Initial experience with a new on-line transthoracic three-dimensional technique: assessment of feasibility and of diagnostic potential

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Methodology;
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Background. **Despite its wide diagnostic potential, three-dimensional (3D) echocardiography is a quite rarely employed technique. The ideal method to obtain transthoracic 3D imaging is on-line 3D echocardiography, but first-generation real-time instruments had technical limitations. A new on-line 3D technology which allows true real-time volume rendering of the cardiac anatomy has been recently introduced and its feasibility and diagnostic advantages have been evaluated in the clinical setting.**

Methods. **The system utilizes a "matrix" transducer with a dedicated software. It allows instantaneous acquisition and rendering on-line 3D images and interactive manipulation of 3D data. Eighty-three adult patients with various cardiac pathologies underwent on-line 3D echocardiography. Long- and short-axis views of the aorta, mitral valve and left ventricle and surgical views of these structures were attempted. The duration of acquisition and reconstruction, and the quality and incremental clinical value of 3D images in comparison with two-dimensional imaging were annotated.**

Results. **The mean time of 3D examination was 10 ± 5 min; the mean number of acquisitions was 10.8 per patient. The quality of the 3D images was optimal in 39%, good in 37%, sufficient in 19%, and insufficient in 5% of the patients. In all cases at least one optimal or good live 3D image was obtained from the parasternal and apical views. The reconstruction of surgical or en face views was easily and rapidly (1-2 min) achieved by two experts in 3D echocardiography. The additional clinical values of 3D vs two-dimensional imaging was demonstrated in 7 patients with mitral valve disease, 3 with aortic valve pathology, and 3 with congenital heart disease. Several on-line 3D images that have not correspondence with two-dimensional echocardiography were reconstructed, creating projections dedicated to the diagnostic goal.**

Conclusions. **On-line 3D echocardiography can be easily performed in adult patients and allows for unique planes and projections. The instant rendering of 3D images facilitates the recognition of cardiac structures and increases the diagnostic potential of transthoracic echocardiography.**

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Introduction

In recent years the widespread clinical application of different new technologies has considerably enriched the diagnostic capabilities of echocardiography. Three-dimensional (3D) echocardiography has been considered as an important research goal with few routine clinical applications. This, despite its wide diagnostic potential in the evaluation of the morphology of the cardiac structures and in the determination of the left ventricular volumes, congenital defects and valve areas, intracardiac mass volumes and regurgitant jets[1-18]. The main limitations of 3D transthoracic and transesophageal echocardiography are related to the acquisition of images and to off-line reconstruction which are time-consuming and complex procedures. Several new methods have been therefore proposed to overcome these limitations[19-21]. However, the ideal method is certainly on-line 3D imaging; first-generation instruments have been introduced in the last decade, but their application is very limited due to the costs (they are dedicated 3D units) and to the technical difficulties in obtaining high quality images[22-25].

A new on-line transthoracic 3D technology which allows true real-time volume rendering of the cardiac anatomy has been recently introduced. We have evaluated the feasibility and diagnostic advantages of this technique in a clinical setting.

Methods

Instrument. The system (Sonos 7500, Philips Medical Systems, Andover, MA, USA) utilizes a "matrix" transducer which offers steering in both the elevation and the azimuth planes thus permitting an instantaneous volume scan. This matrix array probe with a dedicated software using 3000 active elements and micro-beam forming has the potential of allowing the instantaneous acquisition and rendering of on-line 3D images. The acquisition and instantaneous display of a 3D data set without post-processing procedures is therefore possible from different transthoracic windows. Rotational tools allow the exploration of the cardiac structures from different views (Figs. 1-3). Moreover, since the pyramidal volume does not permit the visualization of the entire heart when the structure is far from the transducer (it has an angle of 29 × 46°) or if structures are too wide (for example the 4-chamber view from the apical window), another method, the so-called "full volume" acquisition, may be utilized. It allows the acquisition of four ECG-triggered sequential volumes in rapid sequence, while the patient interrupts breathing, obtaining a volume of 93 × 84°. Figure 4 shows a schematic representation of this method.

Instantaneous or "full volume" acquisitions of 3D data sets may be interactively manipulated for a complete evaluation of the cardiac structures: through an integrated software, images can be cropped or rotated and typical 3D "surgical" or "en face" views are obtained and stored. To date, it is not possible to perform a quantitative analysis.

Patients and procedure. Eighty-three non-consecutive patients with various cardiac pathologies were enrolled in this study after results from a routine echocardiogram (performed with the same ultrasound unit, but using a traditional phased array transducer) showed a good or optimal visualization of the cardiac structures (50 cases) or a peculiar cardiac pathology in which 3D echocardiography had the potential of overcoming some two-dimensional (2D) echocardiographic limita-

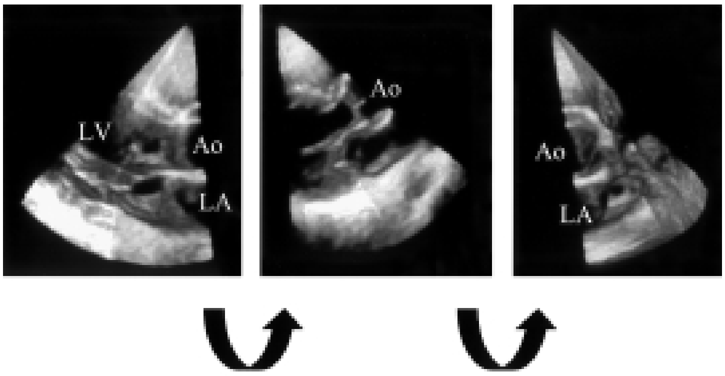

Figure 1. *Live three-dimensional pyramidal volume from the parasternal view. Example of three-dimensional images of a normal left ventricle (LV), left atrium (LA) and aortic valve (Ao); volume rendering images are rotated* (arrows) *instantaneously.*

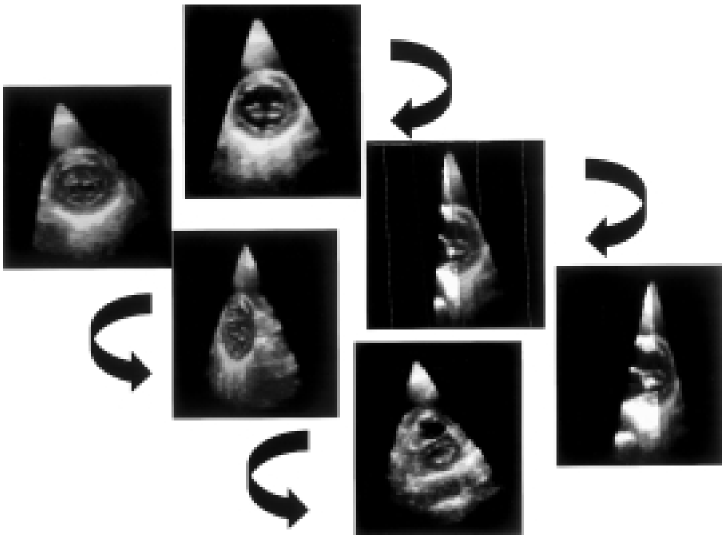

Figure 2. *Live three-dimensional images of the mitral valve (short-axis parasternal view) showing how the pyramidal volume can be rapidly rotated* (arrows) *allowing a complete three-dimensional reconstruction of the anatomical plane.*

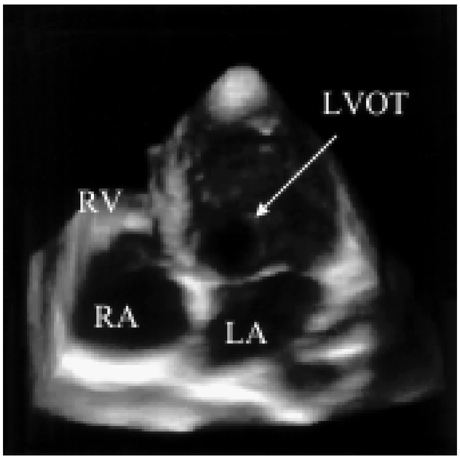

Figure 3. *Live three-dimensional image from the apical view. A 4-chamber three-dimensional image accurately reveals the shape of the left ventricle including the outflow tract* (arrow). *LA = left atrium; LVOT = left ventricular outflow tract; RA = right atrium; RV = right ventricle.*

Table I. Clinical data of the study population.

No. patients	83
Age (years)	51.5 ± 18.7 (range 15-89)
Sex (M/F)	43/40
Normal subjects	12
Aortic valve disease	20
Mitral valve disease	28
Congenital heart disease	8
Coronary artery disease	7
Cardiomyopathies	4
Tumors	2
Aortic fibroelastoma	1
Left atrial myxoma	1
Hypertension	1
Endocarditis	1

tions in terms of spatial morphology (33 cases). Table I reports the main clinical data of the study population.

In all patients images were acquired from the parasternal and the apical windows. In a few cases other echocardiographic windows were also utilized.

On-line 3D images were recorded on videotape and several digital images were stored in the ultrasound unit from both the parasternal and apical windows. From the parasternal view one on-line 3D longitudinal and two short-axis images (one at the level of the aorta and the other at the level of the mitral valve) were always obtained. Moreover, depending on the clinical indications, a single reconstruction was also performed utilizing standard 3D approaches. In particular, surgical views of the aorta and the mitral valves and right and left atrial views were reconstructed and stored in case of patients with valve disease and atrial septal defects respectively. The full volume method with four triggered sequential volumes was also attempted from the apical (all cases) or, in selected cases, from the parasternal window. Cropping and rotational tools were utilized during the examination allowing the rapid morphologic evaluation of the cardiac structures.

The morphologic data of the investigated structures were annotated. All obtained images were reviewed immediately after on-line acquisition and stored in the ultrasound unit and CD disks. Examinations were performed and reviewed by two operators who have experience in all ultrasound technologies apart from 3D echocardiography

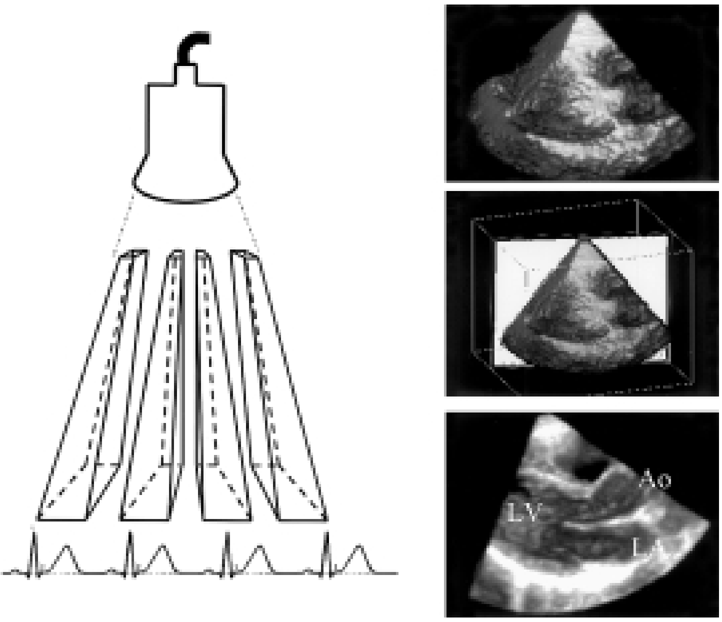

Figure 4. *Full volume analysis.* Left panel: *schematic representation of four ECG-triggered volumes acquired in rapid sequence (while the patient interrupts breathing); the method allowed the operator to obtain a volume of 93 × 84°.* Right panels: *full volume example obtained from the parasternal view.* Upper panel: *full volume data set;* middle and lower panels: *autocropping (visualization of a three-dimensional plane in the center of the three-dimensional volume) of the three-dimensional data set visualizing a long-axis view of the left ventricle (LV), left atrium (LA) and aorta (Ao).*

(PG and AD) and by two operators who have 4-year experience in 3D technologies (transesophageal rotational and transthoracic free-hand methods) (PM and TG).

The quality of images, judged on the basis of the absence of artifacts throughout the cardiac cycle and on the possibility of correctly evaluating the reconstructed image was graded as: optimal (excellent quality without artifacts), good (good quality without artifacts), sufficient (sufficient quality or good quality with artifacts), and insufficient (insufficient quality of cardiac imaging). The quality of images was interpreted by three other observers (BG, DVS, MA); interobserver discrepancies were resolved by the consensus of two other physicians not involved in the study.

Results

The mean time of the 3D examination was 10 ± 5 min, including the first 10 cases in which the learning curve led to more time-consuming procedures. The mean time of 2D transthoracic studies in our laboratory is 25 min and the total time in this series was therefore approximately 40 min.

The mean number of acquisitions in our series was 10.8 per patient. The quality of the 3D images was strictly related to that of the 2D ones and was optimal in 39%, good in 37%, sufficient in 19%, and insufficient in 5% of all attempted acquisitions and reconstructions. In all patients at least one good or optimal live 3D image was obtained from the parasternal and apical views allowing the evaluation of the aorta, mitral valve and left ventricular outflow tract. The full volume data sets were complete and without artifacts in all cases (in a few cases autocropping of the volume showed the presence of incomplete images or of artifacts thus suggesting to acquire a second volume).

The reconstruction of surgical views and en face views (visualization of the mitral valve from the atrial or ventricular view, of the aortic view from the aorta or from the left ventricular outflow tract and of atrial septal defects from the atria) was easily performed by two experts in 3D echocardiography. In approximately 1-2 min the 3D images were obtained and reconstructed by these two experts. The two operators without experience in 3D echocardiography easily obtained on-line 3D images but, not having a specific training, they had difficulties in elaborating specific views from the 3D data set. This was particularly true when the images had to be reconstructed from non-conventional planes.

Even though quantitative analysis of these images was not performed, an additional clinical value of 3D vs 2D methods was demonstrated. In 5 cases with mitral valve prolapse and in 2 with mitral valve stenosis, the 3D visualization of the mitral valve from the atrial or ventricular views was detailed, allowing a complete morphologic description of the mitral valve leaflets. (Fig. 5). As shown in figure 6, the commissures and posterior scallops of the mitral leaflets were clearly identifiable. The same was true for the mitral valve of one patient presenting with a congenital mitral valve cleft. An additional clinical value was also demonstrated in 3 patients with aortic valve pathology (including 1 case with a biological prosthesis) and in 2 with an atrial septal defect. In these 2 cases the so-called en face view of the defect from the right of the left atrium was very accurate allowing the definition of its shape and rims. In figures 7 and 8 respectively a 3D image of the aortic valve and of the atrial septal defect is shown.

The two atrioventricular valves were easily reconstructed from full volume acquisitions in the atrial surgical view. The tricuspid valve was reconstructed with a complete definition of the three cusps by means of images that did not correspond with those obtained at 2D echocardiography (Fig. 5). The same held true for the left ventricular outflow tract and other structures. It is however very difficult to describe all the new projections which may be obtained using this new technology from the complete 3D data set. Non-conventional and off-axis planes with 3D volume rendering may be searched for and reconstructed, thus creating peculiar images dedicated to the diagnostic goal.

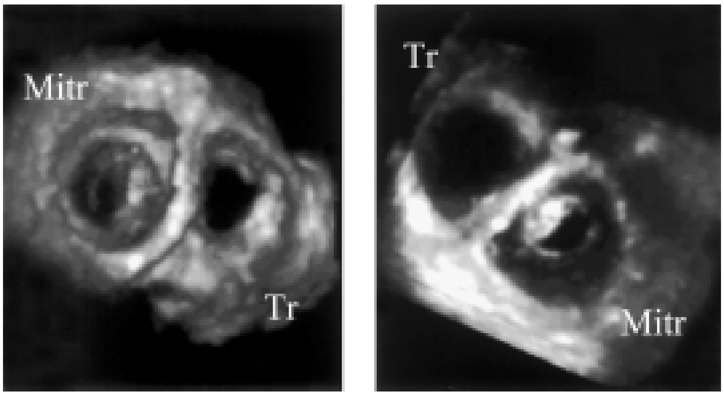

Figure 5. *Mitral valve stenosis.* Left panel: *surgical view from the atria of the mitral (Mitr) and tricuspid (Tr) valves.* Right panel: *in the same example the three-dimensional image has been rotated and the two valves are visualized from the ventricles. Doming of the anterior leaflet of the mitral valve as well as the presence of a stenotic mitral orifice are shown.*

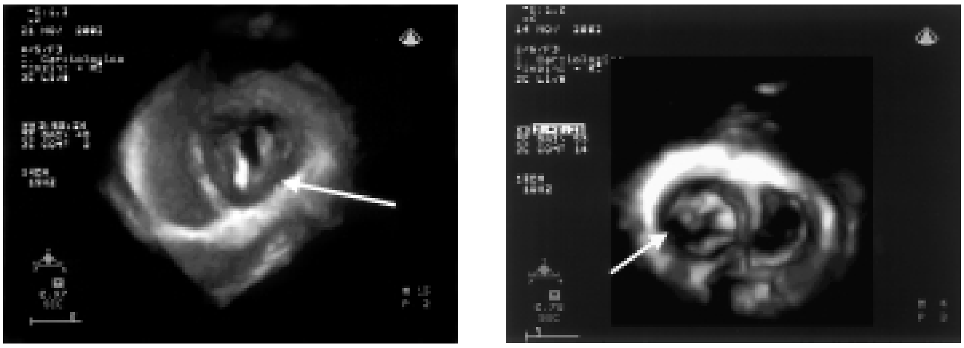

Figure 6. Left panel: *left ventricular view of the mitral valve in a patient with mitral valve stenosis following balloon mitral valvotomy. The* arrow *indicates the morphology of the mitral valve commissure (calcification of the lateral commissure).* Right panel: *surgical view of a mitral valve prolapse. The* arrow *indicates the prolapse of the central scallop of the posterior mitral leaflet.*

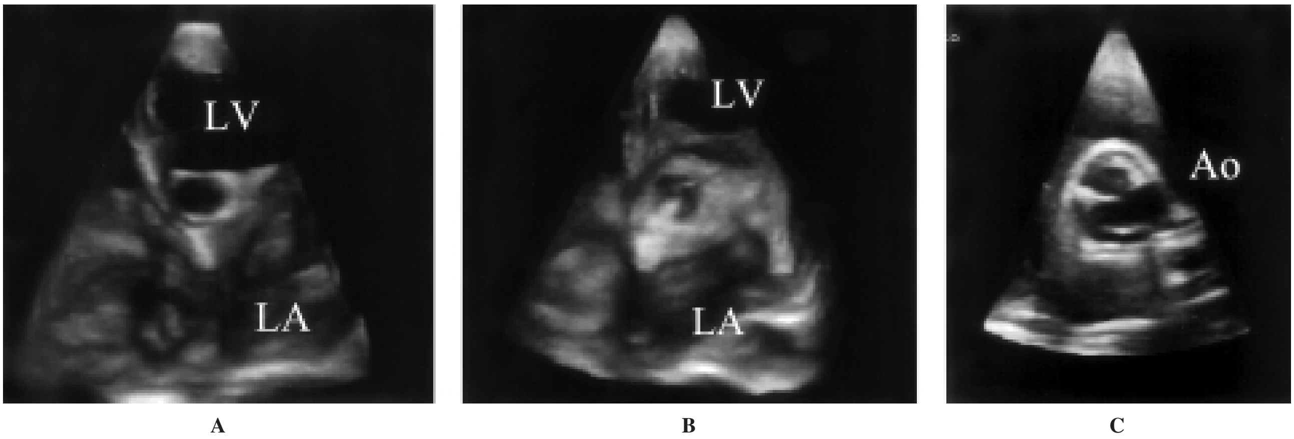

Figure 7. *Biological aortic valve prosthesis.* A *and* B: *apical live three-dimensional images of the prosthetic annulus and of the aortic prosthesis.* C: *short-axis view of the aortic prosthesis (Ao) in the same patient. LA = left atrium; LV = left ventricle.*

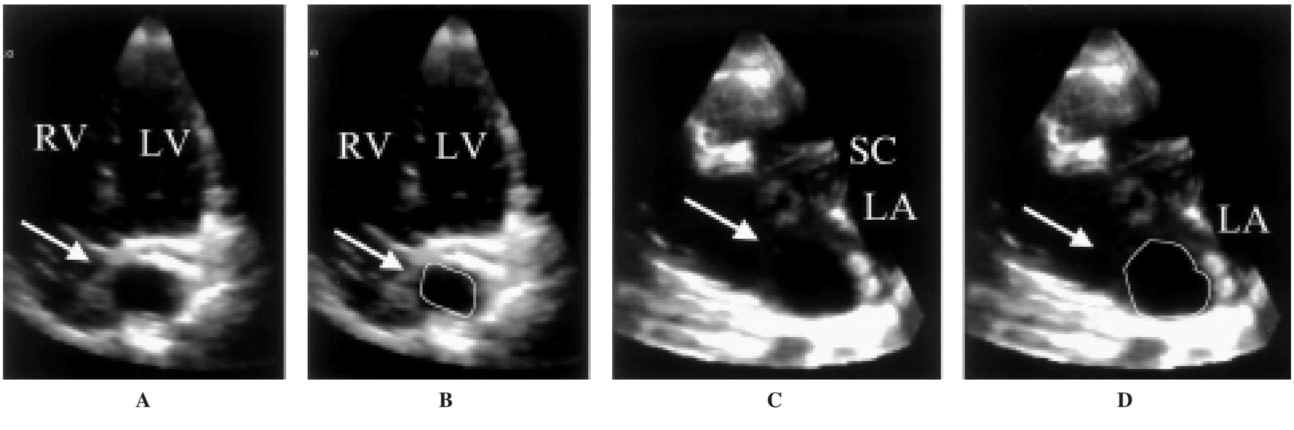

Figure 8. *En face views of an atrial septal defect (ostium secundum defect).* A: *en face view of this large defect during an apical live three-dimensional scan.* B: *the area of the defect is contoured (same image as* A). C *and* D: *the size of the defect is more clearly delineated by using a unique three-dimensional projection. LA = left atrium; LV = left ventricle; RV = right ventricle; SC = coronary sinus.*

Two critically ill patients with unstable hemodynamics were also included in the study. One had an ischemic (acute inferior myocardial infarction) papillary muscle rupture leading to severe mitral regurgitation and underwent the examination during intra-aortic balloon counterpulsation and the other presented with acute mitral regurgitation due to a flail mitral valve. In both cases the system was validated at the bedside in the intensive care unit. On-line 3D images from the parasternal and apical views and full volume acquisitions were easily obtained in these acute patients with overt NYHA class IV heart failure. In both cases the anatomy of the mitral valve and the complications (ruptured papillary muscle and chordae) were correctly identified.

This new on-line 3D method also has the potential of providing and facilitating the planimetry of the valve areas from the volumetric 3D data set in any desired orientation and without limitations due to echocardiographic windows and/or to the linear and area measurements of the different cardiac structures and volumes of the left ventricles. To demonstrate this potentiality we transferred the 3D data of 10 patients into a dedicated 3D system (Cardio View, Tom Tec Imaging Inc., Munich, Germany) and found that the areas and volumes could be very easily calculated from the acquired images.

Discussion

At present, experience with on-line 3D method is limited and our study has been completed before the system became commercially available. Our preliminary experience suggests that in comparison with previous 3D systems this new technique has several advantages, is feasible and simple, and is a useful clinical tool.

Real-time 3D echocardiography has been developed by von Ramm and colleagues[22] and is based on novel matrix phased-array transducer technology in which the elements are arranged in a 2D grid. Using a parallel processing technique this matrix array permits one to immediately scan a pyramidal volume. This first-generation instrument however had several limitations (low quality of images, complexity of the system and high costs of a dedicated 3D unit) and therefore it was not utilized for routine clinical applications, but only for research studies.

The new on-line 3D technology evaluated in our study offers several advantages. The 3D transducer is connected to an ultrasound unit which is not a dedicated system and maintains all the 2D and Doppler modalities. Thus, on-line 3D integrates the routine 2D examination and the operator may easily and rapidly move from one modality to the other.

The quality of the 3D images in a series of patients with different pathologies has been proved to be good and the mean time of the 3D examination (which was always calculated separately from that necessary for 2D routine examination) short. Thus, our study clearly shows that on-line 3D echocardiography has become feasible, easy, practical and not time-consuming. This is in accordance with the very preliminary data from other studies[26,27].

The interface of the ultrasound unit is friendly and the transition from 2D to 3D echocardiography and to different 3D tools easy. However, we found that there is a learning curve associated with the understanding and utilization of 3D imaging. Differences in obtaining and interpreting 3D data were observed between experienced and non-experienced 3D operators. All four operators could in fact easily evaluate on-line 3D images, but the reconstruction of surgical views and the exploitation of the whole potentiality of the system were achieved only by experts in 3D echocardiography. This was particularly true for full volume data which contain a lot of information; in this format, free-cut plane navigation allows one to display any cardiac structure from any prospective without any special alignment during acquisition. Thus, during acquisition the operator has to concentrate on optimizing the storage of all the cardiac structures without artifacts such that immediately after he can navigate inside the data volume. The visualization of the cardiac structures from surgical or en face views requires experience in 3D analysis: experts reconstructed these views in a few minutes; on the other hand, non-experts had difficulties in obtaining the same data. Therefore, adequate training in this specific field should be a prerequisite for utilizing this new technique.

The possibility of acquiring more clinical information than that obtainable at 2D echocardiography was demonstrated in several cases. In accordance with previous 3D reports concerning the sequential transthoracic or transesophageal acquisition of 2D images with off-line processing, on-line 3D echocardiography allows for the unique instant acquisition and rendering of valvular and congenital heart disease improving the identification of anatomical details. Surgical views of the mitral, aortic and tricuspid valves facilitate the comprehensive analysis of the valve morphology. The mitral valve apparatus may be easily evaluated from the atrium or ventricle with the additional benefit of providing more diagnostic information regarding the commissures, leaflets and vegetations. Even though so far this system does not allow quantitative analysis, it has been proved that the mitral and aortic valve areas may be accurately measured by means of previous 3D methods. Therefore, this new live 3D method will also potentially provide and facilitate the planimetry of the valve areas from the volumetric 3D data set in any desired orientation and without limitations due to echocardiographic windows. To demonstrate this potentiality we transferred the live 3D data of 10 patients into a dedicated 3D system: the areas and volumes could be very easily calculated from the acquired images. At present, the ventricular volumes are calculated during routine 2D echocardiography by manual endocardial tracing utilizing different methods. The accuracy and reproducibility of the 2D measurements of the left ventricular volumes are however low, while 3D methods have been proved to be accurate with excellent agreement between interobserver and intraobserver measurements[2,28-32]. We may therefore postulate that on-line 3D technology may also facilitate the acquisition of the 3D volume data of the ventricles allowing off-line quantitative analysis of the left ventricular volumes and of the derived parameters. This is very important for clinical decision-making and serial follow-up studies particularly in cases in which 3D echocardiography obviates any geometrical assumptions of the shape of the measured chamber.

In conclusion, on-line 3D technology could be easily performed in adult cardiac patients providing unique planes and projections. The instant acquisition and rendering of 3D images facilitate the identification of the cardiac structures and increase the diagnostic potential of transthoracic echocardiography. We may expect that the transition from 2D to 3D echocardiography will be easily achieved. However, specific training is necessary. Besides, the system may in the future also permit quantitative analysis. Foreseeable equipment refinements will enhance the potentiality of 3D echocardiography and further improve its diagnostic accuracy.

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