Value of Real-Time Transesophageal 3-Dimensional Echocardiography in Guiding Ablation of Isthmus-Dependent Atrial Flutter and Pulmonary Vein Isolation

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In the past decade, both the range of indications and the efficacy and safety of interventional electrophysiology has improved considerably. This progress is attributed to both the accumulating experience of electrophysiologists and the advances in technological tools facilitating the diagnosis and treatment of cardiac arrhythmias. Real-time 3-dimensional transesophageal echocardiography (RT 3D TEE) has emerged as a new imaging tool in the clinical arena. Its ability to image in “real time” cardiac structures “en face” and the almost entire length of intracardiac catheters has made this technique a promising imaging tool to guide percutaneous catheter-based procedures. More recently it has been used in monitoring ablation procedures. In this review, the advantages and current limitations of RT 3D TEE during ablation of cavotricuspid isthmus-dependent atrial flutter and pulmonary vein isolation are described. (Circ J 2012; 76: 5–14)

Key Words: Atrial flutter; Pulmonary veins; Transesophageal echocardiography

Over the past decade, there have been major advances in interventional cardiac electrophysiology, including the development of novel ablation catheters, utilization of new energy sources, and several new ancillary tools, leading to expansion of catheter ablation indications, and to a significant increase in both therapeutic efficacy and procedural safety. An important contribution to this evolution has also been improved 3-dimensional (3D) navigation in the cardiac chambers supported by visualization of target anatomical structures by different cardiac imaging techniques, both pre-operatively and intra-operatively.

Imaging the catheter position relative to anatomic structures surrounding the ablation target, anatomical structures to which ablation energy is applied, as well as continuous assessment of the catheter–tissue contact point with monitoring of tissue lesion formation during the ablation remain of paramount clinical relevance. Moreover, the vast majority of cardiac imaging modalities currently used in the electrophysiological laboratory are of little help when difficulties in catheter manipulation and navigation, but have a number of limitations, including high cost, characterization to define the scar substrate of arrhythmias.

The clinical advantages of real-time MRI-guided studies include visualization of the soft tissues during the intervention, online cardiac magnetic resonance assessment of procedural success, reduced X-ray exposure, and “online” tissue characterization to define the scar substrate of arrhythmias. Nevertheless, there are several limitations, including high cost,

Non-Ultrasound-Based Cardiac Imaging for Catheter Ablation Procedures

Fluoroscopy is the primary modality used to guide catheter manipulation and navigation, but has a number of limitations, such as exposure of the patient and medical team to radiation, the need for iodinated contrast injections, limited resolution for soft tissue differentiation, and difficulty in assessing catheter contact or major anatomic variations.

Both magnetic resonance imaging (MRI) and computed tomography (CT) provide preprocedural anatomic information that is helpful in identifying anatomical landmarks and structures that are the target of specific ablation procedures. In the past few years, substantial interest in the development of interventional MRI, using MRI-compatible devices, has emerged. The clinical advantages of real-time MRI-guided studies include visualization of the soft tissues during the intervention, online cardiac magnetic resonance assessment of procedural success, reduced X-ray exposure, and “online” tissue characterization to define the scar substrate of arrhythmias.

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Further exacerbated by the use of new MRI-compatible catheters that are largely unavailable, real-time acquisition of imaging (limited by low spatial resolution), difficulty in localizing and tracking catheters within a volume-averaged view of assigned thickness (8–10 mm), and absence of real-time 3D perspectives.

Electro-anatomic mapping enables the creation of a 3D reconstruction of the endocardial surface of the cardiac chambers by acquiring surface location points with the catheter tip. The system allows non-fluoroscopic navigation of conventional catheters. However, sequential data acquisition required for map creation remains time consuming and spatial resolution may be suboptimal. A more detailed assessment of the underlying cardiac anatomy during the procedure can be achieved by merging 3D chamber anatomical segmentation derived from CT or MRI studies with the 3D electroanatomic mapping geometry. This appealing feature of CT/MRI image integration has been widely used in the vast majority of catheter ablation procedures. Its main limitation, however, remains the use of pre-acquired CT/MRI images (usually in late systole) that often differ from electroanatomic mapping volumes because of variations in heart rate, respiration, volume and hemodynamic status.

**Ultrasound-Based Cardiac Imaging**

Intracardiac echocardiography (ICE) uses either linear or circular phased-array catheters. One of the advantages of this technique is that it does not require general anesthesia and can be performed and interpreted by the interventional electrophysiologist, thus obviating the need for additional personnel. 3D ICE has been recently developed and can be used as a sole imaging tool for catheter navigation or can be merged with pre-acquired, segmented CT or MRI volume imaging.

Two different systems are available for 3D reconstruction from ICE: the first involves a special mechanical pull-back device controlled by a 3D workstation and using a stepping motor to move the ICE catheter linearly in a cranio-caudal direction. The second uses a rotational scan with a phased-array ICE catheter; a motor automatically rotates the transducer array around the catheter shaft from 90° to 360° in 2–5° steps using a custom-made stepper. In both systems the 3D acquisition and volume reconstruction require 3–5 min of post-processing time. The benefits related to the use of ICE should, however, be weighed against the incremental procedural cost related to the disposable ICE catheters (single-use only), the need for an additional venous access and the potential risk of additional periprocedural complications associated with its use. Finally, image acquisition and interpretation are still not straightforward.

RT 3D TEE appeared in the clinical arena and was welcomed by echocardiographers as a major advance in the field of ultrasonography in the 21st century. The revolutionary idea at the basis of this new technology was to arrange thousands of new piezoelectric crystals of the phased-array transducer in multiple rows (matrix-array probe), rather than one row, allowing fast sequential scanning of multiple planes. Two-dimensional transesophageal echocardiography (2D TEE)
acquires a sector image of up to 90° in the lateral direction, depth of up to approximately 16 cm in the axial direction, and negligible thickness (elevation axis). The 3D TEE matrix-array probe expands this concept by acquiring not just one but a series of 2D sector images along the elevation axis to create a 3D pyramidal data set. The huge number of piezoelectric elements (3,000 vs. 48–128 of most conventional 2D TEE) has been made possible by a tremendous miniaturization of electronic connections, resulting in a 3D transducer with a footprint comparable to those of conventional transducers. The modern matrix-array probes consist of many rows and columns (52×52) capable of instantaneous (“live”) 3D images, thus circumventing most of the time-consuming acquisition and off-line data processing associated with previous 3D reconstructive methods. The transesophageal window is not limited by significant chest wall acoustic impedance, and the vicinity of the transducer to the heart allows the use of higher frequencies (ie, 7 MHz) compared with its transthoracic counterpart. Better image resolution is therefore obtained (the higher the frequency, the better the ultrasound beam can focus). Higher frequencies and better acoustic substrate yield high-resolution 3D images, especially of posterior structures of the heart (ie, those closer to the transducer).

When compared with conventional 2D TEE, the 2 main advantages of RT 3D TEE are evident: (1) the ability to image structures in an “en face” view (which is not offered by any other currently available real-time imaging technique), and (2) to visualize most intracardiac catheters along their length with clear depiction of their position in relation to the surrounding cardiac structures. These qualities have made the technique a remarkable tool for the guidance of most percutaneous catheter-based procedures. Indeed, RT 3D TEE has been used to guide the repair of many structural diseases, including closure of atrial septal defect,14 mitral valve repair,15 closure of prosthetic mitral valve dehiscence, and aortic valve implantation.16

The right and left atria are very close to the esophagus and specific right and left atrial anatomical structures can be accurately visualized by RT 3D TEE.17 Some of these structures, such as the CVTI or PV ostia, are target of specific ablation procedures (CVTI or PV isolation). Moreover, RT 3D TEE has been shown to have enough temporal and spatial resolution to potentially track catheter movement in the heart, thus enabling real-time navigation of ablation catheters. RT 3D TEE may therefore become a relevant imaging tool during electrophysiological procedures, providing anatomic details, validation of adequate catheter contact, reduced fluoroscopic exposure, and early recognition of collateral damage.4

**Figure 2.** (A) 2D TEE bicaval approach. (B) RT 3D TEE obtained using zoom modality from (A); (C) Up-down rotation (curved arrow) shows “en face” half of the atrial septum. (D) Expanded image in the direction of arrow in (C) reveals the entire septum from a left side perspective; (E) Anatomically correct orientation is obtained by a right-to-left angulation (curved arrow); (F) 180° rotation shows the right side of the septum with a crater-like shaped fossa ovalis (FO); RA, right atrium; LA, left atrium; SVC, superior vena cava; IVC, inferior vena cava; Ao, aorta; AS, atrial septum; CS, coronary sinus; EV, Eustachian valve; RT 3D TEE, real-time 3-dimensional transesophageal echocardiography; 2D TEE, 2-dimensional transesophageal echocardiography.
Image Acquisition Using RT 3D TEE

The RT 3D TEE transducer (Philips, Medical Systems, Andover, MA, USA) and the acquisition modalities have been described in greater detail elsewhere. Briefly, it is a matrix probe with 2,500 elements capable of 2 different “real-time” acquisition modalities: “live 3D” and “3D zoom”. The “live 3D” modality switches the system from 2D to 3D imaging, acquiring real-time 3D images without electrocardiographic-gating reconstruction. The “3D zoom” displays a truncated pyramidal data set. The dimension of this sector can be manually adjusted to display the region of interest (up to 90° × 90°).

Cavotricuspid Isthmus

RT 3D TEE imaging acquisition of the CVTI is obtained using both live or zoom modality from the 2D 4-chamber plane, with a pyramidal data set large enough to include the posterior region of the right atrium. From this perspective, the entire CVTI is imaged, including the coronary sinus ostium, the Eustachian valve (EV)/ridge, the pectinate muscles, and the posterior tricuspid hinge line (Figures 1A, B). The interventional electrophysiologist may not be familiar with 3D TEE imaging. To circumvent this difficulty, RT 3D TEE perspectives similar to that of fluoroscopic projections, such as left anterior and right anterior oblique (LAO, RAO) views are usually obtained (Figures 1C, D).

Interatrial Septum (IAS)

The RT 3D TEE image of the IAS in the “en face perspective” and the surrounding atrial wall can be virtually obtained from the 90° bicaval plane (Figure 2A). Once the 2D TEE bicalval view has been obtained, the zoom modality can be used. The dimension of the sector should be as large as possible to include the entire septum. The extensive area scanned causes a frame rate as low as 5 Hz/s, resulting in an image that appears to move less smoothly than at a higher frame rate. Fortunately, the IAS is relatively immobile, so the low frame rate does not have a significant effect. Once the pyramidal data set has been acquired, a 90° up-down angulation shows the entire left aspect of the IAS in the “en face perspective” (Figures 2B–D). To obtain an anatomically correct orientation, the image should be rotated so that the mitral valve is towards the left lower corner of the image (Figure 2E). A 180° counterclockwise rotation shows the right side of the septum with the fossa ovalis and the entrance of the superior vena cava (Figure 2F).

PV Ostia

Theoretically, 3D imaging of the roof of the left atrium should be able to visualize all 4 PVs. The right and left pairs of veins are, however, widely separated and lie very close to the transducer. At this distance, the pyramidal beam is too narrow to visualize the entire roof of the left atrium including the PVs. Thus, the left and right PVs can only be visualized by using different modalities of acquisition.

The easiest way of visualizing the left upper PV (LUPV) is using the zoom modality directly towards the left atrial appendage (LAA). Once the LAA is visualized, a slight counterclockwise rotation of the staff allows imaging of the entry of the LUPV “en face”. Because the left lower PVs (LLPV) enter the atrial cavity at a different angle, a perfect side-by-side “en face” view of both orifices cannot be obtained from a single perspective. However, when both are inside the pyramidal data set, a gentle angulation of the 3D image may visualize both orifices (Figure 3A). The view inside the veins may disclose the lumen of both veins, with different spatial orientations, and show how these drain into the left atrial cavity.

The right PVs run adjacent to the IAS, so an analogous approach is used to visualize the veins. When the septum is acquired in the “en face” perspective, a 90° rotation from that perspective will disclose the right PV ostia (Figure 3B).

RT 3D TEE During Ablation of Isthmus-Dependent Flutter

RT 3D TEE has shown promise as an imaging tool during ablation of isthmus-dependent atrial flutter. This imaging technique has several advantages: (a) radiation exposure...
may be considerably reduced; (b) anatomic causes for difficult ablation, including deep sub-Eustachian pouch, prominent pectinate muscles or prominent and rigid EV, can be recognized (this information may guide the interventional electrophysiologist in avoiding the obstacle by choosing a more lateral or septal ablation line); and (c) contact between the atrial wall and tip of the catheter, as well as the act of burning, can all be visualized. These aspects are addressed in greater detail as follows.

Advantages of Using RT 3D TEE

Reduced Radiation Exposure

There is concern about radiation exposure during interventional procedures. Because most atrial arrhythmias are not life-threatening and the procedural purpose is mostly improvement of quality of life, the benefit of CVTI ablation should be weighed against procedural success rate, risk of complication, and long-term risk of biological effects from radiation exposure. By using 3D TEE, radiation exposure may potentially be lowered (in our experience at least 3-fold), because mapping catheter navigation is mainly guided by RT 3D TEE than by fluoroscopy. This is particularly true as experience with this novel approach increases; procedural and fluoroscopic times are further reduced in the later patients compared with the first 10 patients treated using this approach.

Recognition of Challenging CVTI Anatomy

Several anatomic obstacles may lengthen and render difficult this otherwise simple procedure.

In approximately 10% of patients a depression is present (sub-Eustachian pouch or sinus of Keith) along the middle area of the CVTI. In some individuals, this pouch may be deeper and appear aneurysmal. For the interventional electrophysiologist this information is relevant because entrapment of the catheter inside a deep pouch may result in poor energy delivery and coagulum formation. Furthermore, the presence of a septal pouch has been described as causing a conduction split, thus rendering ablation during typical atrial flutter more difficult in this region. RT 3D TEE may visual-
ize the CVTI in the “en face” perspective (LAO-similar) or in cross-section (RAO-similar) (Figures 4A, B). The “en face” perspective shows the pouch as a darker area in comparison with the surrounding structures, whereas the cross-section clearly shows the depression of the wall. Further quantitative studies need to clarify the cut-off between normal variation of the CVTI floor and a “true pouch”, as well as define which type of pouch will significantly affect ablation efficacy. Presence of a deep pouch is suspected by “ablationists” when unusual catheter movement is experienced; in these cases, the ablation strategy is modified (ie, creating the ablation line medial or lateral to the pouch).

Occasionally, prominent pectinate muscles may extend onto the CVTI, causing difficulty in ablation. These “prominences” of thickened tissue of the atrial wall may render creation of a transmural ablation lesion difficult. Also, the catheter may become wedged in the “valleys” between 2 “prominences” and in such locations energy delivery is limited by impedance rise and coagulum formation. Finally, catheter stability on prominent pectinate muscles may be challenging. RT 3D TEE shows pectinate muscles encroaching onto the CVTI as a series of “hills and valleys” (Figure 4C). Through knowledge of the distribution of the pectinate muscles offered by direct visualization of CVTI anatomy, the “ablationist” may directly move the ablation line more medially (Figure 4D). Also, a prominent EV may create difficulty in catheter manipulation by becoming the only point of contact and acting as a “fulcrum”. The use of an appropriate guiding sheath with the tip of the sheath distal to the ridge and proximal to the tricuspid annulus will often solve the problem. RT 3D TEE clearly shows the presence of a prominent EV in both the LAO- and RAO-similar perspectives (Figures 4E,F).

Imaging the Contact Between the Atrial Wall and the Act of Burning
To improve the efficacy and safety of a complex ablation procedure, direct and continuous visualization of contact and catheter stability during radiofrequency (RF) energy delivery is very much welcomed. RT 3D TEE has the potential to image catheter–wall contact and the act of burning. Catheter–wall contact is established when RT 3D TEE imaging does not show any gap between the catheter tip and the atrial wall in multiple perspectives (Figures 5A, B). However, at times, difficulty in imaging the tip of the catheter makes this evaluation not straightforward. Manifestation of the act of burning during RF delivery may be appreciated as an emerging stream of 3D microbubbles flowing away from the ablation catheter tip, caused by the cavitation phenomenon produced by tissue heating (Figures 5C, D).

RT 3D TEE During PV Isolation
The PVs play a major role in triggering and maintaining atrial fibrillation (AF) and over the past decade catheter ablation of AF (mainly through PV isolation) has evolved from an investigative procedure to an established treatment option performed in many medical centers worldwide. Because RT 3D TEE can visualize all 4 PVs, it can potentially enable tracking of the catheter around the PV ostia, thus limiting radiation exposure to the patient and to the operator. Catheter
ablation of AF, as with many other interventional procedures, requires access through the IAS.

**Trans-Septal Crossing**
Although trans-septal puncture is relatively safe in experienced hands, severe complications, such as aortic or atrial perforation, cardiac tamponade or thrombus formation, may occur. Complications are often caused by incorrect puncture site and are more likely to occur in patients with abnormal left atrial anatomy. In more challenging cases, 2D TEE is used as the primary imaging modality to guide trans-septal crossing. The most appropriate site of puncture (ie, fossa ovalis) is identified through recognition of 2D TEE “tenting” (Figure 6A). However, following the intracardiac catheter requires multiple views and continuous imaging adjustment. Moreover, because of its “tomographic nature” only a thin slice of septum is imaged at one time and “tenting” may be missed because locations are deeper in relation to the 2D plane (Figure 6C). Finally “ablationists” may not be familiar with the various transesophageal planes, especially when these are continuously modified in an attempt to follow the catheter. Conversely, RT 3D TEE reproduces images of the atrial septum very similar to the true anatomy and therefore implicitly understood. The septum can be visualized from the right and left perspectives (Figure 3), and “tenting” is easily detected because it is always included in the pyramidal data set (Figures 6B,D).

**Electrical Isolation of the PVs**
Electrical isolation of the PVs has evolved over time from ablation within the PV (leading to a high incidence of PV stenosis) to the more proximal venoatrial, peri-ostial region. This approach requires correct identification of the PV ostia. Moreover, given the marked variation in PV anatomy, assessing the number of PVs and the anatomy of their ostia is essential when planning the ablation strategy. Although the preprocedural gross anatomy of the PVs can be easily assessed by MRI or CT, the exact location of the PV ostia in relation to other structures is not easy to define. Moreover, because the transition between the veins and the antral region is tapered by musculature, the atrial wall extends deeply into the vein. The anatomic border between the 2 structures cannot be precisely defined. RT 3D TEE can visualize the entire contour...
of the PV ostia “en face”. Thus, the technique has the potential to become a useful complementary imaging modality in electrical isolation of PV. In our institution, RT 3D TEE is routinely used during isolation of PVs. In the following section we specifically address the advantages and technical issues in the use of RT 3D TEE during PV electrical isolation.

**Advantages of Using RT 3D TEE**

RT 3D TEE provides a unique, instantaneous assessment of the position of catheters at the level of each PV ostium. Point-by-point navigation around the PV with limited use of fluoroscopy may be monitored continuously, enabling assessment of catheter stability and contact in challenging ablation areas such as the prominent lateral crest (Figure 7).²² The lateral crest, also known as the left atrium ridge, results from the infolding of the outer atrial wall towards the inside, causing bulging of the endocardial surface. For PV isolation, this region is particularly challenging because of the possible suboptimal catheter contact and catheter instability. Moreover, the thickness of this area varies from patient to patient and tends to be greater with respect to left atrial wall thickness in other areas. Continuous RT 3D TEE visualization of this area may ensure better catheter contact and stability, while providing greater confidence in safely delivering long-lasting, high-energy RF applications until stable PV isolation is achieved.²²

**Issues and Challenges**

One of the challenges during the procedure is tracking the relatively rapid movement of the catheter. Because of the finite speed of ultrasound there is an inverse relation between frame rate, volume size, and spatial resolution. The entire CVTI may be shown at the cost of a low frame rate.

An acceptable compromise between the largest possible field (which always includes the catheter inside the pyramidal data set) and the highest possible frame rate (which enables the catheter to be followed) can be obtained with the correct use of the zoom modality: using a pyramidal data set of 60°×60°, the entire CVTI can be visualized with an acceptable frame rate (7–10 frames/s). During the act of ablation with the catheter in a fixed position, the “live” modality may be used (thus obtaining a rate up to 25 frames/s) because a narrow pyramidal data set (50°×30°) is enough to create an image focused on the catheter and closer surrounding structures.

Another challenging issue is the artefacts created by highly reflective structures such as metallic catheters. Reverberations (ie, multiple reflections between structures) and shadowing (ie, areas of drop-out in the rendered image beyond the catheter) are the 2 major disturbing artefacts encountered during CVTI ablation. Reverberations can be recognized because they appear and disappear as the catheter moves and usually
they form a sharp angle with the catheter. However, if the catheter is nearly parallel to the ultrasound beam and does not move, the reverberations seem to prolong the catheter and can be misinterpreted as the catheter tip (Figures 8A, B).

Drop-out caused by shadowing is also difficult to distinguish. Because of the angle of incidence between the ultrasound beam and the catheter, the shadowing phenomenon may not produce complete drop-out. Rather, it may create a “sulcus-shaped” drop-out positioned beyond the catheter. In some circumstances, this artefact may be misinterpreted as an anatomic irregularity of the CVTI. However, it can be recognized because it is exactly beyond the catheter, has the same size and shape, and follows the catheter’s motion (Figures 8C, D).

Finally, different catheters from different vendors have different 3D imaging features (because of the different acoustic impedance of the components). Some catheters can be followed more easily than others. Figures 8E, F shows 2 different catheters that, despite the same perspective, appear differently with 3D TEE.

The acquisition modality for visualizing PVs has been described in a previous section. In our experience, there is a marked difference in imaging different PV with RT 3D TEE. Although the LUPV, together with the lateral crest, is visible in 100% of cases, the LLPV is more difficult to visualize (60% of cases). The right upper PV can be identified in nearly 90% of patients, but the right lower in only 40% of cases. The reasons why the lower PVs are more difficult to image are not completely clear. The lower PVs are usually smaller and drain into the atrium at different angles to the upper veins. It is possible that both of these characteristics render these structures difficult to include in the pyramidal beam. This may be a relevant issue limiting the feasibility of RT 3D TEE to follow the entire PV isolation procedure. These shortcomings are more evident for small atrial cavities than for larger atria.

There are several other concerns to consider in relation to the use of RT 3D TEE, particularly during a PV isolation procedure. First, marked displacement of the esophagus to visualize the veins may deform the geometry of the left atrial cavity, interfering with catheter manipulation. Second, the
transducer produces heating that may augment the heating produced by RF delivery, possibly increasing the risk of esophageal injury. The effects of the new source of heating derived from the TEE probe and how this may affect the ablation procedure warrants further investigation. Third, increased patient discomfort is determined during the transesophageal study because general anesthesia is required. Finally, given some current limitations of the technique to obtain adequate PV imaging, an experienced cardiac imaging physician is required during the procedure, thus imposing an additional logistic burden to an already complex procedure.

**Conclusions**

Preliminary experience of RT 3D TEE-guided monitoring of ablation procedures in both the right and left atria is feasible, allowing, in most patients, fluoroscopy-free navigation and precise RF energy delivery with a considerable reduction in the radiation exposure burden. Prospective, and possibly randomized, trials evaluating procedural success, ablation time, and fluoroscopic time and dose need to be conducted to establish the real value of RT 3D TEE in the setting of anatomy-driven atrial ablation procedures, such as those involving the CVTI and PVS.

**References**