Anatomy of Right Atrial Structures by Real-Time 3D Transesophageal Echocardiography
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The rapid development of catheter ablation techniques for atrial arrhythmias has triggered a renewed interest in the anatomy of the right atrium. In particular, some atrial arrhythmias such as focal atrial arrhythmias or atrial flutter have been linked to the anatomic architecture of specific structures such as the crista terminalis or cavotricuspid isthmus. Real-time 3-dimensional transesophageal echocardiography (RT 3D TEE) is a recently developed technique that provides 3D images of unprecedented quality. Because the right atrium is very close to the transducer, this technique may provide high-quality images of those atrial structures involved in ablation procedures. This review describes a step-by-step approach for acquisition and processing of RT 3D TEE images of right atrial structures of relevance to electrophysiologists. For anatomical correlations of RT 3D TEE images, selected images of right atrial structures were matched to anatomical specimens. (J Am Coll Cardiol Imag 2010;3:966–75) © 2010 by the American College of Cardiology Foundation
tures. Given its high imaging quality, RT 3D TEE may provide useful pre-ablation information for proper procedural planning, and it can potentially replace other cardiac imaging techniques that are costly or have limited availability (e.g., cardiac magnetic resonance imaging) or carry some biological risk (i.e., cardiac tomography) for imaging those cardiac structures of potential interest for ablationists.

In this review, we describe a step-by-step approach for acquisition and processing of RT 3D TEE images of right atrial structures of relevance to electrophysiologists such as the CT and CVTI with the surrounding structures. For anatomical correlations of RT 3D TEE images, we matched selected images of right atrial structures to anatomical specimens.

Image Acquisition

The RT 3D TEE transducer (Philips, Medical Systems, Andover, Massachusetts) and the acquisition modalities have been described in detail elsewhere (6). Briefly, it is a matrix probe with 2,500 elements and is capable of 4 different modalities of data acquisition. Table 1 shows the technical features of each acquisition modality. A key step in the visualization of images is the so-called “image-rendering process.” Once the pyramidal volume dataset has been acquired, it is amenable to following online/offline image-rendering steps: cropping and threshold processing. The final result depends on the accurate and complementary use of these processing tools.

The cropping process permits to section the 3D pyramidal dataset, thus allowing views inside the heart by removing the volume information that is covering the target structure(s). There are 2 cropping modules: the X-Y-Z box by which the crop plane is moved along the X-, Y-, and Z-axes and the single arbitrary plane by which the volume dataset has been cropped in any direction (Fig. 1). Both modules are useful to display atrial structures.

Moreover, there are several controls used for threshold process. Suggested settings for the best imaging of right atrial structures are summarized in Table 2.

Display Processing

High-quality 3D imaging by RT 3D TEE provides a countless number of perspectives for any specific cardiac structure. Once the anatomical target has been selected, the volume dataset can be cropped and oriented to obtain the most effective perspective. We call this way of imaging a “structure-oriented” approach. Figure 2 shows how the structure-oriented approach is effective even for visualization of small structures such as the Eustachian valve (EV). Not infrequently, only a few perspectives may clearly reveal a ridge protruding from the atrial wall or a flap of tissue attached to a vascular ostium. This is because a specific software feature assumes the presence of low-level diffuse ambient light and a brighter virtual fix beam of light situated along the line from the viewer’s eyes. Surfaces perpendicular to the single fix beam of light have the highest level of brightness, whereas other surfaces appear shaded. Thus, a slight rotation of the image, by creating shadowing along its borders, may reveal a structure that was partially invisible when it was observed taking a slightly different perspective (Fig. 3). Finally, in some cases, analogous to anatomical dissection, a “virtual anatomical dissection” or slice-by-slice removal of surrounding tissues/structures is made possible by the free crop plane.

Anatomical Structures

In the following section, we describe the anatomical landmarks of the right atrium relevant to electrophysiologists, and the most optimal way for image acquisition by RT 3D TEE and their display (Table 3).

CT

Electrophysiological background. The CT is one of the most frequent sources of focal atrial arrhythmias, followed by the coronary sinus (CS), the parahisian region, appendage, or rarely, along the tricuspid annulus. In patients without structural heart disease, two-thirds of atrial arrhythmias are distributed along the long axis of the CT (5). Catheter ablation for focal arrhythmias has proved

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Table 1. Technical Characteristics of Acquisition Modalities

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Frame Rate</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live modality</td>
<td>High</td>
<td>10–26 Hz</td>
</tr>
<tr>
<td>Zoom modality</td>
<td>High</td>
<td>5–8 Hz*</td>
</tr>
<tr>
<td>Full volume</td>
<td>Up to 30–40 Hz</td>
<td></td>
</tr>
<tr>
<td>3D color Doppler</td>
<td>Medium</td>
<td>Up to 25 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Narrow (30° × 60°)</td>
</tr>
</tbody>
</table>

*At large angle (85° × 85°).

3D = 3-dimensional.
to be safe and effective with a reported success rate between 77% and 100%.

**Anatomy of CT.** The CT demarcates the venous part of the atrium from the right atrial appendage (the true primitive atrium). It is a roughly C-shaped muscle band separating the smooth wall of the venous component of the atrium from the rough wall of the atrial appendage (16). It sweeps from the septal aspect superiorly to pass anterior to the entrance of the superior vena cava before turning

### Figure 1. The “Cropping” Process

(A) X-Y-Z box cropping tool with the intact pyramidal dataset and (B) after removing the front half of the image. (C) Moves the arbitrary cropping towards the pyramidal dataset. (D) Once inside the pyramidal dataset, the arbitrary plane can be moved, rotated, and angulated in any direction, revealing the internal anatomic structures.

<table>
<thead>
<tr>
<th>Table 2. Optimal Set Controls for Imaging Atrial Structures</th>
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<tbody>
<tr>
<td><strong>Scale</strong></td>
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<tr>
<td>------------</td>
</tr>
<tr>
<td>Gain</td>
</tr>
<tr>
<td>Brightness</td>
</tr>
<tr>
<td>Compression</td>
</tr>
<tr>
<td>Smoothing</td>
</tr>
<tr>
<td>Vision control</td>
</tr>
<tr>
<td>Color map vision</td>
</tr>
<tr>
<td>X-Res button</td>
</tr>
</tbody>
</table>
posteriorly to descend along the lateral border of the right atrium toward the entrance of the inferior vena cava. The CT may vary in size and thickness most often appearing as distinct ridge, but it may also be a broad and almost flat structure or narrow and thin structure. Pectinate muscles emerge in branching fashion from the CT spreading out into the right atrial appendage (16,17).

Acquisition of RT 3D TEE images of CT. Since the CT originates from near the medial border of the entrance of the superior vena cava, both the superior vena cava and right atrial appendage are useful landmarks to localize the CT. Visualization of the CT is best done as follows:

1) Acquisition of a volume dataset in zoom modality from a bicaval 2D section (Fig. 3A).
2) Crop the volume dataset along the frontal plane (X-Y-Z box) so that the superior vena cava is entirely displayed on the left side of the image (Fig. 3B). The CT appears as a protuberance arising from the inferior border of the superior vena cava into the right atrium.
3) A rotation of the image so that the superior and inferior vena cava are parallel to the longitudinal axis of the body (Fig. 3C).
4) A slight rotation (left to right and bottom to up) usually shows the CT in its entire anatomical shape and size: a C-shaped structure originating from the border of the superior vena cava and extending for a variable distance on the lateral atrial wall (Fig. 3D). Proper adjustments of the gain, compression, and smoothing controls are useful so as to maximize the perception of depth.

Figure 4 compares the CT and surrounding structures by RT 3D TEE to the corresponding anatomic specimen.

The CVTI and Surrounding Structures

Electrophysiological background. The CVTI is a well-defined anatomical area responsible for isthmus-dependent atrial flutter (5,16–18). Successful linear ablation at CVTI with demonstrated conduction block bidirectionally across the ablation line terminates the arrhythmia and prevents recurrence in the majority of patients (1). Within this area, 3 isthmus lines can be distinguished: the paraseptal isthmus, the inferior isthmus, and the inferolateral isthmus (Fig. 5).
The paraseptal isthmus, also known as the septal isthmus, is between the CS ostium and the tricuspid valve. It is usually deployed for “slow pathway” ablation in atrioventricular nodal re-entry tachycardia (18).

The inferior isthmus, located between the orifice of the inferior caval vein and the tricuspid annulus, is usually the target for linear ablation of common atrial flutter (18).

The 3 most frequently recognized anatomical obstacles with ablation of isthmus-dependent atrial flutter are the presence of a sub-Eustachian pouch, pectinate muscles encroaching the CVTI, and a prominent EV/Eustachian ridge (3). Most of the time, these anatomical obstacles are detected only at the time of the ablation, and each of them impedes in a different manner the optimal power delivery.

### Table 3. Summary of the Most Common Settings for Image Acquisition

<table>
<thead>
<tr>
<th>Starting</th>
<th>Action</th>
<th>Result</th>
<th>Suggested Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crista terminalis</td>
<td>Zoom acquisition from bi-caval 2D section. Large pyramidal data set to include both superior and inferior vena cava</td>
<td>Cropping and rotating the volume data set to obtain the long axis view of superior vena cava parallel to longitudinal axis of the body</td>
<td>The crista will appear as a protuberance originating from the superior vena cava extending for a variable distance on the lateral atrial wall Low gain (10–30) Low compression (10–20) Medium–high smoothing (6–8) Bronze/blue vision</td>
</tr>
<tr>
<td>Cavotricuspid isthmus and surrounding structures</td>
<td>Zoom acquisition from 4-chamber 2D view. Large pyramidal data set to include the entire atrium.</td>
<td>Remove the anterior part of the atrium using the cropping function</td>
<td>The posterior part of the atrium with EV, CS and posterior part of the tricuspid hinge line will appear (view similar to the LAO). In this view both Eustachian valve and coronary sinus ostium can be imaged. With a deeper cut and a slight clock wise rotation, a perspective similar to RAO view is obtained Low gain (10–30) Low compression (10–20) Medium–high smoothing (6–8) Bronze/blue vision</td>
</tr>
</tbody>
</table>

CS = coronary sinus; EV = Eustachian valve; LAO = left anterior oblique; RAO = right anterior oblique; 2D = 2-dimensional.
and limits the creation of a continuous line between tricuspid valve and inferior vena cava.

**SUB-EUSTACHIAN POUCH.** In approximately 10% of hearts, there is a depression (sub-Eustachian pouch or sinus of Keith) on the inferior isthmus just lateral to the CS ostium. In some patients, this pouch may be very deep or even appear aneurysmal (16,19). A characteristic “dip” of the catheter tip when dragging back the ablation catheter toward the inferior vena cava and the inability to block conduction through the isthmus are suggestive of a deep sub-Eustachian pouch. For better catheter contact so as to produce a complete ablation line, it may be necessary to draw the line slightly more laterally, along the inferolateral isthmus.

**PECTINATE MUSCLES ENCROACHING CVTI.** The middle portions of both the inferior and inferolateral lines pass through an inhomogeneous area of the atrial wall comprising, of varying extents and sizes, muscle bundles separated by a thin or almost parchment-like atrial wall. Large-amplitude electrograms accompanied by impedance rise during ablation are suggestive of pectinates encroaching onto the isthmus. When thick pectinate muscles are encountered, the thickness of the myocardium may make it difficult to achieve transmural lesions. On the other hand, deep lesions placed in the thin atrial wall between the pectinates increase the risk of perforation and damage to the right coronary artery (16).
PROMINENT EV. When a prominent EV/Eustachian ridge is present, it acts as a fulcrum for the catheter, and a clockwise torque results in a counterintuitive movement of the tip of the catheter away from the septum (19). An appropriately shaped and placed guiding sheath may overcome the difficulties posed by a prominent EV/Eustachian ridge.

Anatomy of CVTI and surrounding structures. The CVTI is the inferior part of the atrial wall bordered by the tricuspid hinge line anteriorly and by the EV posteriorly, stretching from the CS orifice supero-medially to the final ramifications of the CT inferolaterally. Thus, the superomedial border is lined by the inferior border of the ostium of CS and the atrial vestibule leading to the tricuspid valve, whereas the inferolateral border is delimitated by the final ramifications of the CT and the vestibule.

The pectinate muscles fan out from the CT and encroach upon the CVTI for variable distances. The pectinate muscles have variable height, being more prominent laterally, and ramify into progressively slender branches as they approach the CS ostium. More recently, it has been shown that in about 20% of cases, pectinate muscles end in a distinct posterior atrial bridge (named second CT) and possibly marking a posterior boundary of the CVTI (16).

The EV is usually a semilunar flap of variably developed fibrous or fibrous-muscular tissue that guards the entrance of inferior vena cava. The free margin of EV is concave and directed cephalad. The EV continues medially into the sinus septum that is also known as the Eustachian ridge, which is located between the fossa ovalis and the ostium of CS (19).

The tendon of Todaro is a fine, tendinous cord which runs in the musculature of the Eustachian ridge (16). It is not visible grossly, but its course is projected as an extension of the free-edge of the EV toward the central fibrous body. Its insertion into the central fibrous body marks the position of the compact atrioventricular node at the apex of the triangle of Koch. The anterior border of the nodal triangle is the hinge line of the septal leaflet of the tricuspid valve, whereas the superior edge of the CS ostium marks the inferior border.

The CS ostium opens in the right atrium between the opening of the inferior vena cava and the tricuspid valve.
orifice at the inferior border of the triangle of Koch. In nearly 80% of cases, its orifice is guarded by a semilunar valve, the valve of the CS (valve of Thebesius). A prominent Thebesian valve may create difficulties in cannulation of the CS.

**Acquisition of RT 3D TEE images of CVTI and surrounding structures.** Since the CVTI is a muscular region of the right atrial cavity bordered by well-recognizable anatomic landmarks, a virtual perimeter of the CVTI can be drawn by imaging these structures (Fig. 6). In order to visualize the CVTI and surrounding structures most optimally, we usually take the following steps:

1) Acquire a 3D image from the 2-dimensional 4-chamber plane, using a pyramidal dataset large enough to include the entire right atrium.

2) By using the auto-crop function, the anterior half of the atrium is removed. Moreover, an arbitrary crop can be used to remove further remaining structures of less interest.

3) Most commonly, catheter ablation of the CVTI is performed by taking a left anterior oblique view (between 20° and 30° angulation). Thus, the image should be rotated until a similar position has been obtained (Fig. 6). A slight clockwise rotation and a deeper cut in the frontal plane, as shown in Figure 7, usually permits an image that is close to the right anterior oblique view used for catheter ablation. Both views are particularly helpful to evaluate the depth of a sub-Eustachian pouch (Fig. 8), to recognize a prominent EV/Eustachian ridge (Fig. 9), or to precisely assess the Thebesian valve (Fig. 10).

**Conclusions**

Real-time 3D TEE enables consistent visualization of right atrial structures, provided proper image acquisition and image rendering process have been used. The high image quality not only allows visualization of important structures involved in arrhythmias that are potential targets of ablation, but it gives an unprecedented opportunity to find anatomical correlates to electrophysiological findings.
Although RT 3D TEE pre-procedural imaging of right atrial structures might have a potential role in identifying potentially unfavorable anatomy, there are some major limitations for the intraprocedural use of the technique. The first and foremost important consideration is the significant discomfort that many patients report during RT 3D TEE, which may require anesthesiologic support. This limitation may be overcome by novel nasal RT 3D TEE probes that are currently under investigation. Moreover, given some current limitations in hardware and software, an experienced cardiac imaging physician/technician may be required during the ablation procedure, adding to direct and indirect costs and imposing an additional logistic burden upon the routine of a very busy electrophysiology laboratory.

In conclusion, RT 3D TEE may potentially add significant safety and benefits to pre-procedural ablation of atrial structure by identifying unfavorable anatomy. Additional technological improvements, however, are needed before intraprocedural application of the technique.

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