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Three-Dimensional Echocardiography - Principles and Promises

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Three-Dimensional Echocardiography – Principles and Promises

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Three-dimensional echocardiography facilitates spatial recognition of intracardiac structures, potentially enhancing diagnostic confidence of conventional echocardiography. In addition, 3D-echocardiography allows exact computation of cardiac volumes and could serve as a teaching tool in cardiology. Over the last decade, significant developments in 3D-echocardiography have been made. Refinements in instrumentation, data acquisition, post processing and computation speed together with improvements in 2D-image quality could now allow three-dimensional echocardiography to play an important role in clinical echocardiography. This review focuses on the methodology, current status, potential clinical applications and future direction of 3D-echocardiography. *J Clin Basic Cardiol 2002; 5: 149–52.*

Key words: echocardiography, 3-dimensional, real time 3D-echocardiography

The interpretation of echocardiographic images requires a complex mental integration of multiple image planes for a true understanding of anatomic and pathologic structures.

The representation of images in a 3-dimensional format more closely resembles reality and could therefore enhance image interpretation. In addition, 3-dimensional imaging allows direct calculation of volumes and is, thus, more accurate than current models relying on geometric assumptions.

First attempts to incorporate multiple views to form a 3-dimensional image were made in the seventies. But, because of technical limitations (eg lack of processing power, relatively poor image quality, difficulties in image plane alignment) this technique was limited to an experimental setting.

The advent of transoesophageal echocardiography together with newer imaging probes and enhanced image processing capabilities have now led to a remarkable progress in the field of 3-dimensional imaging.

Numerous applications of three-dimensional echocardiography (3D-echo) have been proposed. For example, improvements in image interpretation with 3D-echo could be of value in the decision making and planning of cardiac surgery, and in the diagnosis of complex cardiac lesions [1]. In addition, 3-dimensional imaging allows quantitative parameters such as valve areas, the size of defects (atrial septal defect, ventricular septal defect) or volumes to be obtained [2, 3]. With new developments that allow system integration of 3D-scanning, rapid or even near real time 3D-reconstruction and measurements, 3D-echo is now on the verge of becoming an integral part of an echo examination.

Principles of 3D-Echocardiography

Data Acquisition

Three-dimensional echocardiography requires the collection of a volumetric data set where each image (cut plane) is defined with respect to its exact position in space [4]. Most systems currently rely on sequential collection of image planes. With this technique it is necessary to use ECG and respiratory triggering or breath hold acquisition to account for motion artifacts caused by respiration and to permit alignment of the images in the time domain.

Newer developments use a transthoracic probe technology with volumetric scanning capabilities, which allows simultaneous acquisition of an entire 3D-data set. As a result, data acquisition is less time consuming and less susceptible to artifacts [5]. 3D-reconstructions have also been applied to the color Doppler information allowing a three dimensional representation of jets superimposed on the 3D-grayscale image.

Image acquisition can be performed from both a transthoracic and a transoesophageal approach (TEE).

Transthoracic 3D-Echo

Three-dimensional transthoracic imaging can be performed with mechanical steering devices, which are attached to standard transducers. These devices steer the transducer motion causing incremental changes in the scan plane either by rotating, shifting or fanning the probe. In addition, various locating systems (ie, acoustic or electromagnetic) have been used effectively. The advantage of this technique is that freely definable image planes can be chosen allowing for more flexibility.

Others have proposed a rapid (6 seconds) acquisition technique that collects apical tomograms (within 6 sec) using an internal continuously rotating transthoracic transducer [6].

Volumetric real-time echocardiography is a recently developed technique based on the design of an ultrasound transducer with a matrix array that instantaneously acquires the image contained in a pyramidal volume. Volumetric real-time echocardiography is a novel imaging concept, which holds promise as a "break-through" technology for 3D-echo. Employing a matrix array echo probe this technique allows instant (real-time) acquisition of a complete 3-dimensional-data set without complex post-processing. Several studies have already demonstrated the validity of real-time volumetric echocardiography for the calculation of cardiac volumes [5]. In addition, real-time volumetric echocardiography allows the reconstruction of freely definable 2D-image planes from a single volume set independently of the acquisition window.

Transoesophageal 3D-Echo

First attempts to acquire a 3-dimensional data set from the oesophagus were made with a specially designed probe (echo-CT, lobster tail probe, Tom Tec). This probe was capable of acquiring parallel data sets by passing a transducer along the oesophagus [7]. Newer technologies, however, use multiplane TEE probes that acquire sequential images at different transducer rotation points (0–180°). 3D-echocardio-

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graphy can, thus, be performed as an adjunct to a routine TEE simply by mounting the steering device onto the TEE probe.

Data Post-Processing and Representation

Post-processing of the data for sequentially acquired images is performed off-line using dedicated software. Varying amounts of user interaction are required to define the region of interest, view, cut plane, rendering algorithm, filter, magnification and thresholds. The systems provide a variety of 3D-tools for advanced image processing. Multiplanar, 3D-reconstructions (volume rendering) as well as wire frame (surface rendering) display formats can be chosen and measurements (distance, area, angle, volume) can be performed. Recent advances in computing capabilities such as parallel processing have greatly reduced the time necessary for data manipulation. Three-dimensional reconstruction can now be achieved within seconds and viewed from different angels in a dynamic format. It is even possible to "electronically" dissect the heart to visualize otherwise concealed structures.

Volumetric scanning allows instantaneous (real-time) display of multiple views (multiplanar) using a split screen. In addition, prototype systems have demonstrated the feasibility of near real-time 3D-reconstruction, which permits almost simultaneous display of 3D-images during the examination.

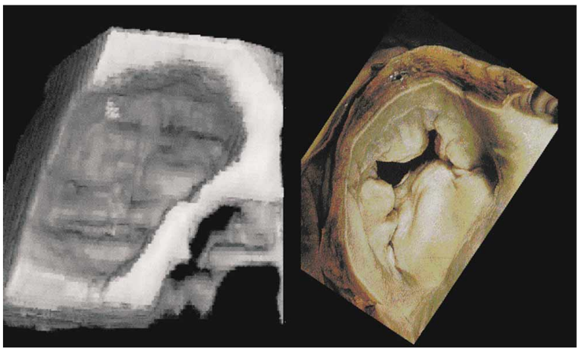

Figure 1. Three-dimensional reconstruction of the mitral valve (left) as seen from the left atrium. An anatomical specimen for comparison is shown on the right.

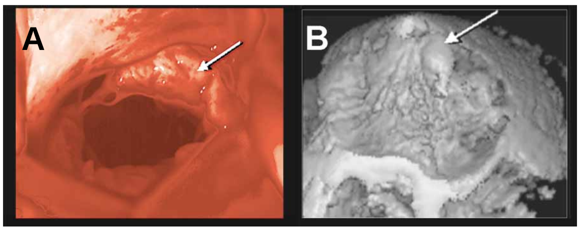

Figure 2. Patient with a partial flail leaflet as seen during mitral valve repair. 3D-Echo is able to demonstrate the location and morphology on the defect (arrow).

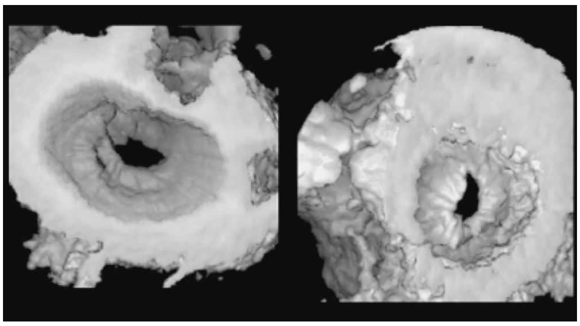

Figure 3. Three-dimensional reconstruction of a patient with mitral stenosis, morphologic features such as doming of the anterior leaflet and commissural fusion can be noticed. In addition, quantification of mitral valve area can be performed.

Potential Applications of 3D-Echocardiography

The potential applications of 3D-echo can be categorized into 3 major areas: (1) Interpretation of morphology and pathology, (2) Quantification of volumes and function, (3) 3D-echocardiography as a teaching tool.

Interpretation of Morphology and Pathology

The clinical potential of 3D-echocardiography has been thoroughly explored. Our own experience and that of others have clearly demonstrated that the anatomy (Figure 1) and pathology of the heart and the great vessels can often be displayed [8, 9] in a more comprehensive format. Even fairly small structures such as coronary arteries, a paravalvular leak or small masses and vegetations can be visualized [7, 10].

Our findings also show that this technique can be applied in numerous settings. For example, in valvular heart disease (Figure 2), to determine the size of infectious vegetations, to determine the mitral valve area in mitral stenosis (Figure 3), for complex congenital malformations, or aortic dissection (Figure 4). Furthermore, it has also been shown that jets can be reconstructed from color Doppler information to assist in the quantification of valvular lesions [11].

Quantification of Ventricular Volumes and Function

3D-echo has been applied to derive quantitative measurements of volume, mass and dimensions of the left and right ventricles and also other cardiac lesions, such as atrial and ventricular septal defects [12]. While quantification of ventricular volumes with two-dimensional imaging requires geometric assumptions, measurement obtained with 3D-echo represents true volumes. Several studies have shown 3D-echo to be superior to 2D-echocardiography for both left and right ventricular volumes [13]. The process

Figure 4. Dissection of the descending aorta. The true lumen is separated from the false lumen by an intima flap.

requires acquisition of a 3-dimensional data set and manual endocardial contour tracing. Several calculations including volumes (throughout the cardiac cycle), global and regional ejection fractions can be computed (Figure 5). The endocardial surface of the ventricular cavity can be displayed from multiple angles in a dynamic mode. Since the process of manual endocardial border tracing is still time-consuming, semi-automated contour detection algorithms are now being developed. In addition, there is experimental evidence that contrast opacification of the left ventricle could further enhance the applicability of 3D-volume computation [14]. The advent of real time volumetric scanning will certainly enhance the applicability of 3D-volume computation [15].

3D-Echocardiography as Teaching and Research Tool
Spatial representation of cardiac structures greatly enhances the understanding of cardiac function and pathology. Thus, three-dimensional images could assist in the teaching of echocardiography where a significant amount of spatial understanding is required. An example of such an application is a system which couples 3D-echo with a virtual reality heart model [16]. The system allows standardized echocardiographic views to be selected on the virtual heart and displayed from the 3D-dataset to provide a correlation between anatomy of the heart and echocardiographic image planes.

Limitations

However, despite the potential of 3D-echo to visualize cardiac structures and perform volume computations this technique has not gained wide spread acceptance to date. This might be related to several factors: (1) 3D can only visualize what is also seen on the two dimensional image, thus, an experienced echocardiographer will obtain similar information from a conventional examination without the need for costly instrumentation and long post-processing times, (2) operator experience with the reconstruction and interpretation of 3D-images is necessary, (3) 3D-image quality greatly depends on the quality of the two-dimensional image and the ability to obtain a motion and artifact free 3D-data set, (4) three-dimensional imaging only creates a "virtual sense of depth" on a flat (2-dimensional) screen. And finally, manual endocardial contour tracing is still required to obtain 3D-volumes.

Some of these limitations will certainly be overcome with newer techniques and growing experience with 3D-echo.

The Future of 3D-Echo

With the rapid advances in digital image processing 3D-imaging is probably just at the beginning of its evolution with a number of innovations already approaching. The integration of 3D-systems into conventional scanners and operator friendly applications will reduce the time and effort required to obtain 3D-images. Improvements in 2-dimensional imaging and 3-dimensional reconstruction software will lead to enhanced image quality. Novel ways of image representation such as stereoscopy, holography or the generation of physical 3D-models (Figure 6) could enhance our perception of cardiac structures [17, 18].

Further advances in real-time 3-dimensional imaging and the advent of real-time 3D-color Doppler will generate 3-dimensional images directly on the screen during the investigation, making the technique as simple as using Doppler or M-mode features [19]. And, finally, other echocardiographic modalities such as contrast echocardiography, tissue Doppler imaging or intracardiac ultrasound could benefit from a 3-dimensional display format [20].

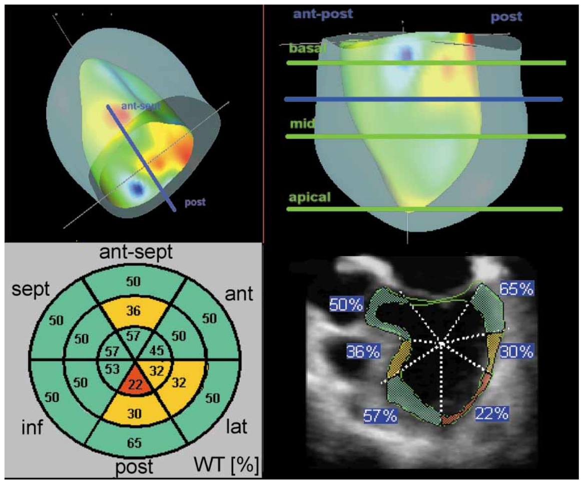

Figure 5. Three-dimensional analysis of left ventricular function allows computation of global and regional ejection fraction (bottom) and the three-dimensional display of the ventricle (top panel).

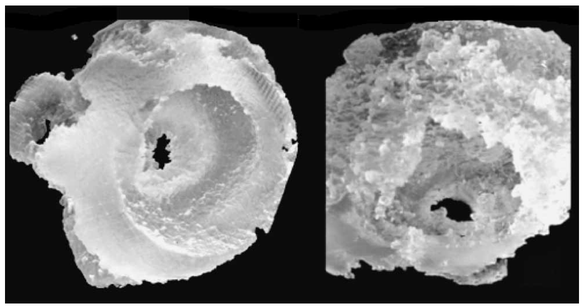

Figure 6. Model of the mitral valve (in a patient with mitral stenosis) created from a 3-dimensional dataset using stereolithography.

Some of these developments could soon become available while others are still experimental. Despite present limitations 3-dimensional imaging could soon be considered as a milestone in echocardiography along with M-mode, 2-dimensional imaging or Doppler techniques.

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