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3D Echocardiographic Visualization for Intracardiac Beating Heart Surgery and Intervention

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One of the major advances that has taken place in surgery over the past 25 years has been the evolution toward minimally invasive procedures. Benefits for patients include reduced morbidity, shorter hospital stays, and more cosmetically appealing incisions, all while maintaining or enhancing long-term outcomes. Cardiac intervention has progressed significantly in terms of coronary intervention but *intracardiac procedures have been hampered by lack of a live, high-resolution three-dimensional (3D) imaging modality*. Two of the major issues that face the physician are the development of tools to work inside a beating heart and the development of visualization techniques that permit reliable procedures to be performed.

X-ray fluoroscopy has been the mainstay of interventional cardiology for the diagnostic assessment of coronary anatomy as well as for the placement of coronary stents. In parallel, electrophysiologists have used x-ray techniques as well, but navigation within a cardiac chamber poses challenges because devices move in 3 dimensions when not confined inside an artery. To circumvent this challenge, tracking devices, many of which use electromagnetic sensing, have been developed to create virtual cardiac chambers that give a 3D representation to the surgeon, interventionalist, or “cardiac proceduralist.”

Therefore, one of the most significant challenges to operating inside a beating heart has been the lack of an imaging modality to provide detailed, real-time visualization in three dimensions—preferably without ionizing radiation. Ultrasound has been the leading modality in imaging cardiac structure and function—particularly of the left ventricle and cardiac valves, the most common anatomic structures of interest for referral. However, this modality has traditionally used two-dimensional (2D) imaging planes (Fig 1).

Two- versus Three-dimensional Echocardiographic Transducers

Ultrasound has been used for cardiac imaging for more than 50 years. Echocardiography combines portability, safety, low cost, and widespread availability. The most significant advances that have occurred include development of 2D over one-(spatial) dimensional imaging in M-mode, development of spectral Doppler techniques to evaluate valve flow and chamber filling, the development of color Doppler to map spatially blood flow movement, and the placement of an ultrasound imaging sensor on a transesophageal gastroscope.¹

The ultrasound transducer renders echo unique among its siblings in imaging technology. It converts electrical energy into mechanical oscillations and vice versa. To understand what sets 3D systems apart from conventional scanning systems, we need to review some acoustic

principles. Current 2D systems transmit and receive acoustic beams *in a flat 2D scanning plane*. This is accomplished by sweeping an acoustic scan line within this 2D plane (Fig 1A).

The radiofrequency scan line is steered using a conventional beam former, and an image is reconstructed by assembling 2D picture elements commonly known as pixels onto a display. The ultrasound system stores pixel coordinates in a pattern similar to that of longitude and latitude (i.e., in 2D) whereas the temporal aspect is added using sequences of frames. Because sound travels at 1540 m/s, the rapid movement of scan lines within two planes occurs within milliseconds and is perceived by the eye to be a “live” 2D image. The transducer needed to operate in this mode classically has used 64 to 128 piezoelectric elements.

Gated Versus Live 3D Imaging

Traditional methods to generate “pseudo” real-time imaging have been to acquire sequences of several hundred 2D images gated the ECG R-wave. These methods have been in use for more than a decade. *While appearing to “beat,” these cardiac images are reconstructed from 90 to 180 different heart cycles. Live navigation with instant feedback to the physician is impossible with such a technique.* Thus, innovation in live 3D scanning was essential if echo was to be used to navigate in 3D space.

True 3D ultrasound steering has been the subject of much academic and industrial research dating back to the 1980s. The key difference in 3D imaging involves beam sweeping in three dimensions, which poses several technical challenges: creating a transducer array with up to 3000 electrically active elements, processing 3D data at rates exceeding 50 to 100 Mbytes/s, presenting 3D data on a 2D screen, quantifying data for physiologic measurements and for 3D intervention, and aligning spatial coordinates with other navigation or robotic instruments.

Figure 2 shows “live” or instantaneous scanning in 3D without gating. New materials that allow more bandwidth (simultaneous high and low frequencies) allow these matrix array transducers to obtain both penetration and high-resolution imaging.

3D echocardiography began with chest wall imaging. This allowed beam-forming circuitry to be contained within the handle, because now thousands as opposed to hundreds of electrical connections needed to be made. In 2007, a 3D TEE imaging transducer was made available due to innovations in miniaturizing beam-forming electronics.² Figure 3 shows the tip of a TEE transducer containing electronics that 10 years ago would have been stacked 50 laptops high. Moreover, reduced power consumption allows low enough heat dissipation to make 3D TEE imaging safe for esophageal use by using thousands of elements.

Visualizing and Quantifying 3D Data

To visualize, navigate through, quantify, and assess cardiac structures, data must be generated in a nontraditional way. 2D computer displays consist of rows and blocks of pixels (picture elements) that make a 2D image (Fig 4). A 3D data set consists of “bricks” of pixels called volume elements or “voxels.” Voxels are made from the 3D scanning as seen in Figure 2. Because the computer screen is only 2D, perspective is used to simulate the appearance of 3D depth as an object is virtually “deeper” or farther away from the viewing screen (Fig 5). The 3D data set, i.e., collection of voxels, can be rotated with respect to the computer screen. Moreover, a process known as “cropping” can be used to cut away into the volume and make some voxels invisible; for example, one can cut away the left atrium to see the mitral valve. After rotation and cropping, the remaining voxels are ready to be projected onto pixels in the same way that 3D objects in a room are projected onto the retina in 2D.

A 2D image of the mitral valve is shown in Figure 4. The benefit of visualizing 3D data as seen in Figure 5 is that the exact nature of the leaflet defect can be seen in its dynamic state. Although multiplane TEE is the current “reference” for visualization (for example, the location of a valvular prolapse), the 3D image provides the view a surgeon would see via atriotomy. This makes visualization of fibroelastic and Barlow's disease more definitive and provides more time for surgical planning before the patient's heart is arrested or even before going to the operating room.

Because the anatomy sits within a 3D “cube” of data, 3D numerical measurements become possible. Many pathophysiologic mechanisms of mitral regurgitation need to be explained using 3D spatial relationships.³⁻⁷ For example, this allows computation of atrial exposed 3D leaflet surface area or annular height. Moreover, the height of leaflet prolapse can be displayed parametrically. Most importantly, measurements can be oriented to the heart's true 3D spatial orientation, thus eliminating foreshortening errors that occur regularly if the imaging plane is not oriented correctly (Figs 7 and 8).

This type of visualization should allow more definitive analysis in differentiating fibroelastic disease from Barlow's disease. For example, it would be useful in referring patients with complex Barlow's disease to appropriate centers experienced in complex mitral repair. It also has the potential for increasing the number of repairs over replacements as mitral pathophysiologic conditions become easier to visualize and quantify.

Image-Guided Intervention

Device closure of atrial septal defects is the most common image-guided procedure in practice today. Criteria for mechanical over medical intervention include the presence of symptoms, the size of the defect, and the presence of hemodynamic abnormalities. Device closure is becoming increasingly common, but not all defects are amenable to device therapy, and these are best reserved for open chamber suture or patch repair with a patient on cardiopulmonary bypass.^{8, 9} Therefore, accurate patient selection of device compared with surgical closure is of paramount importance.

Defects with poor rims or inappropriate adjacency to the aortic valve preclude optimal device closure. 3D echo has significant potential to assess rim size because the full nature of the interatrial septum can be appreciated (Fig 9).¹⁰⁻¹³

The following issues come into play when using echocardiography for interventional/surgical navigation:

- 3D echo image volume size (How much do you see?)
- 3D frame rate (Do you actually see instruments moving smoothly in space?)
- 3D resolution (Do you see sufficient detail?)
- Instrument artifacts (What ultrasound artifacts are generated by tools?)
- 3D depth perception (Can you differentiate shallow from deep structures?)
- 3D virtual reality coordinate (Can you couple 3D data to other 3D modalities such as CT or robotic tools?)
- Can x-ray fluoroscopy time be reduced?

As this list indicates, innovations in acoustic beam-forming, display technology, and instrumentation are needed to maintain forward momentum in image-guided cardiac intervention. Newer transducers and materials improve image quality, but volume size and

frame rate need more than first generation beam-formers. Real-time streaming of 3D data to virtual reality stations that coordinate 3D images enhances the ability to do more complex procedures.

3D streaming can be done using gigabit Ethernet connections using TCP/IP; data are transferred at more than 100 Mbytes per second. Additionally, volume-rendering algorithms can color objects “farther away” a different hue than those “closer” to the screen. This feature allows one to assess spatial relationships among tools and structures.

The evolution of these technologies will allow more types of procedures to be undertaken with better certainty. After atrial septal defect repair, the next candidate for interventional procedures is percutaneous aortic valve replacement. It is especially suited for those patients who are at too high risk for open surgery, such as elderly patients with critical aortic stenosis. Accurate assessment of the aortic root and valve and appropriate alignment of the valve during deployment are important factors for success. Although 2D TEE is used in all procedures, trials are underway to assess the benefit of real-time 3D echo in improving interventional performance.

Whereas mitral valvuloplasty is used to treat selected cases of mitral stenosis, repair of regurgitant mitral disease by device therapy is in a way more complex than that of aortic repair because more pathophysiologic mechanisms are at play in creating mitral regurgitation, especially annular dilatation and other causes of leaflet malcoaptation.¹⁴⁻¹⁶ 3D echo has proved useful in delineating the mechanism involved in generating lack of valve competency. (CITE) Interventions include annular reduction, leaflet “re-approximation” or plasty, and chordal repair. Performing these types of repairs requires precise quantification and is especially challenging in a beating heart.

Summary

3D echo has already shown important advantages in quantifying structural valve disease. New technologic improvements in transducers, beam-forming, and computer analysis have allowed the creation of a commercially available, fully functional 3D TEE probe. It has significant potential for surgical and interventional planning, navigation, and assessment. Research is underway in using this technology for visualizing atrial septal defect and aortic and mitral valve pathologic conditions. Most importantly, the nongated, live aspect of imaging allows one to see actual movement of new instruments that permits avoidance of cardiopulmonary bypass.

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Figure 1.

(A) Standard 2D transthoracic echocardiographic image of the left ventricle. (B) This image appears flat because the scanning lines are in a plane. The frame rates of 2D echo are faster than those of 3D.

Figure 2.
3D scan lines for live 3D transesophageal scanning. Note the scan lines provide instantaneous feedback. This critical innovation allows live navigation of tools and devices.

Figure 3. Transthoracic and transesophageal 3D imaging probes: an adult larger transthoracic imaging probe and a smaller pediatric probe in the center and a 3D transesophageal imaging probe.

Figure 4.

Conventional 2D TEE view of the mitral valve. The image demonstrates a posterior leaflet abnormality. Note that the spatial relationship of the defect cannot be appreciated in reference to the whole valve.

Figure 5.
3D echocardiographic image of the mitral valve. Note how the defect in its entirety can be appreciated with regards to the functional leaflet surface.

Figure 6.

Multiplanar reconstruction of a 3D data set. 2D slices can be “pulled” out of a 3D data set (lower right.) This allows any plane to be examined. Although this method is versatile for its 3D “any plane” capability, it lacks the temporal speed of a conventional 2D echo (see Fig 1). This is because more sound waves are fired to scan in 3D.

Figure 7.

3D mitral annular measurement: functional posterior leaflet surface area. The functional (exposed) posterior leaflet surface area is quantified to be 1138 mm². Note that the prolapsed segment is shaded in red.

Figure 8.

3D computer model displaying exposed or functional leaflet surface area in red. Total leaflet surface area includes the coapted area shaded in blue.

Figure 9.

Still frame capture (A) of an Amplatzer as it is being deployed live. (B) The Amplatzer is now in place with good coaptation. 3D is useful in identifying whether one has sufficient “rim” for attachment.