Just as the growing interest and proliferation of methods to reperfuse the coronary artery system with transcatheter techniques spurred interest and utilization of intracoronary ultrasound (at least in academic centers), so the growth of anatomic cardiac transcatheter interventions and increasingly aggressive transcatheter ablative strategies to treat cardiac arrhythmias has stimulated the use of and development of new methods for intracardiac echocardiography (ICE). This article will review the development, present state of the art, and applications of ICE as well as project its evolution from 2-dimensional to 3-dimensional/4-dimensional visualization and integration of therapy with imaging in the near future.

**History and Evolution of ICE**

It may be surprising to realize that in the earliest days of ultrasound, as early as 1956, the potential of imaging heart structures with catheter-based devices was explored. The earliest investigators used single-crystal probes, some of which were rotated to achieve cardiac imaging. In the mid-1960s, a mechanically rotating 4-element probe was developed by Eggleton et al, and in 1969, a 32-element phased-array coil was developed by Bom and coworkers in Rotterdam.

These interests even preceded the development of interventional catheterization therapy. They were spurred by the problems of angiography in outlining vascular and intracardiac anatomy in large detail as single-plane and eventually biplane angiography. The goal was precise measurement of vascular lumens.

Some of the early explorations of intracardiac imaging with phased-array technology and color Doppler were undertaken with miniaturized transesophageal studies in experimental animals. Higher-frequency rotating catheter probes in the range of 20 to 30 MHz were developed and marketed for intracoronary investigations that yielded new insights into atherosclerosis, vascular response to stents, and coronary remodeling. Lower-frequency (10- to 12.5-MHz) versions of these rotating single-element devices were used for the earliest intracardiac investigations by Pandian et al in 1990.

Our efforts with an intracardiac phased array for guidance of atrial septal defect (ASD) closures occurred before the earliest description of a dedicated side-looking phased-array device at the Mayo Clinic by Seward et al, a method termed **ultrasound cardioscopy**, which was applied to dogs.

The need for ICE guidance of interventions for anatomic device placement for closure of ASDs was rapidly superseded by extremely aggressive approaches to electrophysiological ablation therapy for treatment of cardiac arrhythmias to assist transseptal puncture and localize catheters in proximity to anatomic landmarks including the cavopulmonary isthmus, the atroventricular nodal region, and the upper and lower left pulmonary veins after entry into the left atrium.

The commercially available intracardiac imaging devices are summarized in the Table.

The largest recent stimulus to growth of the use of ICE is the increasingly sophisticated anatomic interventions being performed, including device closure, mitral annulus resizing, mitral annulus repair, and electrophysiological procedures, in which the greatest advantage of intracardiac imaging over transesophageal imaging is presently that the patient does not have to be under general anesthesia for a prolonged procedure.

**Role of ICE in Interventional Cardiac Therapy**

The role of transesophageal echocardiography (TEE) to guide device closure of ASD has improved the success of the procedure. Since then, TEE has been used routinely to guide ASD, patent foramen ovale (PFO), and ventricular septal defect (VSD) device closure. However, because of the length of the procedure (at least 1 hour), with the use of TEE to guide the steps in the closure process, general anesthesia with or without endotracheal intubation is almost always required. For any imaging modality to be widely used in monitoring interventional procedures, such imaging modality has to possess certain ideal characteristic features. Such features include user- and patient-friendly application with simple mechanics. The imaging tool provides full color and Doppler capabilities; if used via the vascular system, it requires a...
A defect in the interatrial septum (ASD/PFO) can be well seen as it relates to the right atrium. The interatrial septum and the defect, the coronary sinus, and the pulmonary veins are well seen. The latter can be seen in more or less detail depending on the exact location of the transducer.

After the ICE catheter is advanced into a more cephalad location toward the superior vena cava (SVC), a view can be obtained that is referred to as the SVC or long-axis view (Figure 1C, c). The resulting fluoroscopic images, showing the position of the catheter as well as corresponding echocardiographic images, are shown in Figure 1C, c. In this plane, the transducer faces the interatrial septum, and the SVC can be seen as it relates to the right atrium. The interatrial septum is shown in a superior/inferior plane and corresponds to the TEE long-axis view. Greater portions of the SVC can be seen as the ICE catheter is further advanced in this flexed position toward the SVC with slightly more rightward flexion. Greater portions of the inferior septum can similarly be imaged by withdrawing the ICE catheter toward the inferior vena cava. A defect in the interatrial septum (ASD/PFO) can be well profiled, and the superior and inferior rims as well as the diameter of the defect can be measured. In this view, both the right and left pulmonary veins may also be imaged, depending on the exact angle of the imaging plane. The imaging angle can be manipulated with clockwise and counterclockwise rotation as well as flexion/anteflexion to achieve these views.

After the ICE catheter is placed into a locked position, the entire handle with the catheter shaft at the sheath hub is rotated clockwise until it sits in a position with the transducer near the tricuspid valve annulus and inferior to the aorta (Figure 1D, d). Minor adjustments of the posterior/anterior knob with less posterior flexion and more leftward rotation in the right-left knob can demonstrate the short-axis view. A fluoroscopic image showing the catheter position and corre-

Table. Presently Available Intracardiac Imaging Devices and Their Capabilities

<table>
<thead>
<tr>
<th>Device Name</th>
<th>Company</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>UltraICE</td>
<td>Boston Scientific</td>
<td>9F nonsteerable rotational motor-driven grayscale only system</td>
</tr>
<tr>
<td>AcuNav</td>
<td>Siemens, Biosense-Webster</td>
<td>Side-looking 64-element phased-array 4-way steerability, 8F and 10F; grayscale, color Doppler, tissue Doppler, 3D localization with Cartosound</td>
</tr>
<tr>
<td>EP Med View Flex</td>
<td>St Jude Medical</td>
<td>Runs side-looking 64-element catheter on the Viewmate scanner, 10F introducer, 2-way flex color Doppler, grayscale, tissue Doppler 8-2 MHz</td>
</tr>
<tr>
<td>ClearICE</td>
<td>St Jude Medical</td>
<td>Derived from the hockey stick, 64-element side-looking highly steerable 4-way side-looking array with 2 sets of electrodes for integration of 3D localization with NavX; runs on the GE Vivid I scanner; grayscale, tissue Doppler, synchronization mapping, 2D speckle tracking</td>
</tr>
<tr>
<td>SoundStar</td>
<td>Biosense-Webster</td>
<td>This is a new catheter, just now marketed as a 10F (3.33-mm) device with integrated ultrasound array (like AcuNav) but with the CARTO magnetic sensor in the tip; this is now FDA approved; FDA 510(k) No. is K070242, May 15, 2007</td>
</tr>
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</table>

3D indicates 3-dimensional; 2D, 2-dimensional; and FDA, Food and Drug Administration.

**ICE Catheters**

**Imaging Protocol for ASD/PFO Device Closure**

One of the authors of this review reported the protocol used to image the atrial septum and to guide various steps in the closure process, which is summarized below. However, we believe that it is crucial to review prior echocardiographic imaging and other diagnostic studies for their adequacy and completeness. The latter will dictate the intensity of the initial anatomic evaluation with the use of ICE. This is especially important in patients in whom anomalous pulmonary venous drainage is suspected.

At the start of the case, a complete evaluation of the defect(s) and surrounding anatomy is performed. For patients with an ASD, the size of the defect via 2-dimensional imaging as well as the measurement of surrounding rims is obtained. Contrast injection via agitated saline microbubbles is performed for patients with a PFO to confirm the presence of a right to left shunt.

The ICE catheter is rigid and introduced without flexion; therefore, it is very important to introduce the catheter into the heart under fluoroscopic guidance. ICE imaging is initiated after the catheter is positioned in the mid-right atrium, also referred to as the “neutral” or home view. In the proper alignment in this view, the ICE catheter is parallel to the spine with the transducer portion facing the tricuspid valve. This is shown in Figure 1. The corresponding fluoroscopic (antero-posterior view) and echocardiographic images obtained with the ICE catheter in this position are shown in Figure 1A, a. In this position, the tricuspid valve, right ventricular inflow and outflow, and long axis of the pulmonary valve are seen. The aortic valve may also be seen (short axis) in this view (see below for VSD imaging). The septum is not seen well in this view. However, on occasion the anterior portion of the septum can be seen, and if color Doppler is turned on, the shunt can be seen. This view is important to assess the tricuspid valve function.

While the catheter is in the neutral position, with the posterior-anterior knob rotated slightly posterior and the right-left knob rotated slightly rightward, the transducer will face the interatrial septum (Figure 1B, b). This is the septal view. In this position, the resulting fluoroscopic image showing the position of the ICE catheter is shown in Figure 1B. The echocardiographic images via ICE are shown in Figure 1B, b. In this view, the entire length of the atrial septum and the defect, the coronary sinus, and the pulmonary veins are well seen. The latter can be seen in more or less detail depending on the exact location of the transducer.
sponding echocardiographic images are shown in Figure 1D, d. In this view, anatomic structures seen include the aortic valve in short axis and the interatrial septum (Figure 1D, d). This view is very similar to the basal short-axis view obtained by TEE and is known as the short-axis view. However, the right atrium is shown in the near field, and the left atrium is in the far field, which is opposite of that seen with TEE.

Before the actual device deployment procedure, the aforementioned views are obtained to image the interatrial communication (ASD or PFO). Additional views can be obtained by advancing the catheter through the ASD or PFO into the left atrium, the so-called views from the left heart. Echocardiographic images from this location are equivalent to the transthoracic and TEE 4-chamber views. Anatomic structures seen in this view include the mitral valve, LV, and right ventricle. The catheter can be manipulated further to view the left atrial appendage, which may be helpful in procedures to occlude the left atrial appendage. The catheter is then withdrawn back to the right atrium.

After intracardiac anatomy imaging and assessment of the defect(s) and the rims as described above, ICE imaging can be used to measure the stop-flow diameter of the defect with the use of the sizing balloon. The balloon can be viewed in either short- or long-axis view (Figure 2). After the defect is balloon sized, the device is loaded into the delivery sheath, as has been described. All of these steps can be monitored with the use of ICE (Figure 3A to 3D).

In cases of PFO closure to prevent recurrence of paradoxical embolism, we perform an agitated saline contrast bubble study before device release and after device deployment.

**Imaging Protocol for VSD Device Closure**

Transcatheter closure of perimembranous VSD remains investigational in the United States; therefore, experience with ICE in guiding device closure of perimembranous VSD is very limited, and we have reported previously on our experience. Briefly, after the ICE catheter is introduced into the mid-right atrium as described above, we obtain the home view. In this view, the perimembranous portion of the septum can be seen, and the defect can be measured. To further delineate the size of the defect, we obtain the short-axis view as described above. One may require slight adjustment with the use of the posterior-anterior or right-left knobs. The VSD is well seen in this view. Once the appropriately sized device is selected, the closure steps should be monitored by fluoroscopy and ICE.
Imaging Protocol for Pulmonary Valvuloplasty
One does not need ICE imaging for pulmonary valvuloplasty. However, in the occasional patient in whom fluoroscopy and or TEE/transthoracic echocardiography imaging is not adequate because of weight, the introduction of ICE inside the right ventricle underneath the pulmonic valve will yield superb images of the valve (see the online-only Data Supplement).

Imaging Protocol for Mitral Valvuloplasty
In cases of rheumatic mitral valve stenosis, balloon mitral valvuloplasty has become the treatment of choice. Many operators prefer to perform the transseptal puncture and the valvuloplasty itself under echocardiographic guidance. Both TEE and transthoracic echocardiography can be used to achieve this goal. However, the use of ICE to perform the septal puncture itself is more assuring than transthoracic echocardiography. Furthermore, ICE does not require anesthesia. To perform the septal puncture, one can position the ICE catheter to obtain views of the septum (septal, short-axis, or long-axis views). Once the puncture is performed and before the valvuloplasty, one needs to assess whether there is thrombus in the left atrial appendage, which would be a contraindication to proceeding further. The next step is to assess the mitral valve before proceeding. This can be done by positioning the catheter in the right ventricle (as above) with some adjustment so that the transducer is directed toward the mitral valve. This position can be maintained during the interventional procedure itself. After the valvuloplasty, one needs to assess the gradient by continuous wave Doppler and the presence/absence of mitral valve regurgitation by color Doppler. Diagnostic-quality continuous wave Doppler can be obtained with the use of ICE devices (see the online-only Data Supplement).

Figure 2. Cine fluoroscopic image and corresponding ICE image during balloon sizing of the defect. Left, Cine fluoroscopy image demonstrating the balloon size of the defect. Right, ICE image during sizing indicating cessation of shunt.

Application of ICE for Guidance of Electrophysiology Procedures

Imaging tools such as ICE and electroanatomic mapping have emerged as effective intraprocedural tools for ablative procedures.

ICE has emerged as a complementary tool to standard fluoroscopic imaging and an ideal modality for imaging structures highly relevant to catheter ablation procedures.

Transseptal Access

ICE is now well established in the intraprocedural guidance of transseptal catheterization. A central concept for transseptal catheterization involves the recognition of the fact that the true interatrial portion of the septum is primarily the fossa ovalis. The flap of the fossa ovalis and the anterior rim of the limbus are the only atrial septal structures that are truly interatrial. Other areas of the septum do not ensure safe passage from the right to the left atrium. Entry into the aorta and the pericardial space poses extremely serious risks. The medial wall of the right atrium has several structures of anatomic significance. The fossa ovalis is immediately recognizable as a membranous structure. The right atrial aspect of the fossa shows a clear ridge (the limbus), which is not seen on the left atrial side of the septum. Aortic entry can occur if the needle is extended superior to the limbus. This results in entry of the needle into the transverse sinus and perforation of the aorta. It is critical to use echocardiographic imaging, pressure, and contrast injection/staining of structures before advancing sheaths into the presumed left atrium (this remains one of the most avoidable complications in transseptal procedures). Pericardial effusions and tamponade also result from aortic entry due to the interposed transverse sinus. Furthermore, there is an added risk of entry into the ascending and descending aorta via the left atrium as the aorta wraps around the atrium. Several variants of this region affect transseptal catheterization; these include lipomatous hypertrophy, fibrosis (which is noted in redo transseptal procedures), and interatrial septal aneurysms. Furthermore, the presence of a persistent left superior vena cava also makes left atrial access challenging mainly by the deformation of the medial right atrial wall by the large coronary sinus. The fossa ovalis and these anatomic variants are instantly recognizable on ICE, and this imaging modality can facilitate safe transseptal puncture.

Catheter Ablation of Arrhythmias

Atrial Fibrillation

The true atria are normally thin-walled structures (≈4 mm); however, the atrial wall can become thinner and taper (2.0 mm) near the atrioventricular grooves. There is considerable anatomic heterogeneity with respect to atrial thickness within the anterior, superior (dome), posterior, and lateral portions of the left atrium. A complex anatomic relationship exists between the posterior left atrium, pericardium, transverse and oblique sinuses, and adjacent structures such as the aorta and the esophagus. During catheter ablation procedures involving the superior and posterior left atrium, any 1 of these structures may be inadvertently damaged. The pulmonary veins are posterior structures and have muscle sleeves that surround them. Phased-array ICE imaging has been very useful for locating pulmonary veins and to ensure that ablative lesions are placed on the atrial side of pulmonary vein left atrial junction. ICE has been used effectively to guide antral isolation procedures for atrial fibrillation. In this setting, ICE has been used to titrate energy delivery by monitoring microbubbles. Furthermore, in this setting ICE imaging has been shown to be superior to the use of electrophysiological indices such as impedance monitoring to identify sites that are safe to ablate. Determination of wall thickness with ICE has the potential to help with lesion assessment during catheter ablation.

Monitoring for Complications and Avoiding Collateral Damage

One of the most valuable roles of ICE in the electrophysiology laboratory is to monitor for pericardial effusions, and it is...
an integral part of working up any hemodynamic instability during catheter ablation procedures. The esophagus poses a considerable challenge when left atrial myocardium is ablated because of its close relationship to the posterior wall. A catastrophic complication of left atrial ablation is the risk of an atrioesophageal fistula formation. ICE has been used effectively for identification of the esophagus during this procedure. Coronary arterial location can also be well defined by the use of ICE during interventional procedures (see the online-only Data Supplement). Emerging Uses

Percutaneous Intrapericardial Echocardiography With ICE Catheters

Limitations of ICE include limited visualization of some structures because of the close distance of the ICE catheter to these endocardial structures, relative instability of ICE catheter images, and catheter-related interference. Recently, percutaneous intrapericardial cardiac echo (PICE) has been performed in patients undergoing epicardial catheter ablation. PICE images provide views of the heart from the pericardial sinuses, and PICE is a safe and effective method for imaging relevant cardiac structures during electrophysiology procedures that involve pericardial access. This approach provides real-time, high-resolution imaging of structures not typically or easily seen with conventional ICE and also provides improved image stability over conventional ICE because of reduced catheter-to-catheter interference (see the online-only Data Supplement). PICE is less limited by near-field artifacts compared with ICE because the catheter sits outside the heart. Image stability is also improved because the catheter is held in place in part by its position in the transverse or oblique sinuses. Further wall motion on PICE has also been shown to correlate well with voltage mapping data.

Intracoronary Sinus ICE

ICE imaging within the coronary sinus provides unique views of the mitral valve and clear views of the left atrium. The anatomic location of the coronary sinus within the oblique sinus of the pericardium allows the acquisition of views equivalent to pericardial imaging described above. ICE catheters have been shown to be effective for characterizing the mitral isthmus, atroventricular groove vessels, intra–coronary sinus muscle bundles, coronary arterial tree, and mitral valve apparatus.

Future Advances in ICE: Forward-Looking Devices, Merging, Mapping, Imaging, and Therapy

Higher Resolution

Given the continued increase in the complexity of electrophysiology procedures and the increased use of multidetector computed tomography for image merging and mapping, additional efforts to advance ICE will be demanded to limit radiation exposure for patients who may have multiple procedures for arrhythmia treatment and/or resynchronization therapy with lead placements. Our research group has applied the tissue Doppler strain capabilities and the expanded field of view of our first device, the side-looking hockey stick catheter, for modeling resynchronization therapy. The entire LV in cross section can often be viewed from the right atrium, and the high-frame-rate, high-resolution images are more than adequate for 2-dimensional strain computations to assess regional synchrony (Figures 4 to 6).

We have also developed a forward-looking microlinear array catheter that carries a port alongside the array for a radiofrequency wire to merge imaging and therapy into the same device (Figures 7 to 9).

Expected advances include higher resolution and frequency agility from the integration of computer micromach-
in ultrasound transducers (cMUTs), which represent the next generation of ultrasound technology. They are more reproducible and more flexible than piezoelectric ceramic and can be made from masks like integrated circuits so that they are extremely reproducible. Flex circuit bonding on the back of the array and the DC bias that tenses the silicon cup, much like a timpani drum, allow significant frequency agility, and, equally important, just before collapse of the membrane against the bottom of the cup, the amplitude of emission increases substantially. Hence, similar to the efforts of applying high-intensity focused ultrasound to cancer therapy under magnetic resonance imaging (MRI) guidance, we have shown that our forward-looking cMUT arrays can potentially be used for delivering high-intensity focused ultrasound energy imaging and therapy from the same array.

Electrophysiology-Enabled Devices for Imaging and Therapy

A number of groups are undertaking further efforts at integration of ultrasound imaging with electroanatomic mapping technologies, fusion, and overlay images, as shown in Figure 10, in which the ultrasound image from a known location based on tracking the position of the scanning catheter with electrofield imaging sensors, such as NavX (St Jude Medical), can be placed as an overlay onto the electroanatomic map, while also showing the position of other electrophysiology or ablation catheters within the heart and the electrophysiology recordings and propagation maps. This requires additional electrodes on the side-looking hockey stick array: 2 ring electrodes proximal and distal to the array, and an additional electrode with a gap so that the Electrofield Navigation can determine which way the array is facing in rotational space. For the forward-looking microlinear array,
this has also been achieved with the addition of 2 electrodes near the tip.39

Four-Dimensional Intracardiac Imaging Devices
The final advances will be integration of 4-dimensional ultrasound intracardiac imaging. Early efforts at pullback of rotational devices have produced 4-dimensional intracardiac maps, as has rotation of side-looking devices like the ICE devices.40 Both approaches require gating and spatial localization and are reconstructions rather than real-time approaches.

An example of a 4-dimensional reconstructed image is shown (Figure 11), but side-looking matrix arrays wrapped around the side of a catheter scanning an arc in 3-dimensional space or forward-looking 4-dimensional devices will most likely be applicable for providing real-time intracardiac guidance for imaging interventions.

In our efforts, a forward-looking cMUT ring array is functioning in prototype fashion on a printed circuit board and has been shown to derive 4-dimensional imaging of targets in a water tank (Figure 12). The bonding and flex circuits necessary to prepare the ring array for catheter implementation are under way.

The ring array, which is a 9F device, also equipped with electrodes for electrofield NavX (St Jude Medical) integration, can scan a cone of information to image internal surfaces within the heart to 4 to 7 cm. The device has a 5F lumen so that a laser fiber, a radiofrequency fiber, an additional core of cMUTs, or an electrophysiology ablation catheter can be placed through the lumen, and its positioning and activity can be observed in real time.

New Ultrasound Transducer Technologies for Providing Imaging and Therapy
Another direction being explored for image fusion for electrophysiology and arrhythmia therapy, and perhaps the most elegant, relates to integration of electrophysiology with MRI. Halperin and colleagues41–43 in Baltimore and the group headed by Dumoulin44,45 in Boston have been working separately in these areas and have prepared MRI-compatible ablation devices that have reduced heat generation and can actually be visualized with a radiofrequency antenna for localization. They can be used to guide ablation in 3-dimensional space with the use of real-time MRI and validate the effectiveness of ablation therapies by late gadolinium.41–43

Figure 10. Fusion image showing the ultrasound image of ablation overlaid onto the NavX (St Jude Medical) shell with a retrograde ablation catheter ablating the left side of the septum, which has brightened. This also requires reading the rotational position of the side-looking hockey stick (HS) catheter into the electrofield NavX (St Jude Medical) milieu.

Figure 11. Imaging with a prototype real-time 3-dimensional ICE system in experimental animals: image of an ablation catheter in the right ventricle from the right atrium.
A number of electrophysiologists and MRI specialists are working in interventional MRI to prepare MRI-compatible versions of our forward-looking microlinear array devices so that they can be localized within an MRI milieu, provide ultrasound visualization of the surface to be ablated, and add real-time ultrasound monitoring to the MRI of the electrophysiology ablation.

It is likely that these more advanced 3-dimensional devices will find their place in other aspects of transcatheter therapeutics, including ASD device closure, coronary sinus–based devices for nonsurgical mitral annuloplasty, and catheter-based repair procedures for mitral regurgitation, that, even in the face of real-time 3-dimensional TEE, will allow extreme near-field and accurate visualization of 3-dimensional anatomy without requiring the general anesthesia necessitated by esophageal intubation for these long procedures.

**Summary**

ICE technology is already being developed commercially, and within our Bioengineering Research Partnership program, which specifically targets electrophysiology guidance and therapy with integrated devices, the evolution of these devices toward higher levels of performance and use of cMUT arrays to yield 4-dimensional ICE will advance diagnostic application and guidance of transcatheter therapies for heart disease.

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**References**


Key words: arrhythmia • catheter ablation • diagnosis • echocardiography • imaging


Intracardiac Echocardiography During Interventional and Electrophysiological Cardiac Catheterization

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Figure I. ICE images during pulmonary valvuloplasty in an overweight patient. A, view with ICE catheter in the right ventricle demonstrating thickened pulmonic valve. B, color Doppler showing the turbulence starting at the valve level. C, continuous wave Doppler indicating gradient of 40 mmHg across the valve. D, balloon inflation. E, color Doppler indicating more mobile valve leaflets and tiny jets of insufficiency. F, final continuous wave Doppler indicating improvement in the gradient to 30 mmHg.
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Supplemental Material

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