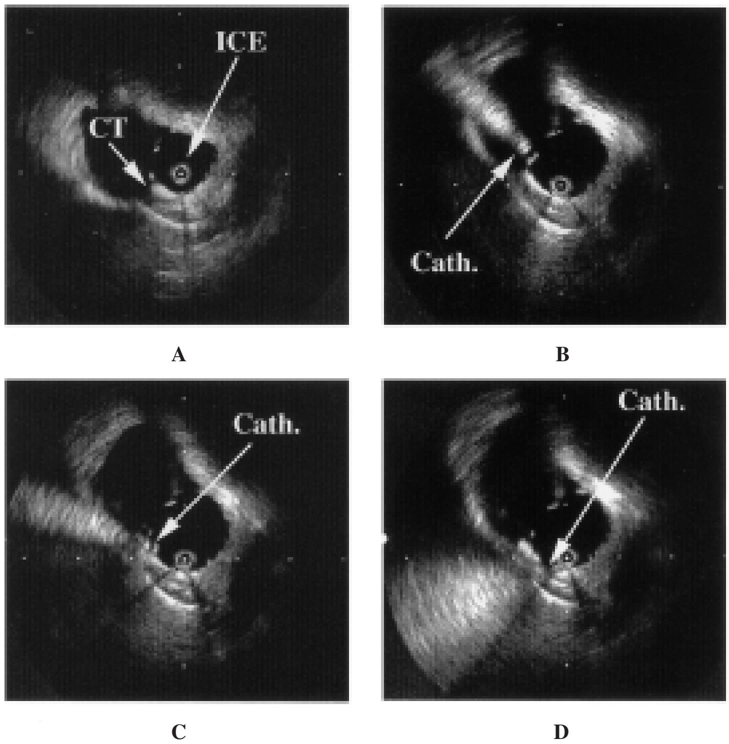


Figure 3. *Echographic view of the crista terminalis (CT) during radiofrequency ablation of an ectopic right atrial tachycardia.* Panel A *shows the intracardiac echocardiography (ICE) catheter in the right atrium close to the CT; a "basket" catheter is used to map the ectopic right atrial tachycardia. In* panel B *the ablation catheter (Cath) is advanced close to the CT (ablation site).* Panel C *shows an adequate tip-tissue contact on the CT during radiofrequency energy delivery. In* panel D *the ablation catheter was accidentally dislocated posteriorly to the CT; for this reason radiofrequency delivery was immediately stopped.*

Atrial flutter. Typical atrial flutter is a macroreentrant rhythm localized in the right atrium. In typical counterclockwise atrial flutter, the wave front runs in a lateral to septal direction along the isthmus between the inferior vena cava and the tricuspid valve, passes between the tricuspid annulus and the Eustachian ridge, and then spreads through the septum in a caudocranial direction. RF catheter ablation of atrial flutter is performed using an anatomical approach to target the isthmus and to create a nonconductive barrier[52]: the ablation catheter is placed on the inferior tricuspid annulus and during RF delivery, is slowly pulled back until the inferior vena cava. A different approach[53] consists in creating a linear lesion between the tricuspid annulus and the coronary sinus. This lesion alone is sufficient when the Eustachian valve is completely carried forward to the ostium of the coronary sinus (about 60% of patients). When the ridge stops short of the coronary sinus, the lesion must be continued from the ostium of the coronary sinus to the inferior vena cava. Despite a satisfactory success rate of fluoroscopy-guided RF ablation procedures, the fluoroscopy time is usually long and this imaging modality does not permit the visualization of some intracardiac structures that could play a critical role in atrial flutter. ICE can be used to visualize the fossa ovalis, the tricuspid annulus, the Eustachian ridge, the crista terminalis, the coronary sinus and the venae cavae, and also allows the precise localization of the intracardiac catheters relative to these anatomic structures[54-58]. In a small percentage of patients with typical atrial flutter that turned out to be resistant to ablation due to conduction gaps, a three-dimensional reconstruction of the isthmus demonstrated that a larger Eustachian ridge was present and that all the gaps were located along this structure. In these patients ICE-guided RF delivery along the Eustachian ridge allowed the achievement of a complete block[30].

Using ICE in order to visualize and exactly place the catheters along the intracardiac structures, Olgin et al.[27] observed typical split potentials at the crista terminalis and proposed that it acts as a barrier to transverse conduction in atrial flutter. However, several observations in animal models have suggested that transverse conduction across the crista terminalis does occur in the normal heart[59,60]. Schumacher et al.[61], using ICE, determined the transverse conduction capability of the crista terminalis during pacing in sinus rhythm in patients with documented atrial fibrillation (AF) or atrial flutter. They concluded that the crista terminalis provides transverse conduction capabilities and that the conduction block during atrial flutter is functional.

Several recent observations[62], however, have suggested that the crista terminalis may not be a barrier to conduction in isthmus-dependent atrial flutter, and thus may not be a critical factor in the arrhythmia mechanism. By means of biplane fluoroscopy and ICE

Friedman et al.[63] characterized the posterior boundary of atrial flutter in 28 patients with this arrhythmia. They found that in all patients a functional line of block was present at the postero-medial (sinus venosa) right atrium during counter-clockwise and clockwise atrial flutter. Pacing near the site of double potentials during sinus rhythm excluded a fixed line of block, and premature atrial complexes demonstrated functional block with manifest double potentials. They concluded that a functional line of block was present at the postero-medial (sinus venosa) right atrium during atrial flutter. Moreover, the absence of double potentials in the region of the crista terminalis suggested that the crista terminalis block was not required for the maintenance of atrial flutter in these patients. Figure 4 shows an example of electroanatomic mapping of atrial flutter by the contemporary use of the "basket" catheter (Constellation catheter, EP Technologies, Inc, Sunnyvale, CA, USA) and ICE.

Moreover, the crista terminalis does not seem to show peculiar anatomical features in patients with typical atrial flutter. We used a three-dimensional echo reconstruction to analyze the morphology, maximum diameter and maximum cross-sectional area of the crista terminalis in patients with atrial flutter, AF and controls[31] (Fig. 5). No significant difference was found between patients with atrial flutter and controls.

Atrial fibrillation. AF is the most common cardiac arrhythmia, and current pharmacological therapy remains unsatisfactory. Therefore, it has been proposed that nonpharmacological approaches be investigated. The classical surgical "maze" procedure, developed by Cox et al.[64], has been progressively replaced by the use

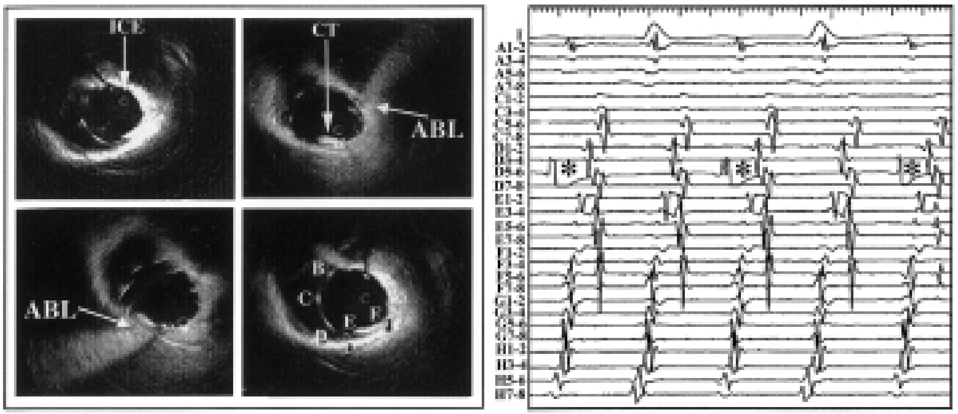


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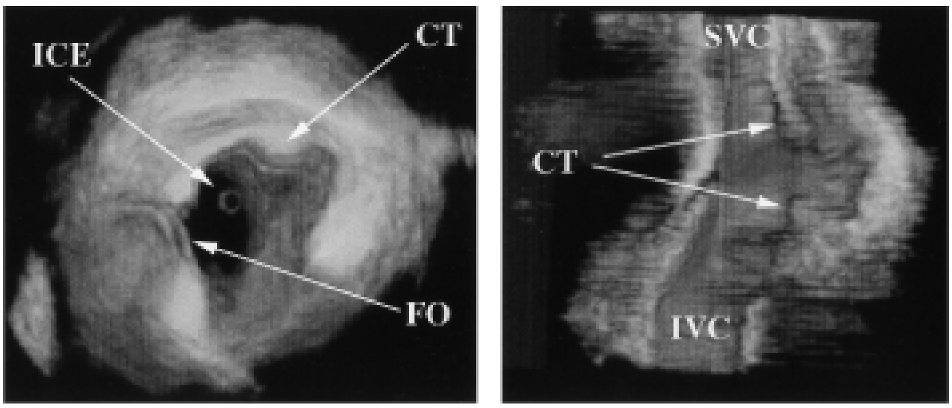
Figure 4. *Extensive mapping of the right atrium during atrial flutter with a "basket" catheter. The origin of the different electrograms recorded from the different "basket" electrodes positioned on the right cardiac anatomic structures (i.e. the crista terminalis-CT) was determined with the aid of the intracardiac echocardiography (ICE) catheter.* Panel A *shows the ICE catheter in the right atrium. The CT can be clearly seen. The tip of the ablation catheter (ABL) with the typical fan-shaped catheter artifact has been moved to the different electrodes to accurately determine their position in the right atrium.* Panel B *shows the bipolar electrograms obtained from the "basket" catheter during mapping of common atrial flutter. The contact between the tip of the ablation catheter (seen at ICE) and the "basket" electrodes D5-6 is visible as an artifact* (*) *on these recordings.*



A B

Figure 5. *Three-dimensional reconstruction of the right atrium in a transversal plane* (panel A) *and in a sagittal plane* (panel B). *In this patient with common atrial flutter the crista terminalis (CT) is particularly prominent in its superior and inferior portions with a gap in the mid-atrium. FO = foramen ovalis; ICE = intracardiac echocardiography; IVC = inferior vena cava; SVC = superior vena cava.*

of RF energy for the creation of linear ablative lesions in the right[65-68] and left atria[17-22]. These procedures are largely anatomically guided and are performed with the aim of creating lesions resulting in a conduction block in some regions of the atria. Early attempts with standard catheters have resulted in very long procedure and fluoroscopic times, an unsatisfactory success rate and recurrent atrial arrhythmias. Indeed, incomplete lesions not only are ineffective, but can also create an anatomical substrate for new arrhythmias (proarrhythmic effect). Despite the use of a technologically more advanced ablation catheter and endocardial mapping systems, AF ablation remains a very complex and long procedure. Fluoroscopic imaging of the endocardial structures is limited and does not provide satisfactory information about the electrode-tissue contact and the lesion depth and continuity that are the major determinants of successful lesions. A three-dimensional electroanatomic nonfluoroscopic mapping system (Carto, Biosense-Webster) has been used to guide RF ablation of AF by creating long linear lesions in both atria[20, 68] or by isolating the pulmonary vein from the left atrium by circumferential lesions around the pulmonary vein ostia[22]. The Carto system facilitates the creation of such lesions by allowing navigation of the mapping and ablation catheter inside the heart with limited use of fluoroscopy and by permitting accurate selection of the target sites as well as electrophysiological evaluation of the completeness of the lesions. Nevertheless, Carto does not permit a direct visualization of anatomic structures; information about the catheter-tissue contact, line continuity and transmurality is only indirect.

Previous experimental studies[8,57,69-71] demonstrated that ICE has permitted the easy evaluation of the coil-tissue contact and the improvement in the depth and continuity of the RF linear lesion in AF. Olgin et at.[57] used a 10F/10-MHz ICE catheter to create linear lesions in the right atrium of an animal model. Pathological evaluation revealed that ICE improved the continuity, completeness and positioning of the linear right atrial lesions. ICE images were used to optimize the coil-tissue contact and to direct the anatomic positioning, resulting in a relatively short procedure time, efficient energy application and accurate lesion targeting. At autopsy, all lesions were discrete, continuous, and without evidence of charring. The lesions were within 0.3 ± 0.5 mm of their target sites. Histology revealed transmural fibrosis through the length of each lesion. Epstein et al.[8], using a 9F/9-MHz catheter, observed that in a pool of 328 attempted energy applications in dogs, ICE guidance resulted in a higher rate of successful energy application compared with fluoroscopic guidance alone. On the basis of ICE imaging, the coil-tissue contact score proved to be an excellent predictor of the efficacy of energy delivery: none of the ablation attempts with a "poorly" defined contact were successful, whereas 92% of attempts with an "excellent" contact were successful. At pathological evaluation no ablative lesion was found outside the targeted areas in ICE-guided procedures; in contrast, ablative lesions were found outside the targeted areas in all the animals in which fluoroscopy alone was used for guidance. Furthermore, Ren et al.[72] recently showed that wall thickness changes and an increased focal echo-density after RF applications in swine atria and left ventricles well correlated with the lesion depth, size and transmurality at pathological analysis. They concluded that ICE may be useful in the on-line quantification of RF lesions during clinical catheter ablation procedures.

Recently, Haissaguerre et al.[17] observed that AF may be linked to "focal" mechanisms that can be treated by RF catheter ablation. The pulmonary veins are the most frequent source of initiating foci amenable to RF ablation. However, this area has a complex anatomy with relevant variations. Moreover, RF ablation inside or around the pulmonary veins may determine stenosis undetectable by fluoroscopic imaging alone[73]. In an experimental study[32] the left atrium, pulmonary vein anatomy and blood flow were accurately imaged from an ICE transducer positioned in the right atrium. ICE was used to position the ablation catheter in relation to the left atrium structures and permitted the detection of anatomic abnormalities or thrombus formation. Furthermore, it allowed an immediate evaluation of the pulmonary vein patency after RF ablation.

Ventricular tachycardia. Few articles regarding the use of ICE in patients with ventricular tachycardia have been published in the literature. In 5 patients with idiopathic ventricular tachycardia of the left ventricular outflow tract, Lamberti et al.[74] demonstrated that ICE could accurately guide catheter ablation by permitting the identification of anatomic landmarks, endocardial contact and ablation electrode movement. Using ICE they were able to have a clear and detailed vision of the aortic root and of the ablation catheter tip. This view was easily obtained by positioning the ultrasound transducer on the anterior part of the atrial septum (His bundle region) or at the base of the right ventricular outflow tract. The ablation site was never localized "on" the coronary cusp, but the ablation electrode was positioned at a distance of 0.6 to 1.2 cm. The left main coronary artery was clearly visible at its origin and it seemed to be at a safe distance from the ablation electrode, even though no more than 1 cm of its course could be identified. ICE imaging allowed us to continuously verify the stability of the ablation electrode-endocardium contact during the whole of RF delivery, although the presence of background artifacts slightly degraded the image quality. Figure 6 shows the potential application of ICE in the mapping of left ventricular outflow tract tachycardia.

A potential utility of ICE to guide RF ablation of ventricular tachycardia in a healed myocardial infarction has been suggested by recent animal studies[12,75]. In a porcine model of a healed anterior myocardial in-

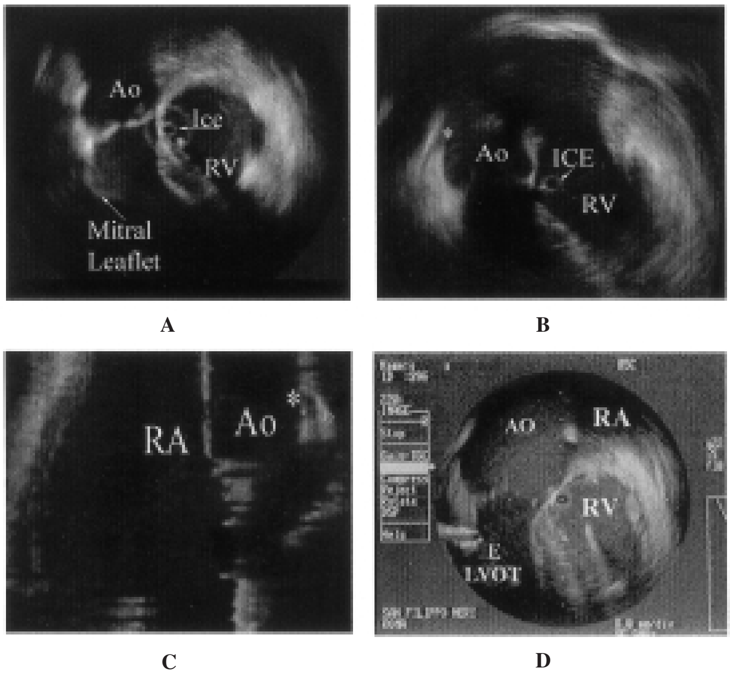


Figure 6. *Echographic view of the left ventricular outflow tract (LVOT) and aortic root (Ao). The intracardiac echocardiography (ICE) catheter is placed in the right atrium (RA) next to the septum membranosus. Right ventricular (RV) inlet, mitral leaflets, LVOT and Ao are shown in diastole* (panel A) *and in systole* (panel B). Panel C *shows a detail of the RA and of the Ao with the origin of the left main coronary artery* (*). *In* panel D *the ablation catheter (E) during ablation of a ventricular tachycardia originating from the LVOT is shown.*

farction Callans et al.[12] used the Carto system to characterize the spatial distribution of normal and abnormal electrograms and correlated the electroanatomic voltage mapping with ICE. The contiguous areas described by the isovoltage 1 mV lines during Carto mapping corresponded with the area of dense scar that in turn correlated well with the area of akinesis as determined at ICE. The same authors used ICE imaging to assess the effects of irrigated RF energy delivered at the border of a healed myocardial infarction for an anatomically-based procedure of ventricular tachycardia ablation[75]. ICE permitted the detection of an increased local wall thickness and of a change in echodensity at the RF site and of transient systolic dysfunction in the adjacent normal myocardium without thrombus formation.

Transseptal catheterization. Needle puncture of the fossa ovalis is a standard technique for the transvenous introduction of catheters into the left heart[76]. The significant development of balloon mitral valvuloplasty and catheter ablation in the left atrium has increased the clinical use of transseptal catheterization, even though a patent foramen ovalis is present in about 30% of cases (Fig. 7). Transseptal puncture is usually performed under fluoroscopic guidance. The possibility of visualizing the anatomy of the interatrial septum and the localization of the fossa ovalis may greatly enhance the safety and efficacy of this procedure. Actually, complications of transseptal catheterization, although rare, can be severe and life-threatening. These complications, including atrial perforation, aortic perforation, and pericardial tamponade, are due to accidental puncture of the wrong structures. The risk increases in patients with anatomic abnormalities. Transthoracic[77,78] and transesophageal[79,80] echocardiography have been proposed as an adjunct to fluoroscopy for transseptal catheterization. Both have significant limitations. Fluoroscopic equipment and the necessity of a sterile operative field limit access to the patient, the image quality often does not allow adequate visualization of the structures being evaluated, an additional operator is necessary (and exposed to the fluoroscopic risk), and the whole procedure is more complex. ICE could provide precise imaging guidance and aid in the prevention of complications.

Epstein et al.[13] evaluated the use of ICE in an animal model as the only imaging modality employed to guide transseptal puncture and catheterization. They studied 10 dogs performing in each animal 10 transseptal punctures guided exclusively by ICE. The standard approach to transseptal catheterization using a Brockenbrough needle and a long vascular sheath was employed except for the use of ICE (with 6.2F/12.5-MHz and 9F/9-MHz catheters) instead of fluoroscopy. Under ICE guidance alone, transseptal puncture was safely performed in each of the 100 attempts, and pathological evaluation did not show evidence of perforation outside the fossa ovalis. The major limitation of this study is the significantly smaller atria of normal dogs as compared with those of humans. In addition, there was no control group using fluoroscopy alone.

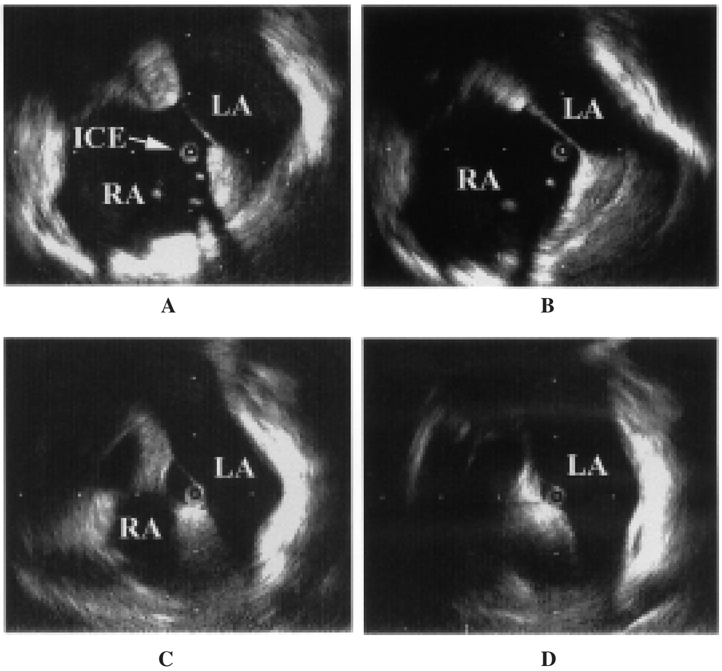


Figure 7. *Intracardiac echocardiographic images of the fossa ovalis.* Panel A: *the intracardiac echocardiography (ICE) catheter can be seen in the right atrium (RA) close to the fossa ovalis which is clearly visible.* Panels B *and* C *show the ICE catheter progressively pushed towards the fossa ovalis.* Panel D: *the ICE catheter can be seen as it is pushed across the fossa ovalis into the left atrium (LA) through a patent foramen ovalis.*

In humans[81-84] ICE has been used as an adjunct to fluoroscopy during transseptal procedures. Hung et al.[81] reported difficulty in identifying the transseptal apparatus with a 10F/10-MHz over-the-wire mechanical ultrasound catheter. Conversely, Mitchel et al.[82] and Schwartz et al.[83] respectively using a 6F/12.5 and 20-MHz catheter and a 6.2F/12.5-MHz catheter found that the fossa ovalis was easily visible. In a larger series of patients, Daoud et al.[84] utilized a 9F/9-MHz catheter positioned at the fossa ovalis to guide transseptal puncture. The tip of the transseptal dilator, tenting of the fossa ovalis and the left atrial wall were simultaneously visualized in a single image in all patients. In 81% of patients the same structures plus the aortic valve were visualized in a single image. In 8% of patients the tented fossa abutted the left atrial wall and the transseptal dilator was repositioned to avoid inadvertent left atrial wall puncture. Transseptal puncture was achieved in a single attempt in 96% of cases with no complications.

Conclusions

ICE has proved to facilitate the targeting of specific anatomic landmarks, such as the crista terminalis, the Eustachian ridge, the tricuspid annulus, the coronary sinus ostium, and the pulmonary veins that cannot be adequately visualized at fluoroscopy. Direct imaging of these sites can be useful for the accurate guidance of the ablative procedure and in order to decrease the fluoroscopy time[85]. The stability of the electrode-tissue contact and the efficacy of the ablative lesions can also be evaluated at ICE. Furthermore, ICE guidance can enhance the safety and efficacy of transseptal puncture by preventing the erroneous puncture of potentially dangerous anatomical structures. Finally, ICE appears to be very useful in leading experimental studies and in combining true anatomical features with electrical activation in an attempt to construct realistic electroanatomical maps. All these reasons suggest its potential use in the ablation of complex arrhythmias, such as AF[86] and ventricular tachycardia. In view of the large number of actual and potential benefits of direct intracardiac visualization during RF ablation procedures, ICE could play a relevant role in the near future of interventional electrophysiology.

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