REVIEW

Three-dimensional echocardiography of colour Doppler flow

L’échographie tridimensionnelle du Doppler couleur

Zhi-Wen Zhou\textsuperscript{a,b}, Ya-Wei Xu\textsuperscript{a}, Muhammad Ashraf\textsuperscript{b}, David J. Sahn\textsuperscript{b,*}

\textsuperscript{a} Shanghai Tenth People’s Hospital Affiliated Tongji University, Shanghai, People’s Republic of China
\textsuperscript{b} Oregon Health & Science University, Portland, OR, USA

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Summary Three-dimensional echocardiography of colour Doppler flow developed quickly with the advent of three-dimensional echocardiography. An increasing amount of research has shown that three-dimensional echocardiography of colour Doppler flow is feasible and facilitates measurement of stroke volume and cardiac output, and assessment of heart valve and congenital heart diseases. Although the technique still has some drawbacks that hamper its widespread use, as the technology continues to improve, three-dimensional echocardiography of colour Doppler flow has the potential to serve as a powerful noninvasive clinical tool, aiding physicians in the serial assessment of heart disease and response to intervention. We review the developmental history and the most recent clinical information related to three-dimensional echocardiography of colour Doppler flow.

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KEYWORDS
Colour Doppler flow; Cardiac heart disease; Three-dimensional echocardiography; Colour flow mapping; Three dimensional Doppler; Tridimensional echocardiography

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* Corresponding author. Fax: +503 494 2190.
E-mail address: sahnd@ohsu.edu (D.J. Sahn).

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au traitement. Nous proposons dans cette revue générale de présenter les étapes du développement de l’échographie Doppler couleur tridimensionnelle, ainsi que les implications cliniques potentielles nouvelles et attendues.

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### Abbreviations

| 2D | two-dimensional |
| 3D | three-dimensional |
| 2DE | two-dimensional echocardiography |
| 3DE | three-dimensional echocardiography |
| 2DE-CDF | two-dimensional echocardiography of colour Doppler flow |
| 3DE-CDF | three-dimensional echocardiography of colour Doppler flow |
| LVOT | left ventricular outflow tract |
| MR | mitral valve regurgitation |
| RT3DE | real-time three-dimensional echocardiography |

### Background

One of the greatest achievements of the past two decades in ultrasound imaging of the heart was the development of three-dimensional echocardiography (3DE) [1–3]. 3DE provides valuable clinical information that gives echocardiographers new levels of confidence in the diagnosis of heart disease. The invention of real-time 3DE (RT3DE) was a technological milestone in the field of 3DE [2–5]. With the growing availability of 3DE technology, 3DE of colour Doppler flow (3DE-CDF) also developed quickly [5,6]. The multiple attractive merits of volumetric colour Doppler flow imaging have sparked significant interest among researchers and clinical workers, resulting in satisfactory achievements, some of which have endorsed 3DE-CDF for clinical use by demonstrating its use in heart examination [7,8].

The purpose of our paper is to review the developmental history of colour Doppler flow and to update readers with the most recent advancements in 3DE-CDF. Our article also pays close attention to the clinical use of 3DE-CDF.

### Development history

During the past few decades, colour Doppler flow imaging has benefited from technical innovations and has become a sophisticated cardiovascular ultrasound technology, which displays blood flow and velocity information on grey-scale images [9,10]. Colour Doppler flow imaging can provide us with more detailed information on blood flow within the body than any other technique. Employing the hypothesis that there was some kind of regular shape within the heart, 2D of colour Doppler flow (2DE-CDF) was used widely in the assessment of stroke volume, cardiac output, valve heart disease and congenital heart disease [5,6,9–11], and has become established as one of diagnostic tools used most frequently in daily clinical practice in cardiology. However, since the advent of colour Doppler flow, most work on colour Doppler flow imaging has been based on 2DE. 2DE-CDF has inherent inaccuracies, because most of the area of the heart where colour Doppler flow works is geometrically complex and changes during the course of the cardiac cycle [6,12]. Moreover, 2DE-CDF has the limitation of angle dependency, which is not easy to overcome in daily work [6,9].

The complex anatomy of cardiac structures requires three-dimensional (3D) spatial orientation of images for a better understanding of structure and function. Twenty years ago, 3DE was developed in order to overcome the drawbacks of 2DE [1–4]. At an early stage, 3DE was based on 2DE and was completed by reconstruction of multiple two-dimensional (2D) images [1,12,13]. The scan head of the 3DE system was rotated around a fixed axis at a set rate for capturing multiple 2D images around the central axis [1,2,6]. The multiple 2D image slices were then processed offline to produce a 3D image. Most recently, RT3DE took a big step forward, as a result of the design of an ultrasound transducer with a matrix array. The matrix probe (e.g., Philips, Andover, MA, USA) houses 3000 elements as opposed to 64 in the usual 2D scan head; these are connected to transmit and receive simultaneously, to form a pyramidal-shaped volume that is gated over a cardiac cycle.

This volume is then displayed immediately on the system [2,6]. The simultaneous display of multiple images allows a 3D perspective and the anatomically correct examination of any structure within the volumetric image. With the RT3DE advantages of fewer artefacts, less operator-dependency and lower time-consumption for patients and echosonographers, reconstructive 3DE was replaced quickly by RT3DE [4,6].

The development of 3DE also promoted the swift progression of 3DE-CDF from reconstructive 3DE to RT3DE [6,14]. 3DE volumes containing colour Doppler flow data are acquired in a similar way to the grey-scale volumes of 3DE systems [15,16] (Fig. 1). Software has been developed to allow calculation of the flow volume in a similar way to 3D methods and the retained velocity assignments in the datasets. 3DE-CDF has several advantages over 2DE-CDF and overcomes the spatial limitations of the 2DE technique, such as a lack of geometric assumptions and less angle dependency [13–17]. Volume acquisition by RT3DE-CDF requires only a few beats, and therefore motion and respiratory artefacts are reduced greatly [6].

Three-dimensional echocardiography of colour Doppler flow enables complete 3D visualization of the blood jet and new ways of assessing blood flow by noninvasive techniques (Fig. 2). Because 3DE-CDF can show the relative spatial location of blood jets and cardiac structures, it can clearly provide 3D information about the actual extension, direction, origin and size of intracardiac flows of regurgitant lesions, shunts and cardiac output [5,6,16–18]. Therefore, combined with the advantages of 3D structure
Three-dimensional echocardiography of colour Doppler flow

Figure 1. Panel A shows three-dimensional imaging scans of a pyramidal volume. Panel B shows the schematic of three-dimensional volume acquisition. The left section of Panel B shows a sweep containing seven (30/7) individual segments triggered by electrocardiography. The right section of Panel B shows a finished three-dimensional volume (the pyramid) that contains the colour flow and cardiac structure. Panel A comes from Lang et al. [2]; Panel B comes from Li et al. [22].

Clinical use

Measurement of cardiac output

Accurate measurements of stroke volume and cardiac output are important in both clinical medicine and medical research. In the past, by assuming cylindrical aortic geometry and laminar blood flow at the left ventricular outflow tract (LVOT), 2DE measured the velocity and diameter of the LVOT and then calculated cardiac output [9,20]. This 2D measurement suffers from inaccuracy, because not only is the LVOT anatomy asymmetrical and sometimes even severely irregular, but also the LVOT diameter changes during the course of the cardiac cycle [12]. Moreover, the peak velocity profiles of LVOT used in 2DE-CDF are not necessarily in the centre and peak velocity must usually be angle corrected; both of these factors tend to lead to an underestimation of cardiac output [6,16,18,20,21]. 3DE-CDF can eliminate these limitations of 2DE-CDF with the advantages of 3D spatial images and less angle dependency (Fig. 3).

Figure 2. The simulated three-dimensional sampling surface and velocity vectors.

Figure 3. Panel A shows the RT3DE signal in the left ventricular outflow tract. Panel B shows that the flow volume from the RT3DE data is calculated by integration of the flow data through the valve, within the aorta, over time; (a) shows a longitudinal projection of the LVOT, (b) shows the flow in a projected cross-section, and (c) shows the calculated flow rate. AV: aortic valve; LVOT left ventricular outflow tract; SV: stroke volume.
In recent years, besides in vitro and animal studies, several human studies assessing the calculation of cardiac output have proved the feasibility and accuracy of 3DE-CDF, and have shown that 3DE-CDF can overcome the limitations of 2DE-CDF [14,20—23]. Using the method of thermodilution as the reference standard, Lodato et al. acquired cardiac output data by 3DE-CDF and 2DE-CDF. They found that 3DE-CDF had better correlation coefficients with thermodilution than 2DE-CDF (r = 0.94 and r = 0.78, respectively), and that the bias and limits of agreement in the LVOT derived by 3DE-CDF were also smaller than those derived by 2DE-CDF (−1.84 ± 16.8 and −8.6 ± 36.2 mL, respectively) [18]. Two clinical studies by our group also showed that 3DE-CDF has good ability to calculate cardiac output compared with the other gold standards [7,24].

Valve disease

Mitral valve

Mitral valve regurgitation (MR) is the valve lesion encountered most frequently in modern clinical practice. While the common 2DE-CDF is an excellent technique for detecting the presence of MR, quantifying the severity of MR and exploring its cause by 2DE-CDF in detail is still difficult. This is because the differences in regurgitant flow through the mitral valve between patients are very large and change dynamically, making them almost impossible to characterize only by 2DE [8,25—27]. The regurgitant flow through the mitral valve is often irregular and non-circular, with wall-hugging jets [17]. Studies have shown that the effective regurgitant orifice area of MR is significantly asymmetric and hemielliptic rather than hemispheric, resulting in poor estimation of the effective regurgitant orifice area with single-plane vena contracta measurements [27,28].

Three-dimensional echocardiography of colour Doppler flow is superior to 2DE-CDF for measuring MR because it has the advantage of volumetric imaging of the geometry of the flow convergence surface without the assumption of rotational symmetry [29]. Clinical research has shown that 3DE-CDF is useful for measuring MR compared with other standards [30]. One recent in vitro study demonstrated that compared with assessing vena contracta diameter by 2DE-CDF, the vena contracta area by 3DE-CDF had a stronger correlation with the known orifice area (r = 0.92 and r = 0.56, respectively); in this clinical study of 61 patients, the vena contracta area by 3DE-CDF correlated with the Doppler-derived effective regurgitant orifice area and the relationship was stronger than with the vena contracta diameter measured by 2DE-CDF (r = 0.85 and r = 0.67, respectively). Moreover, it was found that the advantage of measuring the vena contracta area by 3DE-CDF compared with by 2DE-CDF was that it was better in eccentric jets (r = 0.87 and r = 0.6, respectively), especially in moderate and severe MR [31]. Other studies also found that maximal proximal isovelocity surface area radius and vena contracta diameter.
contracta area were underestimated by 2DE-CDF compared with RT3DE-CDF [27,30,32].

More importantly, 3DE-CDF can also help us to identify the detailed origin and shape of the mitral valve leak (valvular vs paravalvular), which can increase our understanding of the reason for MR and support the surgical approach markedly [8,33,34] (Fig. 4).

Aortic valve

Just as in measuring cardiac output, assessment of the aortic valve area in aortic stenosis by the 2DE-CDF continuity-equation also relies on measurement of velocity, and geometric assumptions of aortic valve area and LVOT, which can lead to errors, because most aortic valve area and LVOT shapes are not regular as had been assumed and the velocity profile is not flat [12,35]. A recent co-study (including patients and sheep models that mimicked upper septal hypertrophy) has shown that RT3DE-CDF-derived LVOT stroke volume in the calculation of aortic valve area by the continuity equation is more accurate than that derived by 2DE-CDF, even with LVOT geometry modification [35].

Aortic regurgitant volume also can be assessed by 3DE-CDF. In one study by our group, using electromagnetic flowmeters as a reference, the maximum jet volume by 3D reconstruction of colour Doppler flow was found to correlate very well with the aortic regurgitant volume \( (r = 0.92; \ p < 0.0001) \), the mean regurgitant flow rate \( (r = 0.87; \ p < 0.0001) \) and the regurgitant fraction \( (r = 0.87; \ p < 0.0001) \). However, the maximum jet area of 2DE-CDF did not correlate with the aortic regurgitant volume \( (r = 0.41; \ p = \text{not significant}) \) and related poorly to the regurgitant fraction \( (r = 0.52; \ p < 0.05) \) [36]. In another study, our group also showed that 3D-based determination of the vena contracta cross-sectional area could provide accurate quantification of the severity of aortic regurgitant [37].

Tricuspid valve and pulmonary valve

Although the assessment of tricuspid valve disease has not been explored as widely as the mitral valve, it is still possible to assess tricuspid valve disease by 3DE and 3DE-CDF [38,39]. Sugeng et al. have verified that quantitative assessment of tricuspid valve regurgitant jets using 3DE-CDF is feasible and has a good correlation with proximal isovelocity surface area-calculated tricuspid valve regurgitant volumes, although 3D-derived tricuspid valve regurgitant volumes were slightly overestimated in relation to 2D-derived volumes [40].

Three-dimensional echocardiography of colour Doppler flow is also a promising tool for measuring pulmonary regurgitation. Research has shown that pulmonary regurgitation and right ventricular forward stroke volumes measured by 3DE-CDF agree well with reference to electromagnetic probes \( (r = 0.91 \text{ and } r = 0.95, \text{ respectively}) \) [41].

Congenital heart diseases

Three-dimensional echocardiography of colour Doppler flow can also play an important role in assessing congenital heart

![Figure 6](image_url)

**Figure 6.** Panels A and C show the normal foetal right ventricular outflow tract. Panels B and D show right ventricular outflow tract in a foetus with tetralogy of Fallot and absent pulmonary valve; the annulus is narrowed and the peripheral pulmonary arteries are aneurysmally dilated.
disease (Fig. 5). In 2001, Ishii et al. showed that the shunt flow rate of the ventricular septal defect calculated by 3DE-CDF correlated well with reference results calculated by cardiac catheterization \((r = 0.95; p < 0.001)\), and this result was a better estimation compared with 2DE \([42]\). In another study, it was shown that 3DE-CDF could also be used to calculate shunt flow of atrial septal defect accurately \([43]\). Moreover, there have been some reports that 3DE-CDF can also help to accurately diagnosis rare congenital heart disease, such as aortopulmonary window and left ventricular outflow tract to right atrium shunt; this can help in the design of optimal surgical or catheter-based therapy \([44,45]\).

The advantages of 3DE-CDF have also been used to improve detailed diagnosis in the prenatal foetal heart (Fig. 6). Several reports have shown that RT3DE-CDF can assist in the evaluation of foetal cardiac anatomy and haemodynamics, and can offer potential advantages over conventional 2DE \([46,47]\).

**Limitations and future direction**

It should be noted that most of the 3DE-CDF study groups mentioned above were small and that some of their results showed small deviations from other standards; they therefore need to be verified further \([7]\). Before 3DE-CDF becomes a viable tool in clinical practice, more studies involving larger numbers of patients are needed to further certify its function.

As a new technology, 3DE-CDF still has several shortcomings that hamper its widespread use in research and clinical practice. RT3DE-CDF is acquired over seven cardiac cycles during a breath hold. This may result in temporal and spatial misregistration, and stitch artefacts of subvolumes caused by movement of the probe, inability to maintain a breath hold, arrhythmias or excessive cardiac translational motion, which may lead to inaccuracies in measurements or completely inadequate data sets for analysis \([6,16]\). Until technology advances to the point of being able to acquire colour Doppler flow data during a single cardiac cycle, this technique may not be applicable to patients with atrial fibrillation, sinus arrhythmias or frequent premature beats.

Another major impediment of 3DE-CDF is that the sector sizes of colour Doppler are too narrow to complete visualization of eccentric jets, particularly if one wants to image the extent of the jet contained within an atrial chamber. In addition, the current RT3DE system does not allow simultaneous acquisitions of colour Doppler flow and pulsed wave Doppler data. Other challenges include a large probe, high frame rates, low depth, the continued presence of aliasing and colour bleeding, and offline analysis \([6,16,18]\). In the coming years, advances in transducer and computer technology ought to focus on the following aspects: acquisition of 3DE-CDF in a single cardiac cycle, non-electrocardiographic gating, lower frame rates, a wider-angle pyramid of data with a wider colour flow sector, miniaturization of the probe and faster processor speed.

**Conclusion**

In the past two decades, the development of 3DE has promoted the rapid advance of 3DE-CDF. An increasing amount of research has shown that 3DE-CDF is feasible and has the ability to overcome the limitations of 2DE-CDF for measuring stroke volume and cardiac output, assessing heart valve disease and detecting congenital heart disease. Although until now the technique has had some drawbacks that have hampered its widespread use, as the technology continues to improve, 3DE-CDF has the potential to serve as a powerful noninvasive clinical tool, aiding physicians in the serial assessment of disease and response to intervention.

**Conflict of interest statement**

None.

**References**

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