Three dimensional colour Doppler echocardiography for the characterisation and quantification of cardiac flow events

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The accurate non-invasive quantification of cardiac flow volumes is an important goal in clinical cardiology. Computation of laminar volume flow through the ventricular outflow tracts would allow direct measurement of stroke volume and cardiac output. Grading of valvar regurgitation and follow up of patients with regurgitant lesions may be more accurately performed through calculation of regurgitant volume and fraction, and regurgitant orifice area. While estimates of these parameters can be made by conventional two dimensional (2D) echocardiographic techniques, these methods may be unreliable when applied to complex, dynamic, three dimensional (3D) flow events (table 1).[1–13]

The advent of three dimensional echocardiography (3DE) provides a solution to this basic limitation. 3DE generates a scan volume (as opposed to a two dimensional scan sector)

which produces a three dimensional dataset containing entire cardiac structures.[14 15]

Surface rendering may then be performed to produce an image with feature contours and depth perspective. Such an approach has proved useful in the representation of complex cardiac structural pathology and in the generation of images which reflect typical "surgeon's eye" views of the heart.[16] In addition, the 3D dataset may be transected by cut planes orientated in any direction within the volume ("anyplane imaging"). As the entire structure under study is encompassed in the dataset, volume calculations may be made without the need to make geometric assumptions regarding its morphology. A number of studies have confirmed the accuracy of 3D echocardiography for the calculation of cardiac chamber volumes.[17–20] 3D flow quantitation methods are currently under development and it seems reasonable to assume that these will be superior to the 2D methods listed in table 1. We review these new approaches to the quantification of cardiac flow events and indicate how they may ultimately be integrated into clinical practice.

Technique of 3DE for the visualisation and quantification of flow events

3D datasets may be generated essentially in two ways:

- By gated acquisition of multiple 2D echocardiographic planes, which are subsequently registered and integrated into a 3D block of data (dataset) by a dedicated 3DE reconstruction computer workstation[21 22]
- Using a dedicated 3D echocardiographic imaging system, which interrogates a pyramidal scan volume and generates a 3D dataset in real time (real time three dimensional echocardiography (RT3D))[23 24]

Naturally, 3DE representation of flow events necessitates the incorporation of colour Doppler flow velocity information into the dataset. While RT3D colour Doppler echocardiography has recently been introduced, at present the suboptimal acoustic sampling rate available for colour Doppler severely restricts frame rates, colour Doppler quality, and hence clinical applicability; therefore we will not consider this method. Nevertheless, the principles outlined for 3D flow quantitation should be applicable to RT3D colour Doppler datasets in the future.

The most common gated acquisition method currently in use involves the rotation of a conventional 2D probe (either a multiplane probe or a conventional transthoracic probe mounted in an external rotation device)

Table 1 Conventional 2D echo-Doppler cardiac flow quantification methods

| Technique	Limitations
"Eyeball" grading of regurgitant jet	Subjective
	As for regurgitant jet dimensions
Regurgitant jet dimensions[1–3] (length, width, area)	Machine settings
	Underestimation in the case of eccentric jets
Flow convergence region surface area[4–6] (regurgitant volume, ROA)	Morphological assumptions (hemisperical/hemielliptical)
Vena contracta cross sectional area[7–9] (ROA)	Angle dependency
	Localisation
Quantitative combined spectral Doppler and M/B mode methods[10–13] (regurgitant volume, stroke volume)	Cumbersome
	Margin for error

ROA, regurgitant orifice area.
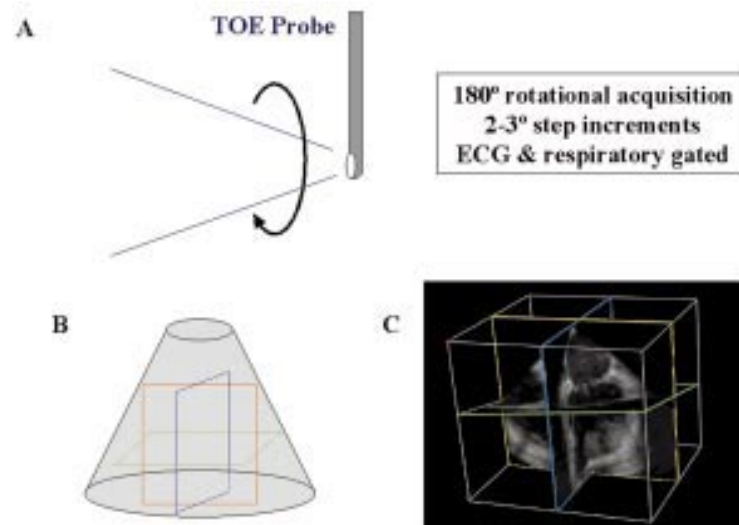
Figure 1 (A) Acquisition of multiple 2D images by rotation of multiplane transoesophageal probe through 180°. (B) Assimilation of multiple 2D imaging planes to generate a 3D volume of data. Coloured lines show typical cutplanes within the dataset. (C) Example of 3D dataset with demonstration of cutplanes.
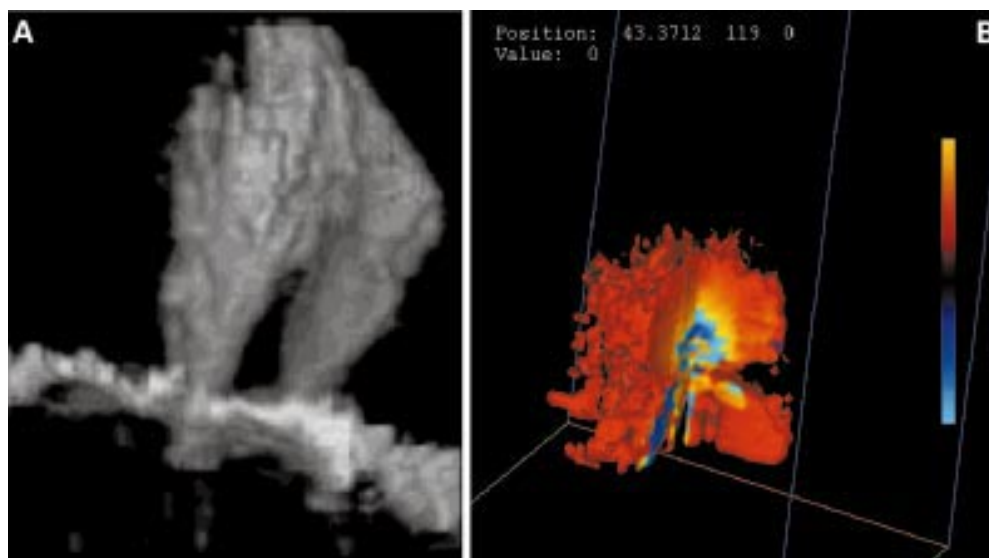
Figure 2   (A) Grey scale reconstruction of twin regurgitant jets extending upwards into the cavity of the left atrium. (B) Digital 3D colour Doppler rendering of a flow convergence region (in vitro acquisition).

through 180° around a central axis which is orientated perpendicular to the scan face. Multiple 2D images are then stored across the cardiac cycle (with ECG and respiratory gating) at fixed step increments over the 180° sweep. Typically, increments of 2° or 3° are employed (fig 1). The 2D data may take the form of video composite data, transferred directly from the "video out" port on the echocardiographic system to the 3D reconstruction workstation, or they may be stored as digital data on board the ultrasound system itself. In either case, these 2D data are subsequently assimilated into a 3D dataset, most commonly through processing by a dedicated 3DE workstation.

Colour Doppler data may be incorporated into the dataset in several ways:

- as a component of the analogue composite video signal, with colours digitised to red/green/blue assignments for representation in the reconstructed dataset
- as digital scan converted and colour encoded raster data
- as digital velocity assignments derived from raw scan-line data, before the application of any scan conversion algorithms.

The acquisition of digital velocity data for 3D datasets facilitates data transfer and storage, since raw rather than scan converted data are involved. Doppler calibration is also more accurate than for 3D images made up of scan converted or colour video data. The major advantage however is that full velocity information is retained in the dataset, providing efficient, reliable, and flexible velocity reconstruction in 3D space. Firstly, this means that the data may be displayed in a variety of formats, allowing the operator to view the reconstructed flow using familiar colour maps similar to those in use on conventional 2D systems. Secondly, as will be discussed shortly, velocity features can be delineated and flow volumes and rates directly computed from these digital velocities. In those datasets generated from scan converted or analogue video data, velocity values must be reassigned to the colour values using the appropriate look-up tables.

3D representation of cardiac flow events

Surface rendering techniques may be applied to colour Doppler datasets to generate images of regurgitant jets and flow convergence regions in three dimensional space (fig 2). In addition, manipulation of cutplanes through the dataset allows the vena contracta (the narrowest cross section of the regurgitant jet,
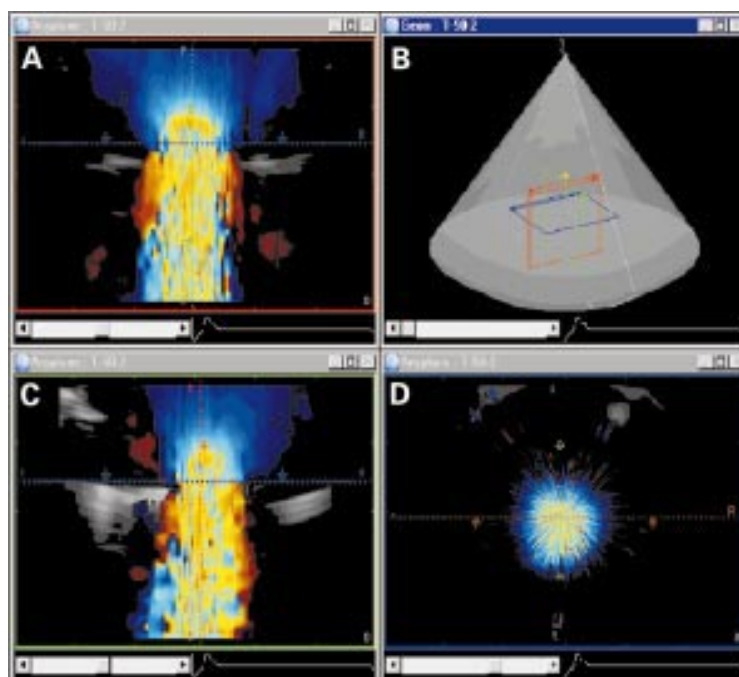

Figure 3   Localisation of the vena contracta in the 3D dataset (in vitro acquisition). Colour Doppler flow data have been acquired parallel to flow. (A) and (C) show direction of flow from top to bottom in the two. (D) A perpendicular (blue cutplane) cut through the narrowest portion of the regurgitant jet, the vena contracta.
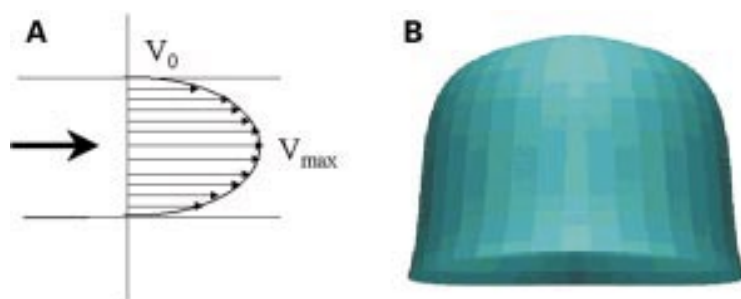
Figure 4 (A) Example of laminar flow pattern, such as might be encountered in the ventricular outflow tracts or the great vessels. (B) 3D reconstruction of a laminar flow profile (in vitro acquisition).
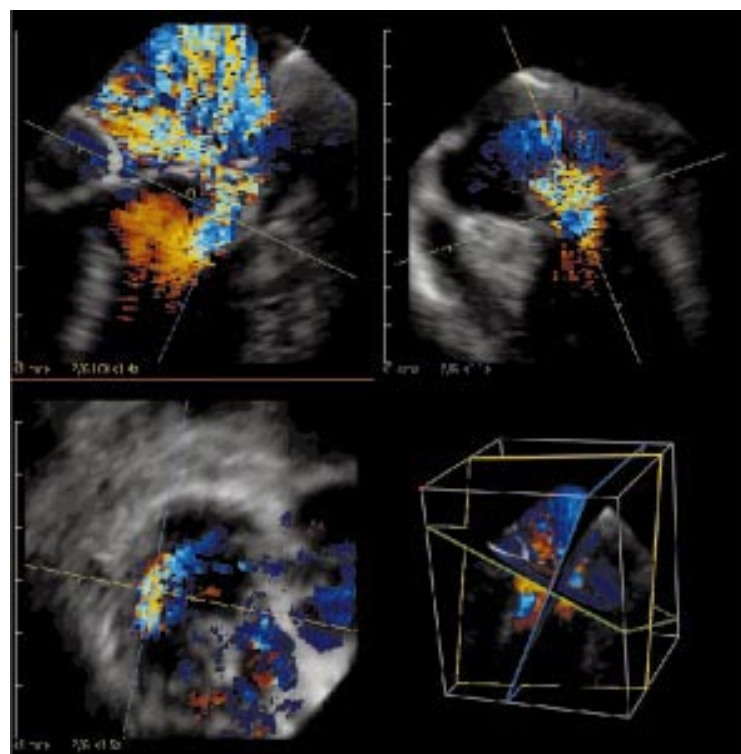

Figure 5 Identification of the vena contracta in a case of anterior mitral valve leaflet prolapse. In spite of the eccentricity of the jet, the cutplanes can still be manipulated to produce a cross section of the vena contracta (bottom left panel). It is then a simple process to measure its area. This should give an approximation of the regurgitant orifice area.

assessment of laminar flows, such as might be encountered in the ventricular outflow tracts or great vessels. Flow in these structures travels in a series of laminar, concentric shells, with flow velocities being greatest in the centre of the vessel and approaching zero at the edges.[25 26] This makes quantification of flow difficult, especially in the case of skewed flow patterns. 2DE methods for the quantification of outflow tract or great vessel flows involve pulsed wave Doppler sampling in the centre of the vessel and an assumption that the velocity measured is representative of the entire cross sectional flow profile.[12 13 27] In the case of laminar flows, particularly if these are skewed, this may well not be the case.[28] More sophisticated digital 2D methods exist which can characterise flow velocity profiles in two dimensional space—for example, Automated Cardiac Output Measurement, Toshiba Imaging Systems[29–32], but assumptions must still be made regarding the morphology of the entire cross sectional flow profile in question. To reliably analyse laminar flow patterns, interrogation of the entire flow cross section is required. This is obviously not possible using conventional 2D imaging (because it would be necessary to image perpendicular to the angle of flow). Through its ability to acquire flow velocity data parallel to flow and subsequently analyse the resulting dataset in any plane, 3DE should permit full characterisation of the entire cross sectional velocity profile (fig 4). This should also allow more accurate quantification of absolute flow volume.

Specific review of 3DE flow quantification techniques

The 2D methods for flow quantification described in table 1 can also be applied to 3D datasets. Their accuracy is currently under investigation both in the in vitro and in vivo settings.

3D JET VOLUME CALCULATION

Calculation of jet volume may overcome some of the problems encountered with 2D jet area methods. In the case of eccentric, wall adherent jets, calculation of jet volume might be a more reliable quantitative technique than jet area, since the latter is based on sections through the thin portion of the jet. This remains to be proved, however. Jet volume calculations will of course be influenced by the same machine factors as 2D jet area measurements, and preliminary results suggest that this may limit their usefulness.[33]

VENA CONTRACTA CROSS SECTIONAL AREA

The ability of 3DE to acquire flow velocity data parallel to flow and make subsequent flow computations in any plane has already been discussed. In addition, 3DE allows the user to navigate through a dataset and accurately pinpoint the position of the vena contracta, even if the jet itself is eccentrically positioned (fig 5). Area measurements can then easily be made. Even early 3D vena contracta studies, where flow events were imaged in grey scale, demonstrated the accuracy of this method.[34]

usually encountered at or in the immediate vicinity of the regurgitant orifice) to be precisely located (fig 3). Measurement of the jet cross section at this point should provide a reasonable approximation of the effective regurgitant orifice area. Such a technique highlights a further advantage of 3DE. Colour Doppler data must be acquired in an orientation parallel to flow to preserve the accuracy of measured velocity values. For conventional 2D colour Doppler, imaging perpendicular to flow to make cross sectional vena contracta measurements may lead to erroneous velocity signals due to the Doppler angle effect. 3DE allows velocity data to be acquired in a direction parallel to flow, and subsequent flow cross section measurements to be made perpendicular to flow within the 3D dataset without loss of accuracy of velocity information.

Of major importance, these features of 3DE (parallel acquisition with accurate digital velocity solutions) prove most advantageous in the
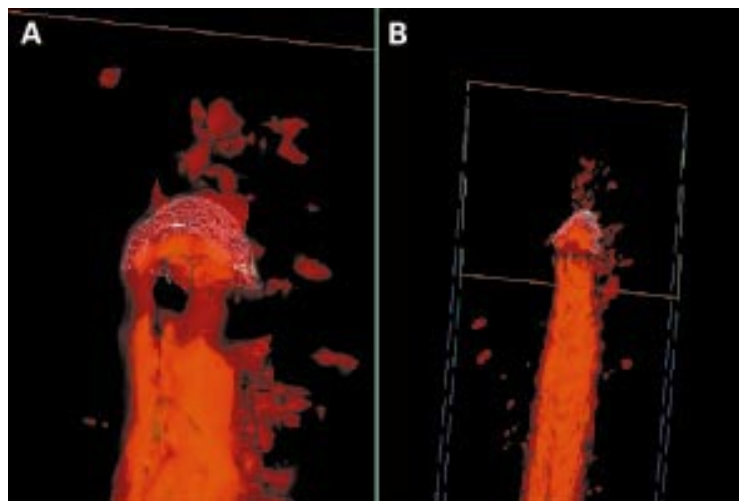
Figure 6   Calculation of the flow convergence region surface area in the 3D dataset. (A) is a magnified view of (B). A wire model framework has been fitted to the surface of the flow convergence region. Surface area computations are made using this model. Note that no geometric assumptions are involved in the measurement of the surface area.

Flow convergence region surface area computation

The flow convergence region (FCR) is an isovelocity boundary within the flow field approaching a regurgitant orifice. Acceleration of flow towards the orifice occurs in an organised fashion, and as flow velocities exceed the aliasing limit an abrupt colour change occurs. Measurement of the area of this isovelocity surface is an integral part of FCR based flow rate and regurgitant orifice area computations. Since 3DE displays the entire FCR, a more accurate assessment of its area can be made without the need to make assumptions regarding its shape (fig 6). 3DE flow convergence based methods have been shown to accurately predict flow rate and regurgitant orifice

area.[35] [36] Moreover, the retention of velocity assignments in digital Doppler 3DE allows user defined isovelocity regions to be extracted automatically from the dataset.

Quantification of cardiac output and great vessel flows

As indicated above, accurate quantification of flow through larger vessels, such as the ventricular outflow tracts or the great vessels, requires a method which can fully characterise complex and dynamically changing cross sectional flows, irrespective of their geometry. We have developed a digital 3D colour Doppler method which computes flow rates and stroke volumes through the spatiotemporal integration of the individual velocity vectors making up the flow cross section within the dataset. The technique is displayed in fig 7 and is described in detail elsewhere.[37] In vitro studies using expansile rubber tubes have shown this to be an accurate method for calculation of instantaneous flow rates and stroke volumes. In addition to permitting full characterisation of the flow profile in three dimensional space, another advantage of this method is that changes in the area of cross sectional flow can be tracked as the vessel expands and contracts during the cardiac cycle. Applying such a method to flow through the ventricular outflow tracts, for example, should allow direct computation of cardiac output.

Conclusion

Continuing improvements in computing power and sophistication have led to the development of 3D workstations which can acquire and produce 3D datasets in a matter of minutes. Real time 3D colour Doppler imaging for clinical use is on the horizon. The accuracy of 3DE
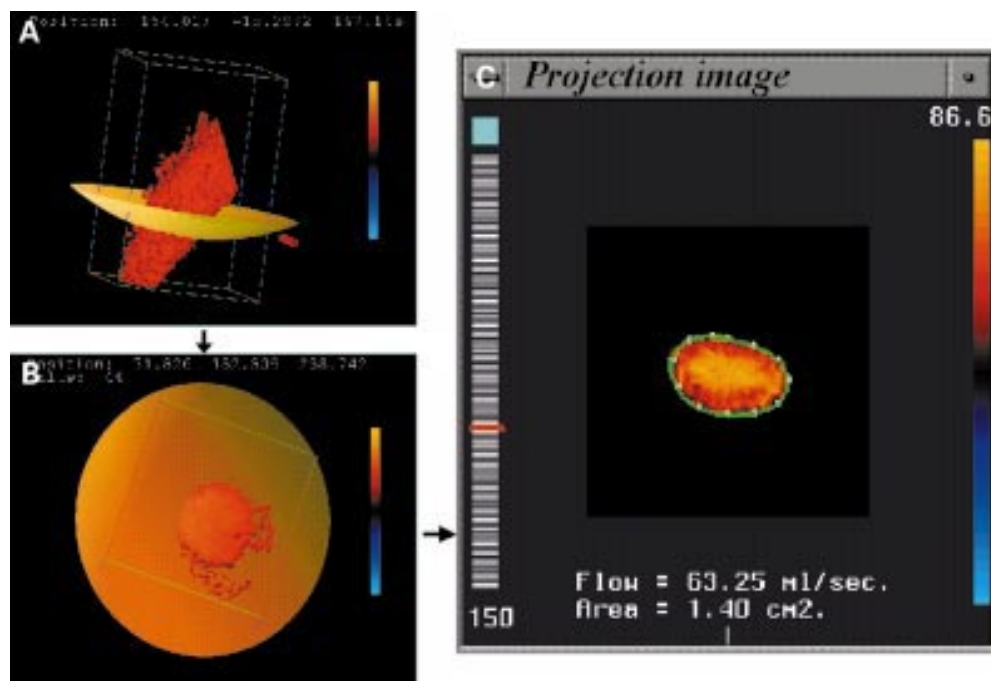

Figure 7   Computation of instantaneous flow rate from a digital 3D Doppler dataset, acquired from an in vitro tube model of laminar flow. The colour flow cross section is identified within the dataset (A), (B). The computer performs a spatial integration of the individual velocity vectors contained within the flow cross-section (C) to generate an instantaneous flow rate.

(and its superiority over conventional 2D methods) for the measurement of cardiac chamber volume has already been clearly shown. While 3DE flow quantification is at present in its infancy, the development and evaluation of new methods such as those described above are proceeding rapidly. We can be optimistic that in the not too distant future 3DE will provide a truly non-invasive method for the accurate quantification of cardiac output and for the reliable and reproducible assessment of valvar regurgitation.

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