Thoracic and Cardiovascular Surgery

3D Echocardiographic Visualization for Intracardiac Beating Heart Surgery and Intervention

Ivan S. Salgo, MD, MS

Three-dimensional echocardiography has emerged as an essential tool for visualizing cardiac anatomy and for making more accurate measurements of cardiac structure and function. Recently, improvements in 3D beam-forming and transducer technologies have allowed higher resolution imaging from a transesophageal echocardiographic probe. This is creating new avenues for real-time visualization of intracardiac procedures without the need for cardiopulmonary bypass or opening the beating heart. Evolutions in visualization will allow a wider array of reparative procedures to be performed minimally invasively within a beating heart.
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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.

Radiograph 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 3D when not confined inside a narrow lumen. 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 3D, preferably without ionizing radiation. Ultrasound has been the leading modality in imaging cardiac structure and function, particularly of the left ventricle and cardiac valves. However, this modality has traditionally used two-dimensional (2D) imaging planes (Fig. 1).

2D versus 3D Echocardiographic Transducers

Ultrasound has been used for cardiac imaging for more than 50 years. Echocardiography combines portability, safety, low cost, non-ionizing radiation and widespread availability. The most significant advances that have occurred include development of 2D over 1D (spatial) 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).

Cardiovascular Investigations, Ultrasound Research and Development, Philips Healthcare, Andover, Massachusetts.
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Address reprint requests to Ivan S. Salgo, MD, MS, Cardiovascular Investigations, Ultrasound Research and Development, Philips Healthcare, 3000 Minuteman Road, Andover, MA 01810. E-mail: ivan.salgo@philips.com

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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 1,540 m/s in water, 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 triggered to 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 to180 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.

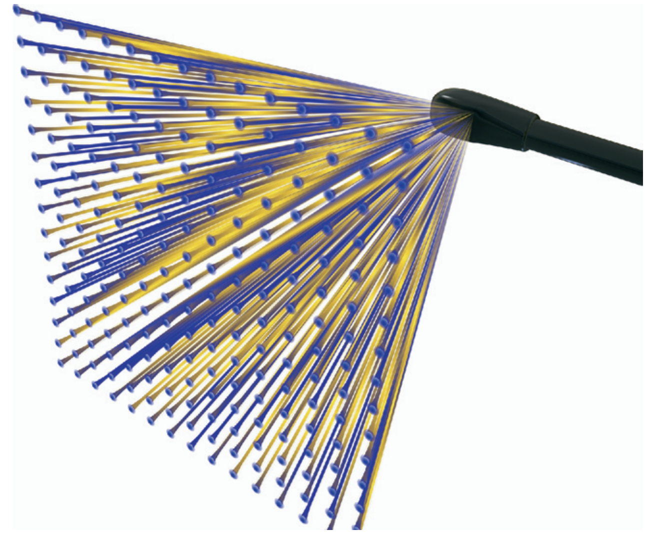

Figure 2 3D scan lines for live 3D transesophageal scanning. Note the scan lines provide instantaneous feedback. This critical innovation allows live navigation of tools and devices. (Image courtesy of Philips Ultrasound.) (Color version of figure is available online at http://www.semthorcardiovascsurg.com.)

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 3D, which poses several technical challenges: creating a transducer array with up to 3,000 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 in 3D and for 3D intervention, aligning spatial coordinates with other navigation or robotic instruments.

Figure 2 shows "live" or instantaneous scanning in 3D without gating. New transducer 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 to the ultrasound system. 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.

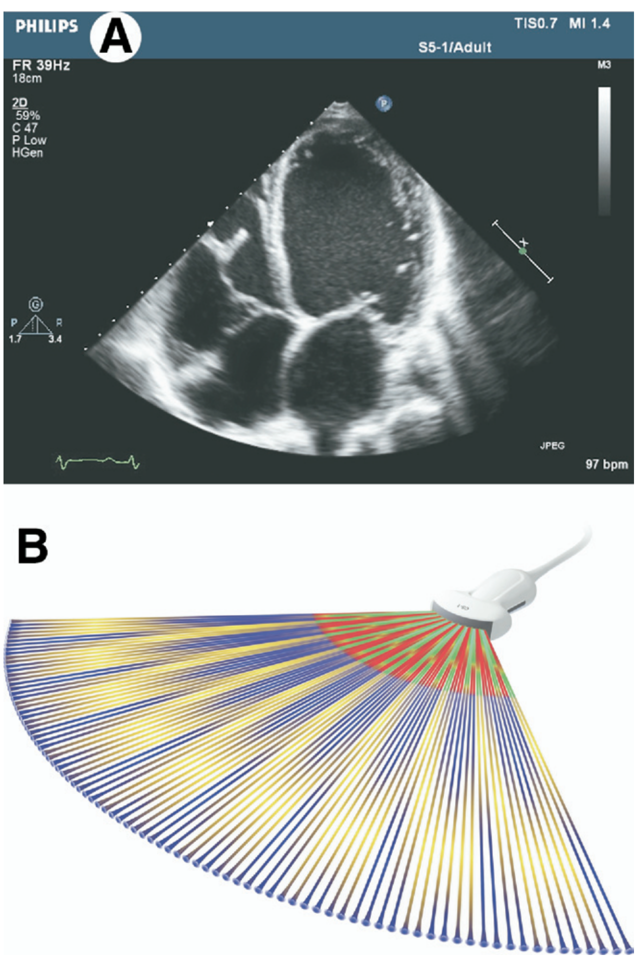

Figure 1 (A) Standard 2D transthoracic echocardiographic image of the left ventricle. (B) This image appears flat because the scanning lines are in a plane. The frame rates of 2D echo are faster than those of 3D. (Color version of figure is available online at http://www.semthorcardiovascsurg.com.)

Visualizing and Quantifying 3D Data

To visualize, navigate through, quantify, and assess cardiac structures, data must be generated in a nontraditional way.