Real-time three-dimensional echocardiography: technology and clinical application

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Several studies reported during recent years showed some new possible advantages of the three-dimensional echocardiography in daily practice. Real-time three-dimensional echocardiography (RT3DE) is the only on-line 3D method based on real time volumetric scanning, as compared with other 3D imaging techniques such as computed tomography and magnetic resonance imaging, which are based on post-acquisition reconstruction and not on volumetric scanning. The aim of this study is to give a brief review of the development of the technology of RT3DE and its clinical application.

Key words: Real-time three-dimensional echocardiography; LIVE three-dimensional echocardiography; new technologies

Introduction

Conventional two-dimensional echocardiography (2DE) can evaluate cardiac structure and function, providing cross-sectional views of the heart. Then the examination requires mental conceptualization of a series of multiple orthogonal planar or tomographic images into an imaginary multidimensional reconstruction, so 2DE seems rather subjective. Furthermore, the mental reconstruction is often difficult and inadequate to provide an appropriate diagnosis and understand complex cardiac structures and their spatial relation with neighbouring structures, above all, in congenital heart diseases. In order to overcome limitations of 2DE, many investigators have studied several methods to depict the cardiac structures in three dimensions since the early 1970s. The aim of this study was to provide a brief review of the development of the technology of real-time three-dimensional echocardiography and its clinical application.

The evolution of three-dimensional technology

Historically, the first step in three-dimensional imaging of heart was made by Dekker et al in 1974[1], who used a mechanical articulated arm scanner to do freehand transthoracic scanning. It marked the birth of static surface rendering, the earliest three-dimensional echocardiographic technique. Since the late 1980s to early 1990s marked the introduction of static three-dimensional echocardiography with the use of a transesophageal transducer to obtain wire-frame greyscale stereoscopic images of the heart for identification of cardiac structures and spatial orientation which it could only display the instant frame of the cardiac cycle. In 1993, Pandian and Roelandt introduced dynamic three-dimensional echocardiography with a multiplane transesophageal transducer[2-6].

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The data acquisition of three-dimensional reconstruction, random or sequential, can be done by either the transthoracic or the transesophageal approach. Positional information can be obtained with a mechanical articulated arm scanner, acoustic spark gap or a magnetic location system. The volumetric data set can be used to extract static wire-frame objects or surfaces of selected structures, which are converted into geometric rather than anatomic representations for projection into two-dimensional screen. By sequential data acquisition, any ultrasound acoustic window can be used providing large sequence of images with predetermined movement of the transducer. Sequential transducer motion can be linear[7], fan-like[8], or rotational manner[9-12]. The most commonly used method by now is the rotational approach. Its relative freedom from environmental effects, the fixed image orientation, and the excellent three-dimensional reconstruction performance not only provide dynamic ventricular display but also resemble closely the true anatomy of the heart. It needs relatively smaller acoustic window compared to the above mentioned two methods.

Although dynamic three-dimensional echocardiography could provide much more information than static three-dimensional echocardiography, it is still based on reconstruction algorithms and is therefore dependent on high-quality two-dimensional data, which have been limited by problems such as speckle, grating lobe, clutter and other artefacts. Routine clinical use of dynamic three-dimensional echocardiography has also been hindered because image processing not only is time-consuming but also requires dedicated manpower to generate three-dimensional reconstructions and useful quantitative data.

Real-time three-dimensional ehocardiography

In 1990s, real-time three-dimensional imaging was developed by group of von Ramm at Duke University[13-14]. It was initially performed using a sparse array matrix transducer (2.5 or 3.5 MHz), which consisted of 256 non-simultaneously firing elements. This transducer can acquire a pyramidal volume data set measuring 60°x60° within a single heart beat. Echocardiographic images can then be displayed “on line” using simultaneous orthogonal (B scan images) as well as 2-3 parallel short axis planes (C scan). These images were of relatively poor quality, low frame rates, with pyramidal volume having a relatively narrow sector angle of 60°, which resulted in the inability to accommodate larger ventricles. Moreover, the images obtained by this system were not volume rendered on-line but consisted of computer generated 2D cut planes derived from the 3D volume dataset.

In 2002, a brand-new RT3DE (SONOS 7500) with a full matrix array transducer (X4) was developed and commercially manufactured by Philips Corporation[15]. This system allows simultaneous visualization of the beating heart and provides excellent image quality. A number of significant technological advances, both in transducer design, microelectronic techniques, and hardware and software computing, have allowed for this development to occur. The most commonly used transducer at present consists of more than 3600 (60x60) to 6400 (80x80) elements with operating frequencies ranging between 2 and 4 MHz[15-18]. The matrix transducer generates ultrasonic beams in a phased array manner. Although the probe is maintained in a stable orientation, the emitted ultrasonic beam can steer automatically in multiple directions under control of the computer.

To overcome the technical bottleneck of inadequate scanning speed, the staff of Duke University and Philips Corporation developed a new microelectronic pulse transmitting-receiving technique, which was characterized by 16:1 parallel processing to scan a pyramidal volume instead of the usual 1:1[15, 16, 19]. This technology allowed many ultrasonic scanning beams emitted simultaneously. As the pulse repetition frequency increases greatly, the interval of the pulses rises15 times with 16:1 parallel processing, which also increases the depth of ultrasound transmission through body tissue.

The RT3DE systems provide several methods of data acquisition [20] as follows:

1.Narrow-angled display

Narrow angle acquisition consists of 60°x 30° pyramidal volumes displayed in a volume-rendered manner in real-time. The advantages of this display method include 1) lack of need for respiratory gating which avoids motion artefacts and temporal discordance issue, thus obtaining the images rapidly and clearly, 2) Observing the real-time three-dimensional image in frontal, lateral, superior, or inferior aspects by rotating the track ball, 3) placing the long axis of a valve orifice or septum along the y-axis (60° edition) which facilitates visualization of the full shape of the valve orifice from both atrial and ventricular sides or of a septal defect from both the left and right sides, and 4) Obtaining a bird's-eye view of the orifice or defect by adjusting the imaging angle. One limitation of narrow-angled imaging is the inability to cover a wide region.

In this real-time mode with Philips SONOS 7500, the pyramidal volume is fixed to 60° x 30° , which can not be manually adjusted. The recently introduced GE VIVID 7 Dimension also provides the real-time three-dimensional imaging, in which the real-time pyramidal volume is 60°x 60°. Moreover, the width and depth of the volume is adjustable, from 90°x15° to 15° x 90°.

This mode allows a magnified view of a subsection of the narrow-angle volume (30°x30° sector in high resolution), which has great value in diagnosing valvular disease.

2.Wide-angled display

The wide-angle displays have an imaging angle of 60° along both y-axis and z-axis and is also called "pyramidal imaging". The pyramidal is not formed by a single, wide-angled scan, but by 4 separate, narrower angled scans (15°x60°), which are combined to produce a 60° x 60° "pyramidal image". One full volume acquisition usually takes 7 cardiac cycles in 5 to 8 seconds. In addition if the patient can hold the breath for this period, respiratory motion artefacts between the 4 subvolumes will be small or even negligible. The advantage of full volume acquisition lies in wider coverage of the region interest. Consequently, anatomic continuity becomes less interrupted than in narrow-angled scans. Furthermore, this modality facilitates the measurement of stroke volume and myocardial mass, the detection of many complex abnormalities, and the assessment of myocardial wall movement and contrast-enhanced myocardial perfusion. The main limitation of wide-angled display is its vulnerability to motion artefacts. As the acquisition takes several cardiac cycles and only ECG gating is so far implemented, motion artefacts, may result from respiration, significant irregularity in cardiac rhythm, and transducer movement within the acquisition period.

3.Color Doppler flow display

Three-dimensional color Doppler flow imaging is the most recent advance in RT3DE. Similar to wide-angled display, in this mode, data are acquired in 7 consecutive or inconsecutive cycles with a resultant narrow pyramidal wedge. These 7 images are combined to produce a 30°x30° “pyramidal wedge”. In this mode, the location, phase, direction, length, width, area, course, and severity of stenotic, regurgitant, or shunt flows can be displayed. The added color flow information can be used to qualitatively visualize the size, shape, and position of valvular or paravalvular lesions and septal defects. Quantitative analysis of regurgitant volumes and effective regurgitant orifice area is available. As to the septal defects, color Doppler flow imaging enables better understanding of the shape of the lesion and its dynamic changes during each cardiac cycle. This information, coupled with simultaneous anatomic visualization of the defect from different views, allows the measurement of the effective orifice shunt area and its hemodynamic implications. One major limitation is that the 30° three-dimensional volume angle is unable to cover a wide region, and occasionally, the wide regurgitant jet may not be fully displayed. Another limitation is that the velocity represented by the current three-dimesnional color Doppler is an average projection velocity, which is different from the velocity in conventional two-dimensional color Doppler.

Clinical application

Because RT3DE can display in real time the stereoscopic views and motions of deeper cardiac structures, which are unavailable by 2DE, it is capable of providing much more useful diagnostic information[16, 18, 19]. Compared with dynamic three-dimensional echocardiography, the main advantages of RT3ED is the elimination of the artefacts occurring during the reconstruction of 2D images and also the avoidance of the time-consuming postprocessing procedures. Moreover, the good quality of RT3DE images can satisfy the need of clinical diagnosis.

Normal heart

RT3DE could show in real time the whole structures and motions of atrial and ventricular walls, which are deeper than could be depicted clearly on 2DE views (Fig. 1). In these views, the morphology of muscular trabecula, location of papillary muscles (Fig. 2), and spatial relations of various other structures could be observed very clearly. In RT3DE, full views of the left surfaces of interatrial and interventricular septa in the left parasternal long-axis approach might be obtained (Fig. 1).

The full volume mode can be cropped using the elevational plane from the apex (Fig. 3), so we can display the whole views of interatrial and interventricular septa and their relations with neighbouring structures. Stereoscopic views of tricuspid and mitral valve apparatus, composed of atrial and ventricular walls, valve anulus, valve leaflets, chordae tendineae, and papillary muscles can be obtained by RT3DE. Surgical and “en face” views of the mitral and tricuspid valve from the atrial and ventricular view can be easily performed (Fig. 4-6). The two atrioventricular valves are easily displayed from the full volume acquisitions in the atrial surgical view. The tricuspid valve is displayed with a complete definition of the three cusps by means of images that do not correspond with those obtained at 2DE (Fig. 5).

Mitral valve disease

Comparing this new method with previously accepted standards such as 2DE, RT3DE has overcome most of the limitations as it measures actual anatomical valve area in an ideal short axis plane, and is independent of hemodynamic variables. In fact, by using the oblique plane on the 3D acquired data set, we can correctly assess the plane of the opening of the valve and by cropping the image in that particular plane at a level, and can get the smallest opening area of the leaflets and actual mitral valve orifice area. In MV stenosis, visualization of the actual stenotic orifice could be accomplished from either the left ventricular or the left atrial side. Severity of stenosis, position and degree of leaflet fusion and thickening, as well as the fused and thickened chordae tendineae could be all visualized clearly on RT3DE. The stereoscopic views and motions of anterior mitral leaflets with doming could be vividly displayed in the left parasternal long-axis view in some cases. MV prolapse is often under-or over-estimated using 2DE because of its non-planar leaflet-annular relations. In these patients, the degree of prolapse, stereoscopic views, and spatial relations of anterior and posterior mitral leaflets in systolic closure could be observed in the left parasternal long-axis view much more clearly on RT3DE than on conventional 2DE. In the bird's-eye view of the MV from the LA or LV side, RT3DE could also provide more accurate images, showing the location, range, and changes of phases in cardiac cycles of the prolapsing leaflet. That the mitral anulus in MV prolapse is significantly enlarged when compared with normal controls can now be clearly demonstrated on RT3DE[21]. An excellent correspondence between the echographic localization of the prolapse and surgical inspection, and between the volume of prolapsing and surgically resected tissue can be also demonstrated[22]. In percutaneous balloon mitral valvuloplasty, which is the procedure of choice for treatment of mitral stenosis [23], RT3DE is an accurate technique for measuring MV area compared with 2DE or Doppler pressure half-time method[24]. Zamorano et al have demonstrated that RT3DE was in best agreement with the invasively determined MV area, particularly in the immediate post-balloon valvuloplasty period [25]. In the catheter-based percutaneous repair for mitral regurgitation, either by coronary sinus-based mitral annuloplasty[26] or transseptal approached clip approximation of the incompetent MV leaflet scallops[27], RT3DE also plays an important role in that it is a very suitable technique for monitoring the efficacy and complications of percutaneous mitral valvuloplasty. Also, in regard to the different mitral valve diseases, unconventional indices, like the geometry and mitral valve volume may be assessed by 3DE[28].

Tricuspid valve disease

Thanks to RT3DE technique, assessment of this valve had been possible with clear delineation of all the three leaflets in confront view (Fig. 7). So we can actually measure tricuspid valve (TV) area by planimetry along with greater details about valvular morphology. RT3DE appears useful in supplementing two-dimensional echocardiography in assessing more comprehensively the morphologic features of Epstein's anomaly, above all assessing the distribution and extent of tethering of each of the three leaflets of the TV and the characteristic bubble-like appearance resulting from bulging of the non-tethered areas of the TV leaflets[29]. Two dimensional echocardiography allows definitive diagnosis of tricuspid stenosis showing thickening and shortening of the valve leaflets.

Nevertheless, unlike evaluation of mitral stenosis, short axis 2D imaging of the tricuspid valve orifice is rarely feasible. In a case report[30], an image of tricuspid valve area was easily obtained using 3D transthoracic echocardiography, and pyramidal full volume 3D image was cropped using an elevation cutting plane to obtain the profile of the tricuspid valve area viewed from the apex perspective. Bedside, this technique provides reproducible images of entire tricuspid regurgitant jet.

Congenital heart disease

In patients with atrial septal defect or ventricular septal defect, the location, size, configuration, type, and motion of the defect, as well as the spatial relations of the defect with the neighbouring structures, from either the left or the right side of the septum and the information about adequacy of rims for device closure can be obtained by RT3DE (Fig. 8, 9). As for complex congenital heart diseases, with the combination of diverse standard and cropped non-standard views, the complicated spatial relations of cardiac lesions could be fully displayed. For example in the patients with endocardial cushion defect, other defects of ventricular or atrial septa, mitral and TV at the same level and the position, dimension, and form of MV clefts from either the ventricle or the atrium can also be observed. In patients undergoing surgical or percutaneous closure of their ventricular or atrial septal defects, the entire shapes, dimensions, and sites of the patches or occluders and their spatial relations with septal myocardium could be clearly viewed on RT3DE[31]. RT3DE provides novel views of congenital septal defects and improves quantification of the size of the defect[32]. The size obtained from RT3DE have better correlation with surgical findings than diameter measured by 2DE[32]. Thus, RT3DE could be a complementary approach to angiography and transesophageal echocardiography in performing transcatheter closure of perimembranous ventricular septal defect. In a recent study CHEN Guo-zhen[33] et al, comparing this new approach with surgical findings and angiography, showed that RT-3DE allowed correct diagnosis of 2 cases (9.5% of patients) among 21 preoperative patients who underwent operations, including one with corrected transposition of the great arteries and the other with single atrium and mitral cleft. The diagnoses initially made by 2DE for these 2 patients were double outlet right ventricle with transposition of the great arteries and complete atrio-ventricular septal defect. RT3DE offers additional spatial information in congenital heart disease without extending examination time, allowing quantitative recording of septal defect dynamics, and enhancing elucidation of the disease mechanism. It is a potentially valuable clinical tool for diagnosing and managing all patients with congenital heart disease[32]. Moreover, quantification by RT3DE of volumes of an enlarged right chamber, often present in CHD patients (e.g. Tetralogy of Fallot), is quite difficult.

Prosthetic heart valves

The entire views and motions of prosthetic heart valves could be optimally displayed by RT3DE in patients with valvular replacement. The images could be obtained from positions parallel to the prosthetic aortic valves in the LV outflow tract or aortic views and positions parallel to the prosthetic MV in the LV or LA views. Furthermore in patients with bioprosthetic

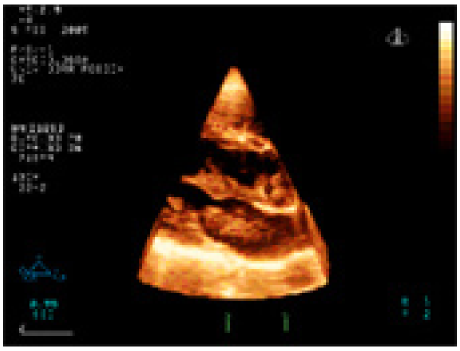

Figure 1. Live three-dimensional pyramidal volume from the parasternal view. Example of three-dimensional images of a normal left ventricle, left atrium and aortic valve.

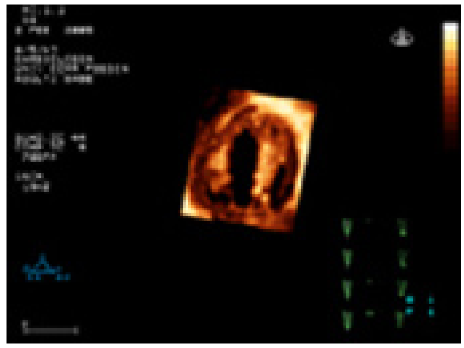

Figure 2. detail of papillary muscles

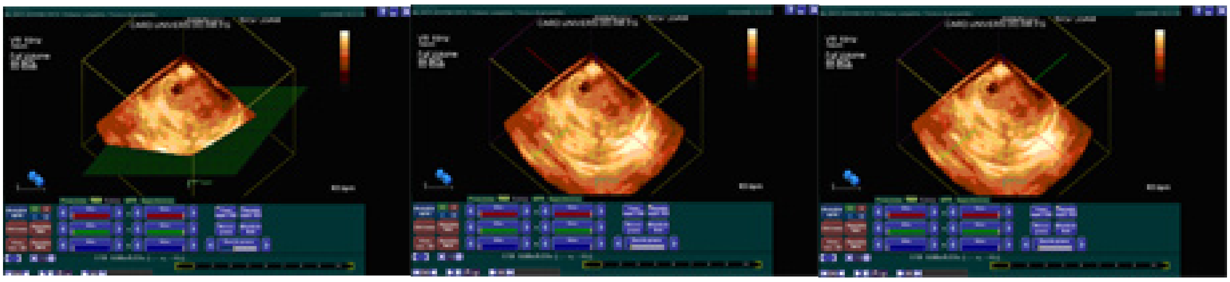

Figure 3 Example of full volume acquisition and image cropped by cut plane

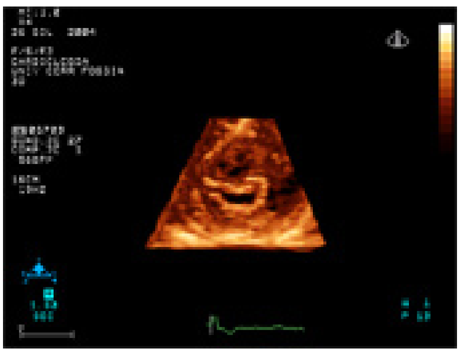

Figure 4. Surgical view from the ventricles of mitral valve and left ventricle outflow tract

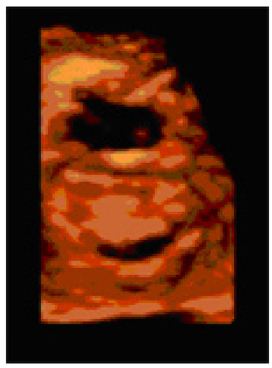

Figure 5. surgical views from the ventricles of the mitral and tricuspid valves

Figure 6. Left panel: surgical view from atria of the mitral valves Right panel: in the same patient the three-dimensional image has been rotated and the mitral valve has been visualized from the ventricle

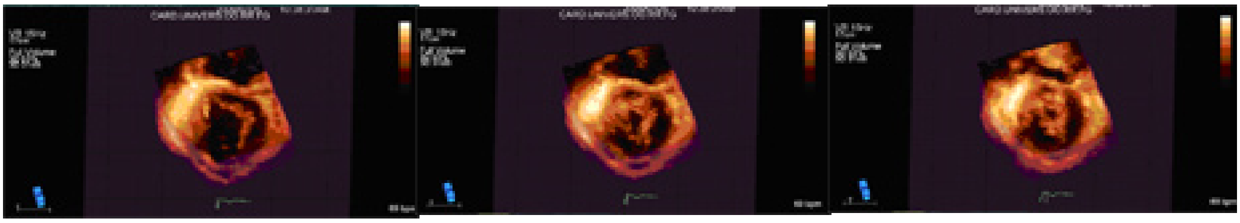

Figure 7. clear delineation of all the three leaflets of tricuspid valve in enface view

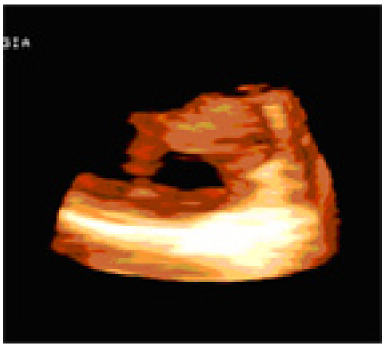

Figure 8. Visualization of interatrial defect (ostium secundum)

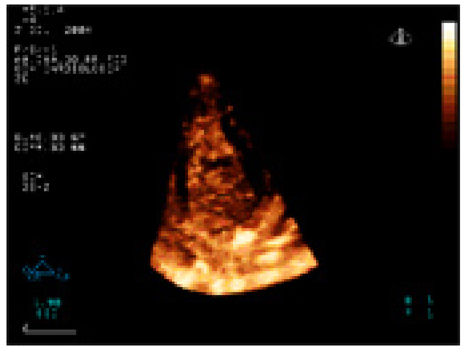

Figure 9. Figure 8: Visualization of interatrial defect (ostium secundum) Visualization of interventricular defect

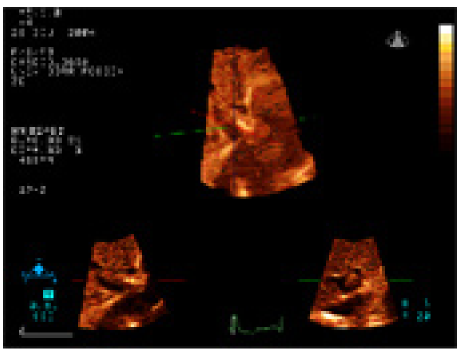

Figure 10. Visualization of tumor mass in inferior vena cava and in right atrium

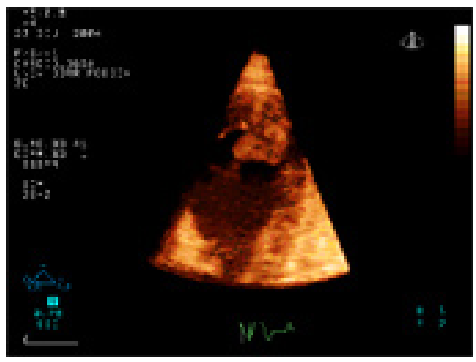

Figure 11. Apical thrombus in the left ventricle

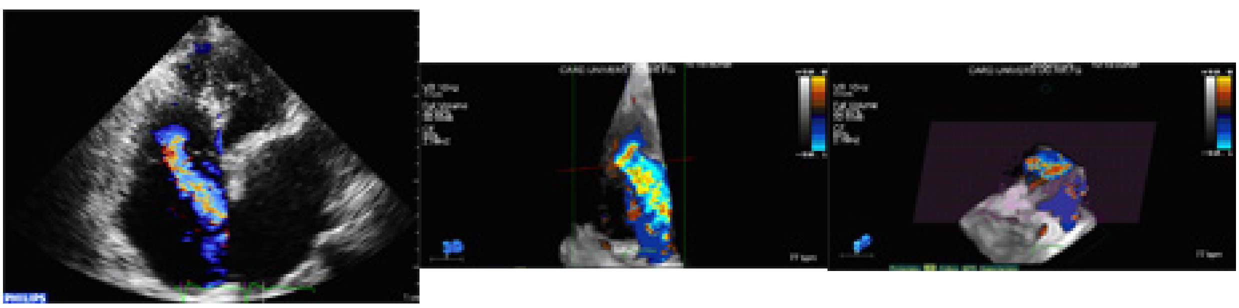

Figure 12. Example of image of valvular regurgitant jet In RT3DE the use of color Doppler flow mapping combined with 3D morphologic data provides clinically relevant supplementary information in patients with valvular regurgitant jets

valves at mitral and aortic positions, we are able to delineate actual site, size and shape of the paravalvular leak and its relation to the surrounding structures.

Infective endocarditis

In patients with infective endocarditis, RT3DE could show the stereoscopic configuration and attachment of vegetations, mobility of vegetations with blood flow, and potential complications, such as valve prolapse and perforation. The 3D images can provide more information than routine 2DE. In fact better definition of the morphologic characteristics of the vegetation and valvular apparatus can be achieved with RT3DE. Furthermore, the information provided by RT3D echocardiogram for the surgical team are accurate and direct because it is not based on detailed verbal information for performing a 3D mental reconstruction but is a simple image similar to what would be found in the operating room[34].

Hypertrophic cardiomyopathy

In patients with hypertrophic cardiomyopathy, the asymmetrical interventricular septal hypertrophy and asymmetry of systolic anterior motion of the MV could be visualized by RT3DE[35, 36]. RT3DE allows a comprehensive evaluation of left ventricular outflow tract (LVOT) obstruction in these patients[35]. In the era of nonsurgical reduction of the LV outflow tract gradient by percutaneous transluminal septal myocardial ablation for hypertrophic obstructive cardiomyopathy[37], RT3DE offers great promise for the pre- and post-interventional evaluation of these patients.

Left atrial tumors

A preliminary study demonstrated the superiority of live three-dimensional transthoracic echocardiography over 2DE in the assessment of pathologically proved left atrial (LA) tumors in four patients (three myxomas, one hemangioma[38]. Because of the unique ability of live 3DE to systematically section and view the contents of an intracardiac mass, LA myxomas in the three patients studied could be more confidently diagnosed by noting isolated echolucent areas consistent with hemorrhage/necrosis in the tumor mass. On the other hand, a definite echolucent area was found by 2D TTE (Trans Thorasic Echocardiography) in only two of the three patients with myxoma. In the fourth patient with a hemangioma, live 3DE showed much more extensive and closely packed echolucencies with little solid tissue consistent with a highly vascularized tumor compared to a myxoma. In contrast, 2DE demonstrated only two isolated echolucencies in the tumor suggesting an erroneous diagnosis of myxoma. Also the RT3DE allows visualization of the stereoscopic views of LA myxoma, its attachment to the atrial septum, and its mobility with blood flow from LA to LV in diastole.

Intracardiac masses

The size of an intracardiac mass (vegetation, tumor, or thrombus) is an important predictor for embolic events and response to treatment[39]. Maximum diameter measurements by two-dimensional (2D) echocardiography are routinely used to determine mass size. However, most masses are irregularly shaped, making it difficult to accurately observe or select the largest diameter. The selection of a diameter that is not truly the largest may lead to underestimation of the true size of the mass and a misrepresentation of the patients' prognosis. RT3DE images the entire volume of a mass allowing for accurate measurements in multiple planes. In a recent study, there was a consistent underestimation of maximum diameter measured by 2D (TTE and TEE , Trans Thoracic and Tranc esophageal Echocardiography) regardless of the size, location, and aetiology of the mass. 2D TTE and TEE underestimated cardiac mass size compared to RT3DE. These findings suggested that RT3DE may be the technique of choice for the noninvasive evaluation of intracardiac mass size. Furthermore, in case of thrombus, we can often section the thrombus sequentially (Fig. 10). Interestingly, for left ventricular apical thrombi, RT3DE is able to provide a clear diagnosis of LV Thrombus whereas 2DE images are merely suggestive of the disorder (Fig. 11). Therefore, RT3DE with real-time volume rendering, is a clinically feasible alternative to 2-dimensional echocardiography,and has great potential to positively affect the diagnosis, follow-up, and care of patients with suspected LVT[40]. In our experience, assessing a voluminous left atrial thrombus by RT3DE, provides a better definition of complex spatial location of the mass, a remarkable preoperative delineation and an excellent agreement between the anatomical findings at surgery and three-dimensional imaging[41].

Coronary artery disease

The abnormal regional wall motion and range of ischemic myocardium could be shown clearly and accurately by RT3DE. Therefore, it is ideal for dobutamine stress echocardiography[42,45,46]. Also Matsumura et al[47] have found no significant differences between three-dimensional-dobutamine stress echocardiography, used for the diagnosis of ischemia, and 2DE in regard to the sensitivity, specificity, and accuracy (P=1.000). This application of RT3DE shows important dependence on available echocardiographic window and quality image. Because of its ability to quantify LV dyssynchrony RT3DE may be useful in patient's selection for cardiac resynchronization therapy[48, 49]. In patients with ventricular aneurysm, position, size, and stereoscopic shape of ventricular aneurysm could be efficiently demonstrated. In patients who had undergone coronary artery by-pass grafting surgery, the improvement in regional wall motion abnormality could be detected with high sensitivity.

RT3DE allows observation of the structure and contraction of the endocardial surface of the left ventricular wall, by which we can roughly estimate the size of myocardial infarction and its healing stage[50].

In Kawasaki disease, RT3DE is superior to 2DE in visualization of the coronary arteries, especially the right coronary artery and circumflex branches of the left coronary artery[51].

Color Doppler flow imaging

The use of colour Doppler flow mapping combined with 3D morphologic data in RT3DE, provides clinically relevant supplementary information. In patients with valvular regurgitation, this mode enables exact definition of jet origin and its relationship to adjacent structures. Furthermore, the direction, length, width, area, course, and dynamic changes in phases of valvular regurgitant jets or intracardiac shunt flows, especially their entire shapes in 3 dimensions can be rapidly and stereoscopically visualized. In regard to eccentric jets, the colour reconstruction of the regurgitant jets could also be analyzed after removing superimposed morphologic data, which allows viewing the jets in their entirety. Thus, the relations between atrial walls and eccentric regurgitant jet could be perfectly interpreted (Fig. 12). Data about planimetry of the area of vena contracta and mitral regurgitation area might also be provided by RT3DE and correlate well with conventional Doppler-based methods. Added colour Doppler information enabled us to show a tumor mass arising from right kidney and extending into inferior vena cava and right atrium, completely encircled by blood flow without infiltration, providing further information on the planning of the operative removal of mass[52].

Measurement of ventricular volume

Quantification of ventricular volumes and mass with 2DE imaging requires geometric assumption, but their determination by RT3DE is real and is not dependent on any assumption to calculate ejection fraction. Recently Jacobs[53] et al, have suggested an alternative approach on the basis of detection of the 3D endocardial surface, which allows direct quantification of LV volumes without multiplane tracing or geometric modelling. Indeed, this approach was recently incorporated into commercial software for analysis of RT3DE data for online quantification of LV volumes and EF. Jacobs has demonstrated that this new approach eliminates foreshortening errors.

Measurement of Stroke volume and ejection Fraction

The determination of stroke volume is a potentially important application of RT3DE. A strong correlation was found between stroke volume measured by thermodilution technique during cardiac catheterization with that of RT3DE[54]. RT3DE is also useful for determination of ejection fraction[55-57]. LV volumes and ejection fraction computed from RT3DE result in higher levels of agreement with MRI than conventional 2-dimensional echocardiography[58]. RT3DE is also feasible for volumetric analysis of the abnormal LV, allowing accurate determination of LV volume and ejection fraction compared with MRI in adult patients with congenital heart disease[59].

Measurement of left ventricular mass

Left ventricular mass (LVM) is an important and independent determinant in the evaluation of patients with heart diseases, especially in patients with hypertension. Echocardiography is the most widely used clinical method for estimating LVM. However, 2DE has its limitation in assuming ventricular shape. RT3DE allows quantitative measurement to be made without geometric assumption and has been demonstrated to be accurate and reliable for human heart[60, 61]. The greater accuracy and reproducibility of RT3DE regarding LVM have obvious important clinical implications.

Three-dimensional echocardiography today

To summarize, at present RT3DE has shown prospects of potential utility in the following aspects[62-68]: 1) displaying stereoscopic views and complicated spatial relationship of cardiac structures; 2) accurate assessment of volume and function of atrium and ventricle, especially the volumetric measurements of geometries with irregular shapes, such as right ventricle and ventricular aneurysm; 3) coordination of the surgical views, which contribute to crucial surgical decisions; 4) direct and accurate assessment of the effect of percutaneous balloon valvuloplasty and the function of prosthetic valves and septal occluder; 5) more accurate qualitative diagnosis and classifications of congenital heart disease; 6) exact localization of infarction and ischemic areas in coronary heart disease; 7) more extensive spatial information about abnormal intracardiac blood flows. Finally, through the volumetric measurements of colour Doppler signals, the clinicians can now be provided with an advanced, accurate, and non-invasive ultrasound device for quantitative assessment of cardiac disease, including valvular regurgitation and septal defects6[9-72]. Moreover, several structures and cardiac diseases had been displayed by RT3DE, highlighting the additional value for spatial information: a) the left ventricular non-compaction diagnosed by RT3DE[73]; b) thrombus in the innominate veins and superior vena cava shown by utilizing right parasternal and supraclavicular approaches[74]; c) visualization of cardiac resynchronization using RT3DE[75]; d) in an adult patient three-dimensional transthoracic echocardiography combined with intravenous use of an echo contrast agent was useful in making a definitive diagnosis of apical hypertrophic cardiomyopathy and characterizing the nature and full extent of the hypertrophy[76]; e) Aortic stiffness is an important predictor of cardiovascular morbidity and mortality. Non-invasive measurement of aortic stiffness is a promising challenge for echocardiography. Nemes A. et al demonstrated the usefulness of RT3DE in assessment of regional differences of aortic stiffness[77]; f) 3-dimensional transthoracic echocardiography was used to diagnose cor triatriatum This modality offers an advantage over TEE, as it allows the septum to be viewed easily without the risks or inconvenience of TEE[78]; g) Prakasa KR et al have demonstrated that RT3DE measurements of RV volumes and ejection fractions closely correlated with Cardiac Magnetic Resonance values and might be useful in the follow-up of patients with Arrhythmogenic Right Ventricular Dysplasia[79]; h) an intracardiac mass, detected by 2DE, was definitely diagnosed as accessory mitral valve tissue by RT3DE and transoesophageal echocardiography[80].

Three-dimensional echocardiography tomorrow

Despite its confirmed clinical value, the present RT3DE has some limitations: 1) to simplify visualization and recording of RT3DE images, standard approach to imaging is needed. The publication of the examination protocol for RT3DE[81] will hopefully simplify the routine clinical examinations; 2) the transducer is so large that in the presence of the narrow intercostal spaces in transthoracic echocardiography, the acoustic window restricts the penetration of ultrasound beams which affects displaying of the entire structures. Because of large transducer, it is difficult three-dimensional approach is difficult in children and newborn; 3) During the volumetric data set acquisition in the full volume mode and 3D color mode, respiration and movement of the patient can affect artefacts; 4) The postprocessing analysis depends on clear image which is precluded in both RT3DE and available echocardiographic window in patients with poor image of the heart. If the LV cavity is too big to be included within the pyramidal scan volume, and some of its segments could not be visualized, the analysis of the synchronicity also becomes impossible; 5) Acquisition angle in real time mode requires technical advances to increase the size of insonated volume and frame rate acquisition. 6) RT3DE provides reproducible images of entire tricuspid regurgitant jet along with actual measurement of regurgitant valve area but requires validation studies before being used for clinical decision making; 7) Until recently, the measurement of three-dimensional distances and volumes had to be made by dedicated TomTec software, which was not easy and not fast enough. A newly introduced quantitative echo system iE33 (Philips Medical Systems, USA) by Q-LAB 3DQ Advanced provided a semi-automated, on-cart or off-cart analysis of LV volumes , using all of the voxels to generate a full 3D endocardial border. This is a 3D border with higher accuracy and lesser dependency on LV shape assumptions than conventional methods, which relies on sparse view analysis. By advanced parallel processing technology and sophisticated, proprietary algorithms, 3DQ Advanced allows rapid generation of a full 3D wire-mesh LV volume, thereby an accurate cardiac ejection fraction is now achievable with on-cart and off-cart in less than one minute. 3DQ Advanced also supports iSlice, a technique that automatically presents the heart as a set of moving, short-axis slices, allowing an intuitive 3D bulls-eye impression of function. In order to achieve a complete contextual motion presentation, iSlice views can be displayed in combination with the full endocardial surface mesh., The core of Live 3D Echo, xMATRIX transducer technology, is used in the new X3-1 transducer. It allows live xPlane Imaging, which displays two simultaneous views of the heart from the same heartbeat. One image is a 2D baseline reference and the second, can be any of 180 different views within the 3D space which is validated by only a short report on this new quantitative echo system. Recently Zeng et al[82] have used the X3-1 (1-3 MHz) matrix array transducer of the IE33 echocardiographic imaging system (Philips Medical Systems) to obtain a full-volume three-dimensional data set from the apical window. They demonstrated that on-line software RT3DE was able to quantitatively evaluate the systolic synchronicity of all the left ventricular segments simultaneously. They also provided highly accurate data for assessing global function based on LV volume and ejection fraction. Progress in cardiology has often followed new technologies especially when they provide a better insight into pathology and allow new questions to be answered. So, RT3DE will have a pivotal role in the clinical practice of cardiology. Further development of this technique, with more experimental and clinical studies, RT3ED will expand the abilities of non-invasive cardiology and may open new doors to the evaluation of cardiac disease. Nevertheless the above list of limitations clearly indicates that currently the applications are still limited and needs further studies.

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