Aims Colour Doppler is the most widely used technique for assessing valve disease, but eccentric regurgitant jets cannot be visualized and measured by conventional 2D techniques. We have developed a new procedure for three-dimensional (3D) reconstruction of colour Doppler signals.

Methods and Results Fifty patients with mitral regurgitation underwent transoesophageal echocardiography and 3D acquisition. The severity of mitral regurgitation was assessed by angiography and the regurgitant volumes were measured by pulsed Doppler. The jet areas were calculated by planimetry from conventional colour Doppler; the jet volumes were obtained by 3D Doppler. A higher degree of mitral regurgitation was found in the patients with eccentric jets. While jet areas showed poor correlation with regurgitant volumes (r=0·61), jet volumes correlated significantly with regurgitant volumes (r=0·93; P<0·001). While jet areas failed to identify patients with different grades of regurgitation, jet volumes could so discriminate.

Conclusions 3D Doppler revealed new patterns of regurgitant flow and allowed a more accurate semiquantitative assessment of complex asymmetrical regurgitant jets. Three-dimensional colour Doppler has a great potential for becoming a reference method for the assessment of patients with heart valve disease.

Key Words: Three-dimensional echocardiography, colour Doppler, Heart valve disease, mitral regurgitation.

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Introduction

Three-dimensional (3D) echocardiography\cite{1–3} is a new technique, mainly used to assess intracardiac anatomy\cite{4–5} and to quantify heart chamber volumes\cite{6–11}. Up to now, the 3D visualization of intracardiac Doppler signals has been attempted by reconstructing video signal information\cite{12}. However, these techniques can only display the Doppler signals in a grey-scale format and do not allow cardiac structures to be separated from flows, or provide quantitative information from Doppler data.

We have developed a new technique for 3D reconstruction of Doppler signals, in original colour coding, using the digital data directly derived from the echocardiographic system. With this technique, intracardiac Doppler flow images are displayed and studied in 3D for the first time, paving the way to new perspectives for the quantitative assessment of mitral regurgitation.

Patients and methods

Fifty patients (26 men, 24 women; mean age 50·4 ± 12·2 years) with mitral regurgitation underwent echocardiographic examinations during cardiac surgery. The grade of mitral regurgitation was assessed by left ventricular angiography on a scale from I to IV\cite{13}. Eleven patients had grade I mitral regurgitation, 14 grade II, 11 grade III and 14 grade IV, according to pre-operative left ventricular angiography. The echocardiographic examinations were performed using commercially available equipment (Sonos 2500, Hewlett-Packard, Andover, Massachusetts, U.S.A.) with a multiplanar transoesophageal probe (5 MHz) and a conventional transthoracic probe (2·5 MHz).
The 3D acquisitions were obtained by rotating the transoesophageal transducer, which was steered by the step motor included in the echocardiographic system. The acquisition was accomplished in 2-degree increments, to obtain 90 slices during 90 heart cycles. The data acquisition was triggered to the R wave on the ECG and to the respiratory cycle. The digital data from 2D echocardiography, coded as a grey scale, and the data from 2D Doppler flow signals, coded as a colour palette, were separately stored on magneto-optical disks for further processing and reconstruction. The aortic and mitral flows were obtained by two-dimensional echocardiographic measurements of the aortic and mitral areas and by the pulsed-Doppler velocities\(^{14,15}\). Mitral regurgitant flow was obtained by subtracting the aortic flow from the mitral forward flow. The areas of the regurgitant jet (JA; cm\(^2\)) were traced on the systolic frame from the 2D images taken at the rotation angle where the greatest area could be measured. The jet volumes (JV; cm\(^3\)) were obtained by counting the voxels with high velocity and turbulence from 3D Doppler. Jet morphology was classified according to the spatial distribution within the left atrium\(^{16}\): eccentric (or asymmetrical) jets were directed towards lateral or septal left atrial walls or along the mitral valve leaflets; central jets originated from the middle of the mitral valve and did

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**Figure 1** Three-dimensional reconstruction of backscatter (in grey-scale) and Doppler signals (in colour) in a patient with moderate mitral valve regurgitation. The left atrial wall has been removed for better visualizing the flow signals. Left, the slow flow components cover the regurgitant jet. Right, the segmentation procedure allows the visualization of the underlying turbulent, high-velocity regurgitant jet.

**Figure 2** Three-dimensional reconstruction of colour Doppler. Left, conventional 2D Doppler showing a central regurgitant jet. Right, 3D images of central jets do not provide additional information about the geometry and the spreading of the regurgitant flow into the left atrium. The additional Doppler signals are due to the systolic flow in the left ventricular outflow tract.
not strike atrial walls or mitral valve leaflets. Colour Doppler flow signals were processed off-line on a UNIX workstation (SGI Challenge). The data obtained by rotational acquisition were rearranged into a cartesian system according to their temporal and spatial coordinates. The Doppler data stored on magneto-optical disks contain information on velocity and turbulence. Regurgitant jets were defined as the fast, turbulent flow component located above the atrioventricular valves. The first step was to determine those parts of the flow pattern with high velocities and turbulence. An entropy-minimizing algorithm that separates turbulent and high-velocity components, by setting a threshold value, was used for segmenting the jets\[17\]. This transformation was performed over the whole 3D data set (Fig. 1). The 3D reconstructions of Doppler data were obtained by means of the ‘Heidelberg Raytracing Algorithm’\[18,19\], initially developed at our institution for visualizing computed tomographic and magnetic resonance images. Compared to other visualization algorithms, this method enhances the 3D perception because two light sources are used for the virtual illumination.

**Statistical analysis**

All data are reported as mean ± SD. Linear regression analysis was used to describe the correlations of jet volumes and jet areas with angiographic grade and regurgitant volume. Differences between groups with a different angiographic grade of mitral regurgitation and between groups of patients with symmetrical and asymmetrical jets were assessed by Student’s t-test for unpaired data. The method of Bland and Altman\[20\] was used for the agreement of different methods for assessing mitral valve regurgitation. Differences were considered statistically significant at a value of $P<0.01$.

**Results**

Adequate reconstructions of Doppler signals were achieved in all patients. The 3D reconstructions and jet volume measurements were obtained in 3 to 5 min depending on the different angle resolutions. The 3D images were displayed on a portable personal computer (PowerBook, Apple, Cupertino, Ca, U.S.A.). The regurgitant jets were visualized in 3D by showing the systolic frame with the largest jet volume. A film, simulating the rotation of the observer from 0 to 360 degrees around the 3D images showed the details, direction and morphology of the jets. In order to maintain the examiner’s orientation, the rotational axis of the observer was the same as that used for data acquisition by transoesophageal echocardiography. Central, symmetrical regurgitant jets were found in 23 of 50 patients. Twenty-seven
Figure 4  Left panels, colour Doppler examinations in a patient with a mitral regurgitant jet recorded at different rotation angles (0 and 90°). Right panels, 3D reconstruction of the central regurgitant jet in a patient with atrioventricular septal defect.

Figure 5  Left panels, 2D Doppler showing a wall-impinging jet at different angles (0 and 90°). None of these conventional views is able to visualize the regurgitant jet entirely. Right panels, 3D Doppler reconstruction shows that the regurgitant jet resembles a ‘spoon’. The lower panel shows the convex face of this spoon jet.
patients showed eccentric, asymmetrical regurgitant jets. The 3D reconstructions of the asymmetrical regurgitant jets allowed us to describe completely new patterns of mitral regurgitant flows not observed before. Examples of different regurgitant jets are shown in Figs 2–5. Some 3D reconstructions of central jets can also be ‘mentally’ accomplished by a well-experienced echocardiographer, just by examining conventional 2D images taken at different angles. In contrast, 3D reconstructions of more complex regurgitant jets render 3D images that cannot be conceived, even by the most experienced examiner.

Table 1 shows the data of the patients with central jets and with eccentric jets. The angiographic degree of mitral regurgitation, maximal jet area and 3D jet volume were significantly greater in patients with eccentric jets. In all patients, the jet areas showed poor correlation with the regurgitant volumes \( r=0.61 \) (Fig. 6), while the jet volumes correlated significantly with the regurgitant volumes \( r=0.93; P<0.001 \). While the jet areas failed to identify patients with different grades of mitral regurgitation, the jet volumes were able to make this differentiation. In the patients with eccentric jets, no significant correlations were found (Table 2) between the jet areas and angiography \( r=0.67 \) or the regurgitant volumes \( r=0.40 \). In contrast, in the patients with eccentric jets, the jet volumes significantly correlated with angiography \( r=0.77; P<0.001 \) and the regurgitant volumes \( r=0.93; P<0.001 \). Figure 7 shows the Bland–Altman analysis of jet volume and mitral regurgitant volume. Despite the good correlations shown in our series, the agreement of the methods was poor, due to the absence of a reference method. Intra-observer variability of regurgitant fraction and regurgitant volume were 5.4 ± 4.3% and 6.6 ± 5.4%, respectively. Inter-observer variability of regurgitant fraction and regurgitant volume were 7.3 ± 5.2% and 6.4 ± 4.4%. Intra-observer variability of jet area and jet volume were 7.9 ± 6.2% and 5.1 ± 4.1%. Inter-observer variability of jet area and jet volume were 4.8 ± 3.3% and 4.6 ± 3.6%.

**Discussion**

Although 3D colour Doppler is a new technique still under development, this investigation raises many new questions and offers new perspectives which may change the clinical management of patients with valvular regurgitation. The quantification of mitral valve regurgitation is still a controversial issue, in spite of the large number of investigations which have dealt with this topic. Invasive methods for assessing the degree of mitral regurgitation, based on the calculation of mitral regurgitation volumes (obtained by thermodilution or indicator dilution and by angiography) have two limitations: the use of two different methods for volume measurements and the dependence of angiography on geometrical assumptions about the left ventricular cavity. There is common agreement that no ‘gold standard’ is available for the clinical measurement of regurgitant volumes. Up to now, the assessment of mitral valve regurgitation in clinical settings has been commonly based on the semiquantitative evaluation of colour Doppler flow information by 2D-Doppler. However, colour Doppler underestimates the severity of mitral regurgitation, particularly in those patients with a higher degree of regurgitation. The clinical management, indications for surgical intervention and intraoperative decisions after valve repair have been based on a subjective estimation of valve regurgitation by 2D Doppler. In contrast, the 3D reconstruction of colour Doppler signals provides unique information about the direction, extent and size of regurgitant jets. New patterns of regurgitant flow, not described previously, can be observed and studied by this technique. The value of 3D Doppler imaging of regurgitant jets goes beyond the mere visualization of the complex geometry of asymmetrical regurgitation flows; it provides a system for displaying and measuring the turbulence and high-velocity components of the jets. This segmentation procedure is a fundamental step for unbiased 2D and 3D measurements of the jet size, independent of subjective interpretations of colour Doppler patterns.

Many methods based on the size of regurgitant jets have been proposed for clinical quantification of mitral regurgitation by colour Doppler. However, conventional 2D assessment of asymmetrical regurgitant jets fails to estimate the severity of mitral regurgitation. The most important finding of our investigation was the significant correlation found between 3D jet volumes and two clinical methods for assessing mitral regurgitation (angiography and pulsed Doppler). This correlation was found not only in patients with central jets, but also in patients with eccentric jets (Table 2). In addition, two fully automated procedures were used for volume measurements: (1) jet segmentation, based on an automated selection of turbulence and high-velocity components, and (2) the computation of all volume units (voxels) containing the selected Doppler information. Both procedures are independent of manual planimetry or subjective estimation and allow more precise measurements not only of 3D jet volumes but also of 2D jet areas and hold promise of becoming an essential tool for a reliable quantitative assessment of mitral regurgitation in clinical practice.

The absence of a gold standard for quantitative assessment of mitral regurgitation is a major limitation of all clinical studies dealing with valve regurgitation.
The regurgitant volumes obtained by pulsed Doppler\(^{[14]}\) and the angiographic grade of mitral regurgitation\(^{[13–29]}\) were used in our study for comparing the quantitative assessments of 3D jet volumes. Although these methods have been used in most clinical studies dealing with this topic\(^{[16–25]}\), they do not provide a reliable quantification of the mitral regurgitant volumes.

In addition, we measured conventional jet areas at maximal systolic expansion and maximal systolic jet volumes in order to maintain the comparability of the present study to previous clinical investigations dealing with the quantification of mitral regurgitation by jet size\(^{[16,23]}\). However, 3D acquisitions and reconstructions were accomplished on data from the entire cardiac cycle. The study of time-related changes of jet areas and volumes require further investigation. The primary aim of the present study was not to assess the precision of different Doppler echocardiographic methods, including 2D and 3D Doppler, for measuring mitral regurgitation, but rather to assess the clinical practicability of 3D colour Doppler and to investigate possible clinical applications.

Many physiological variables can influence regurgitant jet size as well as systolic pressure, atrial pressure, atrial size, atrial compliance and venous compliance. In addition, jet size measurement may also be influenced by technical factors such as gain setting, pulse repetition frequency, imaging of low velocity flow, jet geometry and temporal variation during systole. Three-dimensional Doppler retains all the above fundamental

Figure 6 Regression analyses and scatterplots of jet areas, jet volumes, regurgitant volumes and angiography. (a) Jet area vs regurgitation volume. (b) Jet volume vs regurgitation volume. (c) Scatterplot of the jet area for each angiographic grade of mitral regurgitation. Considerable overlap between the groups is evident. (d) The scatterplot of jet volume vs different angiographic grades of mitral regurgitation shows that the jet volumes identify well the patients with different degrees of mitral regurgitation. \(*P<0.01\) compared with grade I; \(**P<0.01\) compared with grade II; \(***P<0.01\) compared with grade III; otherwise, \(P=\text{ns.}\)
<table>
<thead>
<tr>
<th>Parameters</th>
<th>All jets (n=50)</th>
<th>Central jets (n=23)</th>
<th>Eccentric jets (n=27)</th>
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<tr>
<td></td>
<td>r</td>
<td>SEE</td>
<td>y=a+bx</td>
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<tr>
<td>Angio vs JA</td>
<td>r=0·80*</td>
<td>SEE=1·57</td>
<td>y=0·4+1·8x</td>
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<tr>
<td>Angio vs JV</td>
<td>r=0·89*</td>
<td>SEE=11</td>
<td>y=−19+19·4x</td>
</tr>
<tr>
<td>Regurgitant volume vs JA</td>
<td>r=0·61</td>
<td>SEE=2·1</td>
<td>y=3·0+0·1x</td>
</tr>
<tr>
<td>Regurgitant volume vs JV</td>
<td>r=0·93*</td>
<td>SEE=9·2</td>
<td>y=−3·2+0·9x</td>
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Angio=angiographic degree of mitral regurgitation; JA=jet area (cm²); JV=3D jet volume (cm³); r=linear correlation coefficient. SEE=standard error of estimate. *=P<0·01; otherwise, P=ns.
assessing the volume of mitral regurgitation. intervals, due to the lack of a gold standard method for investigation\[30–31\]. Up to now, regurgitant jets and visualization in original colour coding is still under limitations of colour Doppler, but the significant correlations between 3D jet measurements and conventional methods clearly showed that this technique provides a good and unbiased estimation of mitral regurgitation.

The 3D reconstruction of colour Doppler signals and visualization in original colour coding is still under investigation\[10–31\]. Up to now, regurgitant jets and cardiac structures have only been visualized in a grey-scale format\[12\], and previous efforts to obtain 3D reconstructions of intracardiac flow jets in colour coding required manual digitizing of Doppler flow signals\[30\]. The major limitation of previous approaches is the use of video signals, which only carry poor information and prevent a separate visualization of cardiac structures and flow. In addition, quantitative 2D Doppler information cannot be retrieved from video data, and the quantitative analysis of single flow jet components and the differentiation of slow velocities from turbulent flows cannot be performed by these procedures. Earlier studies did not consider the intrinsic Doppler information, since they analysed 2D Doppler as angiographic information. Quantitative assessment of colour Doppler was based on the analysis of Doppler data, including jet size, but omitted the study of velocity information contained in the jet. In contrast, by using digital signals coming directly from the echo equipment, we were able to separate the Doppler flow signals from cardiac structures, thus avoiding inaccurate manual segmentation for visualizing the regurgitant jets and for measuring the jet volumes.

Another important general limitation of most current methods of 3D echocardiography is that the acquisitions are not performed in real time. During the acquisition of Doppler signals in a transoesophageal echocardiographic examination it is mandatory that the position of the transoesophageal probe is stable\[32\]. In our series of patients it was possible to maintain the transducer in a very stable position inside the oesophagus since the examinations were performed under general anaesthesia immediately prior to heart surgery. During the examination, no significant variations occurred, either in arterial blood pressure or in left atrial pressure during data acquisition, and a very narrow range of heart rate variations was set for ECG triggering.

Today, the image acquisition of 2D Doppler signals can be obtained using commercially available echocardiographic systems, and 3D reconstruction is not beyond the capacity of current hard- and software. With the advent of real-time 3D echocardiography some limitations will be overcome and the clinical relevance of this technique will increase exponentially. These first 3D Doppler images reveal how complex the geometry and how misleading the visual assessment or the planimetry of the regurgitant jets based on 2D Doppler can be. In addition, the 3D measurements of the jet volumes are based on an automated segmentation and voxel count procedure, and, hence, independent of manual planimetry or subjective estimation. Therefore, we think that three-dimensional Doppler has a great potential for becoming a reference method for the assessment of patients with heart valve disease.


