The Use of Intracardiac Echocardiography and Other Intracardiac Imaging Tools to Guide Noncoronary Cardiac Interventions

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The limitations of standard fluoroscopy have led to the development of improved imaging techniques to guide noncoronary cardiac interventions. Imaging tools that are used in the interventional laboratory can be categorized as invasive and noninvasive. Noninvasive cardiac imaging tools include ultrasound, computed tomography, and magnetic resonance imaging. These modalities can generate high-resolution images of the heart and are increasingly being used to guide cardiac interventions. Despite these advances, there remains a strong role for invasive imaging tools in the interventional laboratories. Such invasive imaging tools include transesophageal echocardiography, intracardiac echocardiography, intracardiac endoscopy, and electroanatomic mapping systems. Despite the risks inherent to the invasive nature of these tools, these modalities can provide excellent real-time, detailed images that can be invaluable in guiding certain cardiac interventions. This review will propose the features of an ideal intracardiac imaging tool, summarize the intracardiac imaging tools that are currently available or under development to guide noncoronary cardiac interventional procedures, and suggest opportunities for improvement. One opportunity in this field is to couple imaging systems directly with the interventional devices themselves. The use of intracardiac imaging to guide select cardiac procedures including transseptal catheterization, catheter ablation procedures for arrhythmias, and percutaneous placement of cardiac valves and closure devices will also be discussed. Most of this review will be devoted to intracardiac echocardiography, which currently has the broadest number of applications. (J Am Coll Cardiol 2009;53:2117–28)

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The development of new percutaneous interventions for patients with arrhythmias and structural heart disease is fueling an increasing demand for improved intracardiac imaging techniques to guide cardiac interventions. Historically, fluoroscopy has been the mainstay of imaging to guide cardiac procedures. However, there are several limitations to the use of fluoroscopy: radiation exposure to the patient and the physician, poor resolution of soft tissue structures, and problems associated with the use of iodinated contrast agents. Because of these limitations, other imaging techniques have been developed to guide cardiac procedures. Imaging tools in the interventional laboratory can be categorized as invasive and noninvasive. Noninvasive imaging tools include ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI). These modalities can generate high-resolution images of the heart, and in the past have been used effectively during the planning stages of an intervention. These imaging systems are now being brought directly to the interventional laboratories. Surface echocardiography can be used to guide endomyocardial biopsies, systems that can acquire 3-dimensional (3D) CT images in the interventional laboratory are under development, and real-time MRI can be used to guide peripheral vascular interventions and electrophysiology procedures (1).

Invasive imaging tools in the interventional laboratory include transesophageal echocardiography (TEE), intracardiac echocardiography (ICE), intracardiac endoscopy, and electroanatomic mapping systems. Despite the additional risks inherent to the invasive nature of these tools, they can provide excellent real-time, detailed images that are often invaluable in guiding cardiac interventions. This review will summarize invasive, intracardiac imaging tools that are currently available or under development to guide noncoronary cardiac interventional procedures. Most of this review will be devoted to ICE, which currently has the broadest number of applications.

Intracardiac Imaging Tools

Characteristics of imaging systems. There are numerous features that characterize the ideal intracardiac imaging tool;
these features are summarized in Table 1. Each of the currently available intracardiac imaging technologies possesses some, but not all, of these features. Of course, the relative importance of each feature depends on the type of procedure being performed. An ideal intracardiac imaging system would provide real-time, 3D images of the inside of the heart displayed in a way that would be useful to the interventionalist to increase success and minimize risk. That system would ideally provide high-resolution images, account for cardiac motion, and allow the interventionalist to easily acquire the images and minimize reliance on a second operator. The imaging technology should be capable of providing both near- and far-field views: a near-field view to provide sufficient detail of endocardial structures and the details of the intracardioc tools themselves, and a far-field view to provide perspective and orientation. The imaging tool should not interfere with execution of the procedure and vice versa. Use of the imaging tool should not require additional anesthesia.

Current intracardioc imaging tools are catheter-based, endocardial imaging systems that acquire and display images of the heart using a variety of views: cross-sectional, sector-based, or forward-looking endoscopic views. Endoscopic views provide useful near-field images of the endocardial surface, but provide no imaging depth. Tools that provide imaging depth are useful in viewing structures that surround the heart such as great vessels and the esophagus.

Additionally, the ideal tool would be one that adds the least additional cost to the procedure. The cost of a phased-array ICE catheter ranges from $2,000 to $2,500, depending on the volume of catheters purchased. Although ICE catheters are labeled for single use only, there are companies approved to resterilize ICE catheters so that they can be reused. Because the resterilization process can significantly reduce the cost-per-use of a catheter, the ability to be resterilized and reused is an ideal feature of ICE as an imaging tool. Any additional imaging used during a cardiac intervention will increase the cost of the procedure compared with the use of fluoroscopy alone. However, supplemental imaging has the potential to reduce overall cost of cardiac interventions by improving procedural efficacy, thus reducing the need for repeat procedures and preventing complications. Further studies are needed to establish the cost-effectiveness of invasive imaging to guide cardiac interventions.

ICE. Transthoracic echocardiography (TTE) can be used to image the heart during cardiac interventions such as endomyocardial biopsy, pericardiocentesis, and transseptal catheterization. However, TTE use during an intervention can be problematic due to relatively limited acoustic windows, the need for a separate operator (a sonographer) to acquire and manipulate the images, compromise of the sterile field, and potential interference with the interventionalist.

In contrast, the use of ICE avoids those limitations. As such, ICE has become the most widely used ultrasound-based imaging tool in the interventional laboratory (2). Imaging with ICE has evolved from cross-sectional imaging using a rotating transducer (similar to intravascular ultrasound) to sector-based imaging using a phased-array transducer. There are 3 commercially available ICE catheters that differ with respect to various features summarized in Table 2. In addition, feature availability is also dependent on the ultrasound console used with that particular catheter. The ICE catheter ideal for use depends on numerous factors including type of procedure to be performed, catheter cost, operator familiarity with the system, and the need for Doppler measurements. In general, rotational ICE is useful for near-field imaging, such as during transseptal puncture (TSP), but is more limited in its far-field view, offering inadequate imaging of the left atrium (LA) from the right atrium (RA) (Fig. 1). In addition, the rotational catheter is not steerable and must be positioned in the RA through a long guide sheath. Phased-array ICE has many advantages over rotational ICE including a greater frequency range, greater depth of field, steerability, and the possibility of acquiring Doppler and color flow imaging (Fig. 1). With their steerability, phased-array catheters can be easily advanced and positioned through short sheaths rather than through long guide sheaths.

**Intracardiac endoscopy.** Endoscopy is a powerful medical imaging technique allowing for near-field, intraluminal views of various structures. In particular, for intracardioc
imaging, fiberoptic endoscopes are ideal in that they are flexible, provide a forward-looking view, and can be minia-
turized enough to image from within small structures.

Visualization with endoscopic imaging is dependent on the wavelength used. Wavelengths in the visible spectrum (400 to 700 nm) do not allow for imaging through blood: light at this wavelength is scattered by red blood cells and creates only a red reflection. One solution to this limitation is to use a balloon to displace the blood to allow endocardial visualization. Such a balloon-tipped fiberoptic endoscope has been used successfully in humans (Fig. 2) (3). Anh et al. (4) used a deflectable fiberoptic endocardial visualization catheter (Acumen Medical, Inc., Sunnyvale, California) to successfully image the coronary sinus (CS) ostium and adjacent endocardial structures in 58 patients with the aim of facilitating implantation of a left ventricular pacing lead. The same group subsequently characterized CS valves by direct visualization (5).

Instead of visible light, infrared light (>700 nm) presents a second wavelength option for endoscopic imaging. As the wavelength of imaging light is increased into the infrared spectrum scattering is reduced significantly; this is due to the extension of the wavelength beyond the effective optical diameter of the scattering particle (here, erythrocytes). This decreased scatter with longer wavelengths is counterbal-
anced by an increased absorption by hemoglobin, which diminishes visualization. Optimal wavelengths that mini-
mize both scatter and absorption in blood while allowing for successful imaging have been determined to fall around 1,620 nm. Using infrared endoscopy, direct intracardiac visualization has been demonstrated of the CS ostium, pulmonary vein (PV) ostium, radiofrequency (RF) ablation lesions, and the electrode-tissue interface during RF deliv-
ery (6,7) (Fig. 2).

Electroanatomic mapping systems and image integra-
tion. Computerized electroanatomic mapping systems are designed primarily to generate 3D displays of cardiac activation, but also effectively serve as imaging systems. While most imaging systems create an image by trans-
mitting a signal and recording the reflection, electroana-
tomic mapping systems rely on localization in space of the tip of a specialized catheter as it is sequentially posi-
tioned in various endocardial sites. There are 2 different electroanatomic mapping systems that are currently avail-
able: NavX (St. Jude Medical, Minnetonka, Minnesota) and CARTO (Biosense Webster, Inc., Diamond Bar, Californ-
ia). The NavX system delivers current at a specific fre-
quency to dynamically measure the spatial position of 1 or more specialized catheters inside the heart. The CARTO system uses a low-power magnetic field to triangulate the

Table 2 Features of Commercially Available Intracardiac Echocardiography Systems

<table>
<thead>
<tr>
<th>Ultrasound Method/ Name of Catheter</th>
<th>Catheter Size (F)</th>
<th>Frequency Range (MHz)</th>
<th>Viewing Sector (°)</th>
<th>Depth of Field (cm)</th>
<th>Steering</th>
<th>Doppler and Color Flow?</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational/UltraICE*</td>
<td>9</td>
<td>9</td>
<td>360</td>
<td>Up to 5</td>
<td>None</td>
<td>No</td>
<td>+</td>
</tr>
<tr>
<td>Phased array/ViewFlex Plus†</td>
<td>9</td>
<td>4.5–8.5</td>
<td>90</td>
<td>Up to 21</td>
<td>Anterior/posterior (120°)</td>
<td>Yes</td>
<td>++</td>
</tr>
<tr>
<td>Phased array/AcuNav‡</td>
<td>8 or 10</td>
<td>5.0–10</td>
<td>90</td>
<td>Up to 16</td>
<td>Anterior/posterior (160°)</td>
<td>Yes</td>
<td>++</td>
</tr>
</tbody>
</table>

*Boston Scientific, Natick, Massachusetts; †St. Jude Medical, St. Paul, Minnesota; ‡Siemens Medical Solutions USA, Inc., Malvern, Pennsylvania.

Figure 1 Comparison of Rotational and Phased-Array ICE

(A) Rotational or cross-sectional view of the right atrium (RA), left atrium (LA), and interatrial septum using a rotational intracardiac echocardiography (ICE) catheter. Note that the shaft of the ICE catheter (circular structure) can be seen in the RA, with the tip apposed to the interatrial septum for optimal imaging of the fossa ovalis. (B) Two-dimensional view of the interatrial septum using a phased-array ICE catheter. The catheter terminates within the body of the RA. (C) Schematic drawing of a phased-array ICE catheter in the RA in the optimal position to image the interatrial septum. Note that the ultrasound array is facing the septum but is not in apposition to it. Figure 1C provided by St. Jude Medical and used with permission.
position of a catheter in space. Both systems allow for a 3D anatomic reconstruction of the cardiac chamber of interest. The more locations sampled, the more accurate the reconstruction becomes. The images can be accurate enough to guide needle injections to endocardial sites. Various categories of electrical information such as the local activation time, electrogram complexity, signal amplitude, or impedance can also be collected at each location. Each category can then be superimposed on the anatomic frame using a color-coded display, thus creating an electroanatomic map. These electroanatomic maps are invaluable in many circumstances, especially in identifying the origin of a focal arrhythmia.

Because computerized mapping systems use geometrically derived interpolation to fill in the spaces between points to create a smooth appearing shell, they can lack sufficient accuracy in areas of complex anatomy such as the junction of the left atrial appendage (LAA) and PVs. However, these systems have been improved to allow integration of additional imaging information to supplement the electroanatomic map. Images using CT or MRI can be reconstructed and segmented before the procedure and superimposed during the procedure on the 3D endocardial map. Accurate image fusion requires careful registration using closely correlating landmarks on each image. Suboptimal image fusion can occur when images are obtained during different phases of the cardiac cycle or when the electroanatomic map is distorted by displacement or tenting of the chamber wall by the mapping catheter. Successful fusion can provide valuable additional anatomic information to guide ablation procedures. Intraprocedural 3D angiography may soon eliminate the need for preprocedural CT imaging.

A new system has recently become available that allows for manual reconstruction of a 3D ICE image using multiple 2D ICE image slices (Fig. 3). The image can then be merged with a 3D CT image and used for intracardiac mapping. Although this technique provides anatomic information that is real-time, it can be time-consuming to apply, and its accuracy depends on the ability to image a chamber in its entirety. Real-time 3D ICE should provide many advantages over current imaging
systems and will likely be integrated into electroanatomic mapping systems. Although image integration is used mostly for electrophysiological procedures, it has the potential to be useful for other types of interventions where multiple imaging tools are used.

**Other emerging invasive imaging techniques.** There has been significant progress in the field of nonfluoroscopic imaging of the coronary arteries to detect high-risk vulnerable plaques and to guide coronary stent deployment. Many of these novel imaging tools also have the potential to be applied to the guidance of noncoronary cardiac interventions. One such technique is invasive MRI (9). Due to the limitations of imaging deep blood vessels with standard noninvasive external-coil MRI, self-contained MRI probes have been developed. Catheters with a magnet, RF coil, and electronics at the tip have been developed and used to acquire high-resolution images of blood vessels in vivo. Larose et al. (10) used a 0.030-inch-diameter intravascular MRI detector coil to image atherosclerotic lesions in the aortoiliac arteries in humans. Magnetic resonance also has the potential for molecular and targeted contrast imaging. Of note, other novel intravascular imaging technologies that may be adapted for noncoronary interventions include intracoronary thermography (11), palpography (12), near infrared spectroscopy (13), and optical coherence tomography (14). While promising, challenges related to use of these technologies include poor soft tissue penetrance and motion artifact.

**Use of Imaging to Guide Selected Cardiac Interventions**

**Imaging to guide transseptal catheterization.** Many cardiac interventions including mitral valvuloplasty, LA ablation, and percutaneous LAA occlusion require TSP and LA catheterization. Although TSP can be accomplished with fluoroscopic guidance alone, one review found that the incidence of perforation with fluoroscopic guidance only ranged from 1.0% to 4.3% (15). Ultrasound-based imaging allows for direct imaging of the soft tissue structures that are relevant to TSP, including the fossa ovalis (FO), posterior atrial wall, and aorta, providing reassurance that the puncture site is optimal. Nonfluoroscopic imaging during TSP may reduce complications, especially when the anatomy is distorted or when double TSP is required. Both TTE (16) and TEE (17) have been used to guide TSP; however, both approaches can be cumbersome and require a second operator. ICE imaging during TSP can overcome these issues while providing, in many cases, superior...
imaging quality (Fig. 4). ICE also permits site-selective transseptal catheterization to optimize access to specific sites within the LA (18) and can be used to guide the remaining portion of the interventional procedure.

To guide TSP, an ICE catheter is advanced initially to the mid-RA, and a survey of the cardiac anatomy is performed. When using a phased-array ICE catheter, a useful starting point is the “home” position with the transducer facing the tricuspid valve. Here, the tricuspid valve and right ventricle are viewed from the RA. Cranial advancement of the catheter with a clockwise rotation and posterior tilt achieves a “septal” view. This view allows imaging of the FO (Fig. 1). The FO should be inspected to determine its diameter (which can range from 5 to 26 mm [19]), its thickness, and the presence of a patent foramen ovale (PFO). If a PFO were present, the need for needle puncture of the interatrial septum may be obviated. Identification of a thick septum by ICE might lead one to consider using a powered transseptal needle that uses RF current to perforate the septum rather than manual force (20). The aortic root and valve can also be visualized to demonstrate their relationships to the interatrial septum.

During transseptal catheterization, ICE imaging allows direct visualization of the transseptal sheath and dilator apparatus, especially as it approaches the interatrial septum during retraction from the superior vena cava (Fig. 4A). When the dilator tip engages the FO, “tenting” of the FO can often be seen (Fig. 4B). Because there is often shadowing of catheters and sheaths during ICE imaging, it can be difficult to determine the precise location of the dilator tip. However, the point of maximal tenting of the FO usually correlates with the location of the dilator tip. As such, determination of the point of maximal tenting allows for localization of the tip. If the dilator is well engaged in the FO, the needle will usually cross into the LA at the point of maximal tenting. Determination of the trajectory of the needle before advancing the needle also allows for appreciation of the proximity of critical neighboring structures, such as the posterior LA and the aorta. Successful crossing of the FO membrane with both the needle and the dilator...
can be confirmed with loss of tenting. At times the needle will cross the FO, but the dilator does not follow it into the LA. In this case continued pressure usually allows advancement of the dilator over the needle with subsequent loss of tenting (Fig. 4C). After successful puncture, ICE allows for continued direct visualization of the needle tip and its relationship to the surrounding cardiac structures. Finally, when the needle tip is free within the LA, injection of nonagitated saline or contrast during ICE imaging will result in the presence of small bubbles in the LA; this can be used to confirm the location of the tip of the needle and/or dilator when shadowing is present (Fig. 4D).

**Imaging during catheter ablation procedures.** As catheter ablation of cardiac arrhythmias has become more anatomically based, the role for real-time intracardiac imaging during catheter ablation procedures has grown. Heart rhythm disorders that are associated with complex cardiac structures, for which the ablation approach is typically anatomically based, include atrial tachycardias arising from the crista terminalis (21), challenging RA flutters involving the cavotricuspid isthmus (22), ventricular tachycardias arising from the left ventricular outflow tract or aortic cusps, re-entrant substrates in close proximity to previously implanted intracardiac devices, and ablation of the PV antra and LA for atrial fibrillation (AF). The most common ablation procedure during which nonfluoroscopic imaging is used is an ablation procedure for AF; the most commonly used nonfluoroscopic imaging modality during an AF ablation procedure is ICE.

Uses for ICE during AF ablation procedures include a baseline survey of the anatomy; guidance of transseptal catheterization; identification of catheter tip location, contact, and stability; and monitoring for complications. After the interatrial septum is visualized to guide transseptal catheterization, the LA and PVs can be imaged with more clockwise rotation of the catheter to focus on the left-sided PVs. Further clockwise rotation of the ICE catheter combined with slight flexion toward the lateral wall of the RA along with advancement of the catheter allows for imaging of the right-sided PVs. PV anatomy can vary considerably, especially with respect to ostial diameter and configuration and the presence of a common ostium (23).

Multiple imaging modalities are typically used to identify ablation targets before and during a catheter ablation procedure. For AF ablation, TEE, contrast CT, and MRI can be performed before the procedure to define the LA and PV anatomy. Advanced computerized mapping systems allow for pre-operative CT images to be imported and registered with an electroanatomic map as described in the preceding text. Contrast venography of the PVs is also commonly performed, although it is limited by its 2D view.

ICE imaging has the advantage over CT and magnetic resonance of being able to be performed during the procedure. As such, ICE can provide real-time imaging and feedback regarding electrode-tip localization, contact, and stability (Fig. 5). Specifically, visualization with ICE of the narrow ridge of tissue between the left superior PV and LA appendage can permit more accurate power delivery at this site. Similarly, ICE can identify the junction between an upper and lower PV when there is a common ostium—a junction that can be several millimeters deep within a common antrum. One study found that placement of circular mapping catheters using fluoroscopic guidance alone resulted in the catheters being located a mean of 5 ± 3 mm distal to the true ostium (24). Similarly, a study examining the accuracy of pre-operative LA/PV CT image registration with intraoperative electroanatomic mapping found that points taken on the registered map alone could be up to 5- to 10-mm away from points taken by ICE-guidance.
alone (25), highlighting the potential inaccuracy of image registration using a pre-operative CT (26). ICE also appears to offer advantages when attempting to connect sequential focal lesions to create a linear ablation lesion (27).

In addition to anatomic guidance and lesion delivery, ICE allows for real-time monitoring for potential complications, such as thrombus formation, PV stenosis, and pericardial effusion. One of the most serious complications of RF ablation for AF is thromboembolism. One estimate from a survey of centers that had performed more than 1,000 procedures reported a 1% incidence of stroke (28). ICE-guided ablation allows for closer monitoring of the factors that are associated with an increased risk of stroke, including thrombus formation on catheters and sheaths, thrombus formation at endocardial lesion sites, and coagulum formation on ablation electrodes. One prospective study of ICE-guided power delivery during AF ablation procedures in humans found that titration of the energy to avoid the formation of dense showers of microbubbles, possibly a reflection of tissue overheating, was associated with a reduction in thromboembolic events (24). The use of ICE to titrate power delivery based on the development of microbubble formation is less common now that open-irrigation ablation electrodes, which continuously generate microbubble formation, are increasingly used during LA ablation.

PV stenosis is a well-defined complication of ablation for AF (29). Efforts to prevent PV stenosis include limitation of the amount and duration of power delivery and avoidance of power delivery within the PV. ICE guidance provides definition of anatomy and confirmation of contact and stability, thereby potentially reducing the risk of PV stenosis. It can also be used to more directly monitor the PVs for development of stenosis, whether through planimetry (30), measurement of ostial diameter, estimation of blood flow velocities and transostial gradients, (31) and color Doppler analysis (32–34). Figure 5 shows a catheter that is repositioned out of a PV using ICE imaging.

ICE can be useful in the detection of a pericardial effusion during an ablation procedure. Identification of an effusion before a patient develops pericardial tamponade provides additional warning time to prepare for a pericardiocentesis and to reverse anticoagulation, if needed.

Finally, development of a fistula between the LA and esophagus as a complication of catheter ablation occurs in probably only 1 per 1,000 cases, but it can be lethal. While the esophagus can be adequately visualized with ICE (35), whether direct visualization or titration of energy using information obtained during ICE monitoring will reduce the incidence of LA-esophageal fistula is yet to be determined.

Overall, ICE imaging has emerged as a useful tool during AF ablation procedures. Most interventional electrophysiologists who have had the opportunity to experience the utility of ICE in the electrophysiology laboratory routinely use ICE for all of their AP ablation cases.

Role of ICE during cardiac interventions for structural heart disease. Hellenbrand et al. (36) have demonstrated that the use of TEE to guide device closure of atrial septal defects (ASDs) has improved results significantly. The addition of 3D TEE to the armamentarium of the interventional team no doubt will enhance the selection of patients who will undergo device closure of ASDs (Fig. 6). Furthermore, the use of 3D TEE during the closure procedure itself will allow the team to have a comprehensive assessment of each procedural step as well as closure results (Fig. 6). However, as discussed in the preceding text, ICE has some advantages over TEE. Hijazi et al. (37) have demonstrated that the use of ICE to guide device closure of ASDs and PFOs was as good as the use of TEE without the need for general anesthesia or the need for an expert operator. Further, Alboliras and Hijazi (38) demonstrated that the use of ICE was not associated with higher cost than TEE. Currently, ICE is considered the imaging tool of choice in many cardiac centers to guide device closure of ASDs and PFOs.

Imaging protocol for ASD and PFO device closure. Laux-enberg et al. (39) previously have reported a protocol using a specific phased-array ICE catheter that allows bidirectional deflection in orthogonal planes to image the interatrial septum and to guide various steps in the closure process of an ASD or a PFO; the protocol is described briefly here. 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 2D imaging as well as the measurement of surrounding rims is obtained. Contrast injection via agitated saline microbubbles is performed for patients with a PFO in order to confirm the presence of a right-to-left shunt.

The ICE catheter is initially positioned in the RA as described in the preceding text to guide TSP. The corresponding fluoroscopic (anteroposterior view) and echocardiographic images without and with color Doppler obtained with the ICE catheter in the initial neutral or "home" position are shown in Figures 7A to 7A2. In this position the tricuspid valve, right ventricular inflow and outflow, and the long axis of the pulmonary valve are well seen. The aortic valve may also be seen (short axis) in this view. The anterior portion of the septum can be seen in this view; if color Doppler is turned on, the shunt may also be appreciated. This view is very important to assess the tricuspid valve function.

The catheter is then positioned to achieve the "septal" view (Fig. 7B). The resulting fluoroscopic image showing the position of the ICE catheter is shown in Figure 7B. The echocardiographic images without and with color Doppler via ICE are shown in Figures 7B1 and 7B2. In this view, the entire length of the atrial septum and the defect, the CS, and the PVs are well seen. The PVs can be seen in more or less detail depending on the exact location of the transducer.

After advancing the ICE catheter cephalad (toward the superior vena cava), a superior vena cava or "long-axis view" can be obtained (Fig. 7C). The resulting fluoroscopic images, showing the position of the catheter as well as corresponding echocardiographic images without and with color Doppler are...
shown in Figures 7C to 7C2. This view is similar to the TEE long-axis view. 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 PVs may also be imaged, depending on the exact angle of the imaging plane.

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, inferior to the aorta. Minor adjustments of the left/right knob with more leftward rotation can demonstrate the short-axis view. A fluoroscopic image showing the catheter position and corresponding echocardiographic images without and with color Doppler are shown in Figures 7D to 7D2. In this view, anatomic structures seen include the aortic valve in short axis and the interatrial septum. This view is very similar to the short-axis view obtained by TEE and is known as the “short-axis view.” In contrast to TEE, with ICE, the RA is shown in the near field and the LA is in the far field.

Additional views can be obtained by advancing the catheter through the ASD or PFO into the LA, the so-called “views from the left heart.” Echocardiographic images from this location are equivalent to the TTE and TEE 4-chamber views. Anatomic structures seen in this view include the mitral valve, left ventricle, and right ventricle. The catheter can further be manipulated to view the LAA, which may be helpful in procedures to occlude the LAA. The catheter is then withdrawn back to the RA.

ICE imaging can be used to measure the “stop-flow” diameter, or what some may call “stretched diameter,” of the defect using the sizing balloon. The balloon can be viewed in either short- or long-axis view. After the defect is balloon-sized, the occlusion device is loaded into the delivery sheath as has been described. All subsequent device deployment steps can be monitored using ICE.

In cases of PFO closure to prevent recurrence of paradoxical embolism, we perform agitated saline contrast bubble studies before device release and post-device deployment.

**Imaging protocol for pulmonary valvuloplasty and percutaneous pulmonary valve implantation.** Usually ICE imaging is not required for pulmonary valvuloplasty. However, in the occasional patient where fluoroscopy and/or TTE/TEE imaging are not adequate, the introduction of an
ICE catheter inside the right ventricle underneath the pulmonic valve will yield superb images of the valve. The ICE catheter is positioned in the right ventricular outflow tract with the imaging transducer facing up. In this position the pulmonic valve and the main pulmonary artery and its branches can be visualized.

Imaging with ICE also can be useful during percutaneous pulmonary valve implantation using the Edwards Sapien THV (Transcatheter Heart Valve, Edwards Lifesciences, Irvine, California). Again, the transducer is positioned in the right ventricular outflow tract. The outflow tract is assessed by color Doppler and continuous-wave Doppler to assess the severity of regurgitation and the extent of obstruction. After the valve is deployed, ICE can be used to assess the presence or absence of insufficiency across the valve and to evaluate the degree of residual obstruction. Furthermore, ICE can detect any complication that may occur during the procedure.

**Imaging protocol for mitral valvuloplasty.** Balloon mitral valvuloplasty has become the treatment of choice for rheumatic mitral stenosis. Imaging with ICE to perform...
TSP is very useful, as described in the preceding text. Once the puncture is performed, and before the valvuloplasty, one needs to confirm the absence of an LAA thrombus, which would be a contraindication to completing the procedure. In most cases, the absence of an LAA thrombus is excluded before the procedure using TEE. Next, the mitral valve anatomy is assessed. This can be done by positioning the catheter in the right ventricle (as in the prior text) with some adjustment so that the transducer is directed toward the mitral valve. This position can be maintained during the interventional procedure itself. Often the mitral valve can also be seen from the RA by positioning the transducer near the atrial septum with the transducer facing leftward. However, due to the enlarged LA present in these patients, it is best to position the ICE catheter in the right ventricle, close to the septum to assess the mitral valve. After the valvuloplasty, one needs to assess the gradient and the presence or absence of mitral valve regurgitation and the size of the atrial communication created.

Imaging during percutaneous LAA occlusion. Percutaneous LAA occlusion devices are under development, and trials are ongoing. The protocols for these trials have required TEE guidance during device placement to assure accurate positioning of the device within the appendage and to exclude residual flow around the device. Imaging with 3D TEE allows for visualization of the entire circumference of the device in relation to the LAA. There may also be a role for ICE during percutaneous LAA device occlusion. Although it can be more challenging to image the entire LAA using ICE compared with TEE, reasonable views can usually be obtained across the septum from the RA, from within the CS, or from the LA itself.

Future of Invasive Imaging to Guide Noncoronary Cardiac Interventions

Several advances have been made in the field of cardiac imaging to help guide noncoronary interventional procedures. ICE is the most commonly used nonfluoroscopic imaging tool in the interventional laboratory. Opportunities to further improve the usefulness of imaging during cardiac interventions include further reductions in catheter size, improved visualization of left heart structures from the right heart, improved catheter stability, integration of real-time imaging with electrophysiologic mapping systems, and 3D ICE.

Another opportunity in this field is to couple imaging systems directly with the interventional devices themselves. One example of this coupling is a balloon-based PV ablation tool that is under development for the treatment of AF (40). This system permits endoscopic visualization through a balloon that also functions to deliver therapeutic laser energy (Fig. 2). A second example of coupling device imaging and therapy is an ultrasound catheter that also performs ablation. Such a catheter is under development and could allow for real-time direct imaging of the endocardial-electrode interface and lesion formation without the need for a separate catheter dedicated to imaging. Without a doubt, the field of imaging to guide cardiac interventions will continue to evolve rapidly for the benefit of patients and interventionalists.

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REFERENCES


