CHAPTER 1

Historical Perspective

The history of echocardiography is a series of successful advancements in the technology to image the heart. This started with A-mode images derived by a thin ultrasound beam and advanced to M-mode displays and then to 2D examination of the heart in motion. This was followed by the addition of Doppler and color Doppler, the recent introduction of tissue Doppler, speckle imaging, contrast echocardiography, and 3D reconstruction, and ultimately the development of real time 3D transesophageal echocardiography (3DTEE) [1–3]. It is, therefore, not surprising that on top of its predecessors, this new technique has proven useful, versatile, and revolutionary in the assessment of cardiovascular diseases. In this book, we will discuss in detail the benefits of this developing technology and its incremental value on top of 2DTTE and/or 2D transesophageal echocardiography (2DTEE).

Although 2DTTE revolutionized noninvasive imaging, its limitations in clinical practice soon became clear. 2DTTE provides real time tomographic images resembling thin slices of cardiac structures that require mental reconstruction of 3D cardiac structures. This has shown clinical value but has been imperfect due to the complex geometrical anatomy of most cardiac structures. Since this imaging modality is noninvasive, does not utilize harmful radiation, and is portable unlike many of its competitors, there has been a great interest in further development of this technology. This led to several attempts to develop 3D echocardiography [4–10]. Morris and Shreve [11] introduced the spark gap position-locating approach (an acoustic spatial locating system) to provide 3D coordinates, but this method could not record or view 3D images. This method was further developed by other investigators to allow for the ability to model organs and calculate volumes [12]. Ghosh et al. [9] developed a simple approach that was able to image the left ventricle (LV) in 3D. This approach used a 2D transducer that was mounted on a mechanical arm that allowed it to rotate around its axis and measured the degrees of rotation. Placement of the transducer in this way ensured that any other form of motion or tilting was not allowed. This transducer could then be placed on the patient’s chest wall at the cardiac apex and rotated every few degrees in a sequential manner to obtain multiple slices of the heart, at end systole and end diastole, which were then computer-reconstructed to obtain 3D images of the LV (Figure 1.1). The volumes obtained using this method were validated by angiography [9]. This work was further extended by Raqueno et al. [13] and Schott et al. [14] to successfully incorporate velocity information and color-coded reconstruction. This allowed 3D imaging of the magnitude of flow disturbance that accompanies valvular regurgitation. Similarly, data on flow patterns obtained by color Doppler could be easily merged with the 3D-reconstructed images of the LV since both datasets were obtained in the same coordinate system (Figure 1.2) [13].

The field of 3D echocardiography was further strengthened by the introduction of TEE with its superior 2D image quality (compared to 2DTEE) due to the close proximity of the probe in the esophagus to the heart, allowing the use of higher frequency and higher resolution transducers, which led to the development of 3DTEE. Investigators used a monoplane TEE probe mounted on a sliding carriage within a casing. Transverse sections
at various parallel cardiac levels were obtained by moving the probe up and down the esophagus in small increments by a computerized system, and the images were then reconstructed to provide 3D images (Figure 1.3) [15,16]. Electrocardiographic and respiratory gating was performed to allow for the spatial and temporal registration of images [15]. The large size of the probe, however, precluded routine clinical use. Attempts were then made to use a regular biplane TEE probe for 3D imaging [17]. A protractor mounted on the bite guard was used to accurately determine the probe rotation angle.

The probe was angulated at 90° and manually rotated in a clockwise direction in small increments to provide sequential longitudinal images, which were then reconstructed in 3D since their spatial orientation and relationship to each other was known. Offline, the endocardial surface and the intima of the great vessels were manually traced to allow the conversion of the images to a digital format which was reconstructed in 3D (Figure 1.4) [17]. Nanda et al. [18] then used a multiplane TEE transducer to reconstruct 3D images by ensuring that the probe remains stationary at a given level and rotating it at 18° intervals at a time (Figure 1.5). Offline, the images were digitized by using a frame grabber and the digitized frames were imported into a 3D modeling program which provided a 3D-reconstructed image of the LV (Figure 1.6) [18]. The superior image quality of TEE images allowed for a much better quality of reconstructed 3D images, and this reignited the interest in 3D echocardiography (Figure 1.7) [19]. Furthermore, the ability to slice the 3D dataset using dissecting planes in any direction allowed for the accurate measurement and the visualization of defects and masses from any direction (Figures 1.8 and 1.9) [20]. The 3D reconstruction of images from multiplane TEE was widely utilized by multiple investigators to provide clinically useful incremental information over 2D imaging and even resulted in the publication of a book with
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Figure 1.3 (a) Probe used for 3D transesophageal echocardiographic (3DTEE) reconstruction. It was mounted on a sliding carriage within a casing (TomTec, Munich, Germany) and interfaced with a computed tomography ultrasound system for data acquisition and 3D reconstruction. (b) A tangential section of a 3D image of the heart during diastole displays open mitral valve and the left ventricle (LV). Portions of the left atrium (LA), right ventricle (RV), and aorta (AO) are also seen. (Reproduced from Pandian et al. [15], with permission.)

Figure 1.4 Regional display of 3D-reconstructed image. (a) 3D image of superior vena cava zone, showing 3D-reconstructed longitudinal structures of superior vena cava (SVC), inferior vena cava (IVC), right atrium (RA), left atrium (LA), and right pulmonary artery (RPA). (b) Stereo-sectional display of the structures shown in Figure 1.3a. (Continued on next page)
Figure 1.4 (Continued) (c) 3D image of ascending aorta zone, displaying the stereo-structure of longitudinal ascending aorta (A) and the aneurysm (AN) of right sinus of Valsalva. (d) Stereo-sectional display of the structures shown in Figure 1.4c. (e) 3D image of the left ventricle (LV), showing its outline. (f) 3D display of a cut-open left ventricle (LV). The arrow points to normal closure of the mitral valve in systole. (g) 3D image of right ventricular outflow tract (RV)-pulmonary artery (PA) zone, showing the longitudinal outline of these structures which are oriented perpendicular to the aortic root (AO). (h) Display of cut-open structures shown in Figure 1.4g (stereo-sectional display). (Reproduced from Li et al. [17], with permission.)
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Figure 1.5 Multiplanar transesophageal probe. (Reproduced from Nanda et al. [18], with permission.)

Figure 1.6 (a–f) 3D reconstruction of the left ventricle (LV) using sequential planes obtained from multiplane transesophageal examination in one of the patients. For 3D reconstruction, all frames were obtained in mid-diastole using the mitral valve motion as the reference. (a) Shows the "rib cage" on the left. (Continued on next page)
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Figure 1.6 (Continued) (f, g) Show the “volume cast” of the left ventricular cavity. A, anterolateral wall; ALPM, anterolateral papillary muscle; I, inferior wall; LW, lateral wall; P, posterior wall; PMDM, posteromedial papillary muscle; S, ventricular septum; T, trabeculation.

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contributions from many investigators around the world [21]. With further development of these techniques and applying them to color Doppler data, 3D imaging of dynamic abnormal intracardiac blood flow was possible (Figure 1.10) [22].

A limitation of this method was the introduction of artifact due to the time needed for the acquisition of images over several cardiac cycles with patient and/or probe motion during the procedure in addition to inevitable changes in heart rate. To obviate this problem, live/real time 3D TTE and subsequently 3DTEE imaging were developed, and remain the mainstay of 3D echocardiography as it is currently practiced in the clinical setting today. Initial attempts at the development of 3D TTE resulted in a standalone system which was able to provide B-mode images only [23]. The advantage of live/real time 3D imaging is that an entire volume of heart is obtained using one cardiac cycle which is a major advancement from the thin slice, sector imaging that 2D provided [24]. A matrix probe was then developed and incorporated into the regular ultrasound system to provide not only B-mode images but also color Doppler live/real time 3D images, therefore facilitating its use in day-to-day clinical practice [25]. Subsequently, the transducer was miniaturized and incorporated in the TEE probe, providing superior quality 3D images [26]. With these advancements, 3D echocardiography evolved from predominantly a research tool in its early development to a modality that is highly valuable and useful in everyday clinical practice.
Figure 1.7 Transesophageal 3D reconstruction of stenotic aortic valve (AV). (a–c) The AV shows multiple echodense areas in both diastole (a) and systole (b, c) indicative of severe thickening and calcification. Although the AV is considerably distorted, three leaflets are easily identified in systole (b, c). The AV orifice is very small and measured 0.7 cm² by planimetry (c). (d, e) Oblique cuts through the data cube of the same patient resulting in incomplete visualization of the AV orifice (arrows in (e)). D, diastolic image; E, systolic image. Transverse cuts (as in a–c) are essential for complete and accurate delineation of the AV orifice. (Continued on next page)
Figure 1.7 (Continued) (f, g) Visualize the AV and the left ventricle (LV) in long axis. Note the markedly restricted opening of the AV in systole (g) and the hypertrophied ventricular septum (VS) seen in both diastole (f) and systole (g). IAS, interatrial septum; LA, left atrium; MV, mitral valve; RA, right atrium; RVO, right ventricular outflow tract. (Reproduced from Nanda et al. [19], with permission.)
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Figure 1.8  (a) Various techniques used to “slice” and obtain 2D sections from 3D-reconstructed images. (b) A 2D image using the paraplane technique. (Reproduced from Nanda et al. [20], with permission.)

Figure 1.9  (a) Large vegetations (arrows) are seen involving the aortic valve (AV) reconstructed in short-axis (left) and long-axis (right) views. (b) A large vegetation (left, arrow) is noted on the AV together with an abscess cavity (right, arrow) involving the mitral-aortic intervalvular fibrosa. (Continued on next page)
Figure 1.9 (Continued) (c–e) “Peeling off of layers” of the aortic root and valve to delineate more clearly AV vegetations (arrows). In (c), both diastolic (left) and systolic (right) frames are shown. AO, aorta; AML, anterior mitral leaflet; LA, left atrium; LVO, left ventricular outflow tract; RA, right atrium; RVO, right ventricular outflow tract. (Reproduced from Nanda et al. [20], with permission.)
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Figure 1.10 Dynamic 3D images of intracardiac shunt. (a) Shunt jet (arrow) from the left atrium (LA) to the right atrium (RA) and then through the tricuspid valve into the right ventricle (RV) in atrial septal defect. (b) Cross-sectional view of shunt jet (arrow) from the RA in the same patient, as shown in (a). (c) Shunt jet (arrow) from the left ventricle (LV) to RV in another patient with a ventricular septal defect. (d) Cross-sectional view of shunt jet (arrow) from the RV in the same patient shown in (c). AO, aorta. (Reproduced from Li et al. [22], with permission.)

References


