Three Dimensional Echocardiography*

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Conventional ultrasound images are two-dimensional (2 D). Therefore, multiple images have to be integrated in the observer's mind to develop a three-dimensional (3 D) image. This is time consuming and under certain circunstances can lead to misdiagnoses and increased operator variability. The patient's anatomy or orientation can sometimes restrict the image angle, making it impossible to obtain the optimal image plane for diagnosis. To overcome these limitations, recent advances in computer technology, digital image acquisition, and ultrasonic imaging have made possible 3 D reconstruction of the heart from conventional 2 D images.

It should be possible to view, manipulate and "slice" the 3 D image interactively to provide distinct 2 D planes, oriented in any direction. It is important that the 2 D planes obtained from the 3 D volume be similar in appearance to those obtained in a standard 2 D exam. It is also important that "slicing" of the 3 D images occurs rapidly and that the data acquisition and reconstruction time are short. The data acquisition time must be short because of voluntary and involuntary patient motion.

Despite the shortened duration of scanning, clinicians can spend unlimited time reviewing the images. This image evaluation can be done at any time and cases be discussed with colleagues long after the patient has left. Because the images are digital, they can be transferred by the usual methods of digital data transfer - diskettes, phone line and computer networks - allowing remote consultations and discussions, resulting in the telemedical communication. 3 D imaging should be more useful in tele-consultations than 2 D since we can collect data from a larger region and from selected portions of the image to verify a certain diagnosis. This provides a more flexible remote exploration of the images and understanding of the picture.

3 D echocardiography may allow for quantitative monitoring of disease progression and response to therapy, thus providing greater insight into the nature and extent of cardiac diseases. The potential *clinical benefits* of 3 D are: *(1)* better delineation of pathology through visualisation of any desired imaging plane; *(2)* accurate quantification of chamber volumes, function and geometry; *(3)* improved reproducibility for follow up studies; *(4)* better description of complex anatomy by dynamic 3 D display and *(5)* more comprehensive surgical planning.

TECHNICAL PRINCIPLES

There are several essential steps to be followed to successfully create a three-dimensional reconstruction of the heart. The basic requirements for 3 D reconstruction are :

(1) Acquisition - sequential rotational cardiac cross sections with spatial and temporal information .
(2) Processing - resampling and conversion from polar to Cartesian coordinates.
(3) Interpolation - filling the space between individual cross sections.
(4) Enhancement - noise suppression .
(5) Display - anyplane echocardiography; volume rendered images.

Since blood flow is pulsatile, the acquisition of the image slices is gated to the ECG and respiration. After acquisition of the gated sequence of images, a 3 D image is processed, reconstructed and made available for interactive manipulation and display. The 3 D imaging systems are based on the acquisition of a sequence of 2 D images using motorised transducer scanners. The imaging plane is rotated around its central axis by a computer controlled system.

To scan the patient, the operator moves the hand-held transducer while the remote localizer monitors its position and orientation and transfers this information immediately to a computer. The operator has to find the centre axis around which the imaging plane is rotated to include the structure of interest in the centre of the sector during the whole rotation. Since the spatial coordinate system changes with transducer movement, the operator must be able to keep the transducer stationary during the procedure. Furthermore, movement of the patient during the image acquisition must be prevented by explaining the procedure before the study. At the same time, the 2 D ultrasound images are digitised by the computer and associated with the appropriate position and orientation coordinates.

Different displays from 3 D data sets can be produced: (1) a two dimensional display from individual selected cut planes (*anyplane echocardiography*); or from parallel short axis cuts; (2) *a volume rendered technique*: from any defined cut plane, different algorithms are applied to represent the information in space. For volume rendered display, a threshold value is used to define which structures should be taken into account for 3 D reconstructions. Brightness and opacity are used to give the perception of depth.

CLINICAL APPLICATIONS

Currently, three-dimensional echocardiographic reconstruction software is not routinely used in daily practice. The measurement and serial follow - up of *left ventricular volumes* [3-5] provides important prognostic information in patients with a wide variety of cardiac disorders. Traditionally, left ventricular chamber volume is calculated from single plane or biplane two-dimensional images with the use of complex mathematical equations that require several geometrical assumptions and include a tedious process to outline the left ventricular (LV) endocardial borders. The ability to reconstruct the ventricle in all its dimensions and slice it three-dimensionally could aid in measuring left ventricular volume and ejection fraction accurately, particularly in ventricles with distorted shape, such as in aneurismatical LV. In *left ventricular aneurysm,* for example, although the 2 D echocardiography can detect or exclude it, with a high level of sensitivity and specificity, the current echocardiography methods of left ventricular volume are most limited by heterogeneous geometry and also fail to provide separate volumes of the aneurysm and nonaneurysmal residual left ventricular cavity. 3 D echocardiography has potential advantages for assessing aneurysmal left ventricular, because it’s not dependent on geometric assumptions, doesn’t require standardised imaging planes, can provide a better appreciation of the morphologic and functional mechanisms and measure separate aneurysm and nonaneurysm cavity volumes of any shape.

In *valvular heart disease,* the abnormalities can be delineated more precisely and in greater detail than conventional imaging. The mitral leaflets, comissural fusion and the severity of stenosis can be discerned clearly. Detailed definition of mitral apparatus in mitral stenosis, regurgitation and in endocarditis can aid in deciding when and how to intervene [6].The major advantage of 3D volume rendered echocardiography is in the evaluation of the pathologic mitral valve, by the presence of dilated left atrium in these patients, which provides an optimal acoustic window. Because the left atrium is visualised so well with transesophageal approach, 3 D reconstruction gives an excellent view of the stenotic mitral valve from above. The domed leaflets are appreciated in severe stenosis.

Fig 1. Mitral valve seen from the left atrium, with the mitral orifice open in diastole in the centre of the picture.

Mitral valve prolapse is a disease in which 3 D reconstruction may provide information not obtainable otherwise. The major feature relies on the visualisation of both leaflets from the left atrial view.

Fig. 2 Mitral valve prolapse.

Complex *congenital heart disease* are a group of lesions where 3 D reconstruction will enhance the maximal morphologic information for the cardiac structures [7,8]. Reconstruction of double outlet right ventricle, left-sided obstructive and regurgitant lesions and subaortic obstructive cases have been performed. The mitral valve, aortoseptal continuity and atrial septum are the structures that provide more details. *Atrial and ventricular* septal defects can be visualised en face from either side of the atrial and ventricular septum, displaying size, geometry and relationships to other structures. Although many of the distances measured can potentially be obtained from 2 D images, the 3 D technique has advantage to measurement the distance from an outlet defect to the apex.

Fig. 3 Atrial septal defect seen from the right atrium.

Besides anatomic abnormalities, another expression of cardiac disorders is *blood flow* disturbances [9]. Visualisation of flows in 3 D dimensions could allow for a better qualitative and quantitative assessment of their size and severity. Some efforts have been made to reconstruct flow jets by manually digitising color Doppler flow borders. More recently, several groups have generated 3 d flow images by combining Doppler velocity information with reconstructive techniques. The pictures generated allow a good perception of the size and shape of mitral, aortic and tricuspid regurgitation jets, by examining them from a new perspective. The 3 D echocardiography of flow jets also has the potential to display the flow convergence zone and for quantification of regurgitant volume.

The major limitation of transthoracic 3D data acquisition is often the poor standard of grey-scale image quality available for reconstruction. In contrast Doppler myocardium imaging is relatively independent of the amplitude of the ultrasonic signal returning from the interrogated myocardium and is less affected by the attenuating effect of the chest wall and the Doppler myocardium imaging algorithm is a powerful boundary detection technique, and hence potentially is able to provide a more complete data set for 3D reconstruction than that obtained by grey scale imaging [10,11].

FUTURE DIRECTIONS

Recent studies have clearly demonstrated the feasibility of performing three-dimensional imaging in a variety of cardiac diseases, but continued development of ultrasound technology must be necessary to improve better image resolution. The prolonged acquisition time is the most important limiting factor that currently restricts the routine use of 3 D echocardiography. Development of faster computers will shorten the time needed for image acquisition, postprocessing, and data analysis, contributing to the goal of easy access and widely use, including on line imaging. With improvements in computer technology and production of interactive software, 3 D echocardiography will provide a dynamic view of the surgical anatomy of the hear [12]. The concept of electronic dissection will be used to facilitate surgical planning and the ability to section a displayed object in any plane, will provide a *surgeons'view* of the cardiac anatomy. Thus, three- dimensional reconstruction concept has the potential to aid in every facet of diagnostic assessment of cardiac pathology.

In brief, we can summarise the current concepts on 3D on the following:

1. The full representation of tissue grey levels with volume rendered display together with the perception of depth is particularly helpful in assessing the real anatomy of a given structure. It gives a better understanding of complex morphologies which are for example very common in congenital heart diseases.
2. Both precordial and transesophageal images are acquired without any standardisation, so far.
3. The possibility to select a multitude of cut planes from the data set (anyplane echocardiography) is undoubtedly one of the major advances of 3D echocardiography. However there are no standardisation yet for an optimal interrogation of the affected structure in a given pathology. Considering the time requested for the volume rendered display after the selection of a single cut-plane, it could be of great help and time saving to reduce potential views to a reasonable set of predefined (standardised) cut-planes. This would decrease the time needed for reconstruction and facilitate the communication between cardiologists or between cardiologist and surgeon. This will probably enhance the additional diagnostic value of the method.
4. The selection of appropriate 3D views is time consuming since currently there is no spatial guidance. This is even more problematic in congenital heart diseases.
5. In case of hemodynamic functionality the 3D images allow more accurate volume measurements. Therefore more accurate Ejection Fraction (EF) can be calculated compared to 2D imaging techniques. Colour Doppler flow is also considered as a desirable element of 3D US but not yet available.
6. The introduction of myocardial imaging techniques in the 3D world will certainly add significant improvements in accuracy and image quality for morphology and function.

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