Feasibility and clinical decision-making with 3D echocardiography in routine practice

J L Hare,[1] C Jenkins,[1] S Nakatani,[2] A Ogawa,[2] C-M Yu,[3] T H Marwick[4]

[1] University of Queensland, Brisbane, Australia; [2] National Cardiovascular Centre, Osaka, Japan; [3] The Chinese University of Hong Kong, Hong Kong, People's Republic of China; [4] University of Queensland, Brisbane, Australia

Correspondence to: Professor T H Marwick, University of Queensland Department of Medicine, Princess Alexandra Hospital, Ipswich Road, Brisbane, Q4102, Australia; t.marwick@uq.edu.au

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ABSTRACT

Objective: To assess the feasibility and potential impact of routine three-dimensional (3D) echocardiographic assessment of left ventricular (LV) ejection fraction and volumes on clinical decision-making.

Methods: Patients referred to three hospital-based echocardiography laboratories underwent 2D echocardiography (2DE) and 3D echocardiography (3DE). Feasibility was assessed in a group of 168 unselected patients and decision-making assessed within an expanded group of 220 patients. The time for acquisition and measurement was obtained. Feasibility was defined by ability to measure LV parameters. The potential of 3DE to alter clinical decisions based on 2DE was evaluated by the ability to identify four clinically relevant measurement thresholds: (1) LV end-systolic volume (LVESV) >50 ml/m^2 (indication for surgery in regurgitant valve disease); (2) LVESV >30 ml/m^2 (prognosis after infarction); (3) LV ejection fraction (LVEF) <35% (indication for implantable defibrillator); and (4) LVEF <40% (indication for heart failure treatment).

Results: 3DE was technically feasible in 83% of unselected patients. The additional time for 3D acquisition and measurement was available in 184 patients and was 5.4 (SD 2.0) minutes. The use of 3DE changed categorisation in between 6–11% of patients. Within threshold categories, 3D reallocated 17.5% (11/63) of patients with LVEF <35%, 16.1% (13/81) for LVEF <40%, 12.4% (13/105) for LVESV >30 ml/m^2 and 8.5% (5/59) for LVESV >50 ml/m^2. Most of the impact of 3D was within 10 ml/m^2 of selected volume thresholds (⩾75%) and 10% of EF thresholds (>80%).

Conclusion: Measurement of LV volumes and EF by 3DE is clinically feasible and has the potential to significantly alter clinical decision-making.

Accurate measurement of left ventricular (LV) volumes and ejection fraction (EF) is an important aspect of prognostic assessment, monitoring of therapy and assessment of disease progression in many cardiac conditions.[1–3] Conventional measures of LV function using two-dimensional echocardiography (2DE) have less accuracy and greater test-retest variability than newer methods such as cardiac magnetic resonance imaging (MRI),[4] and this is of particular importance in patients referred for sequential or follow-up studies. However, the utility of cardiac MRI in routine clinical practice continues to be restricted by limited availability and expense.

Three-dimensional echocardiography (3DE) may address some of these limitations, and the evolution of this technique from reconstruction to real-time acquisition has made this approach more feasible for clinical use.[5] Real-time (RT)-3DE is more accurate for assessing LV volumes and EF, with less test-retest variability and better interobserver reproducibility than 2DE.[4] These observations have extended to people with both normal and abnormal LV morphology,[6] with an accuracy comparable to cardiac MRI and exceeding that of nuclear techniques.[7] Despite these findings, the clinical feasibility of RT-3DE in routine practice and its incremental benefit over 2DE in terms of clinical decision-making are undefined.[8 9] In this study, we sought to evaluate the feasibility and potential clinical impact of accurate measurement of LV volumes and EF by 3DE compared to 2DE. Specifically, we sought to examine the time cost of adding a 3D assessment of EF and volumes to a standard 2D echocardiogram, and the ability to change management decisions made on the basis of LV volumes and EF.

METHODS

Patient selection

We studied 249 patients who were referred for clinically indicated routine 2DE at three hospital-based echocardiography laboratories. Feasibility and incremental time for 3DE were assessed in 168 unselected consecutive patients (age 60 (SD 15) years, 61% male), while a further 81 clinical patients were included on the basis of the presence of congestive heart failure and/or low EF. The final patient group with both 2D and 3D data available for analysis comprised a total of 220 patients (61 (15) years, 70% male). The three different hospitals contributed 54 (Japan), 131 (Australia) and 35 (Hong Kong) patients, respectively.

Clinical indications for routine echocardiography were grouped into one of seven categories according to the predominant clinical query: (1) ischaemic heart disease; (2) valvular heart disease; (3) congestive heart failure; (4) hypertension; (5) pulmonary hypertension; (6) arrhythmia; and (7) other/unknown. Patients underwent conventional 2DE and additional 3DE assessment of LV volumes and EF. Feasibility of 3DE was defined as the ability to measure LV parameters.

Study design

The potential for 3DE to alter clinical decisions was assessed by the identification of four clinically relevant measurement thresholds:

1. Left ventricular EF (LVEF) <35% (indication for implantable defibrillator)[10 11]
2. LVEF <40% (indication for treatment of systolic heart failure)[12 13]
3. LV end-systolic volume index (LVESVi) >50 ml/m^2 (indication for surgery in regurgitant valve disease),[14–17] and

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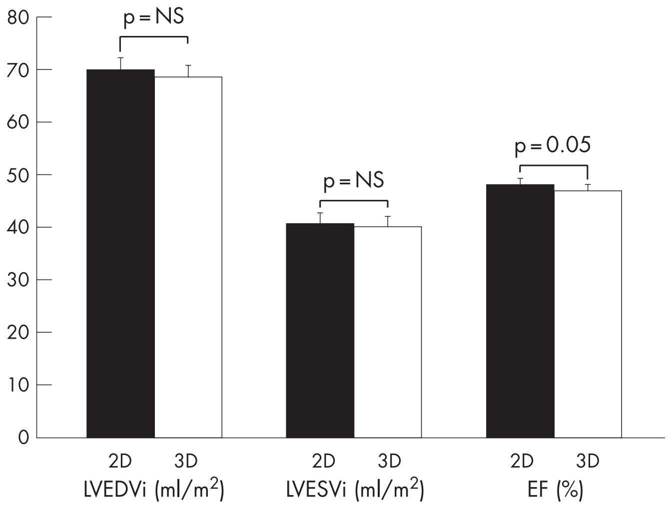

Figure 1 Differences between mean 2D and 3D EF (ejection fraction) and volumes. LVEDVi, left ventricular end-diastolic volume index; LVESVi, left ventricular end-systolic volume index.

4. LVESVi >30 ml/m^2 (prognosis post-myocardial infarction).[1 18]

The ability of 3DE to reclassify the 2DE categorisation of a patient was then assessed as a measure of potential to alter clinical decision-making. We additionally sought the ranges of 2D measures where 3D added most to patient categorisation.

2D echocardiography

Transthoracic 2D echocardiography was obtained with harmonic imaging using a 3-MHz phased array transducer (iE33, Philips Medical Systems, Andover, MA, USA). Measurement of LV end-diastolic volume (LVEDV), LVESV and EF were obtained using on-board software using the Simpson's biplane method, with images taken from the apical and two-chamber views, in accordance with the American Society of Echocardiography guidelines. All volumes were indexed to body surface area using the DeBois method.[19]

3D echocardiography

A full volume image for 3D analysis was obtained over four cardiac cycles using a matrix array transducer (×3 transducer, iE33 System, Philips Medical Systems, Andover, MA, USA). Semi-automated LV border detection was used to obtain 3DE measurements (Qlab, Philips, Andover, MA, USA). Full volume data were manipulated in three cross-sections to derive conventional four-chamber, two-chamber and short-axis views. From these views, annular and apical points were selected in order to facilitate contour tracing, with subsequent formation of a 3D endocardial shell and calculation of 3D volumes.[20]

Statistical analysis

Measures of EF, EDV and ESV are expressed as mean (SD). Patients were then categorised as below or above each of the clinical thresholds outlined above, firstly, by 2DE measures and then subsequently by 3DE. The proportion of patients who were reclassified by 3D was then assessed to give some indication of potential impact of the 3D measures on clinical decision-making. Differences within subgroups (that is, volumes, ejection fraction) were assessed using a t test. Statistical analysis was performed with standard software (SPSS 14, SPSS Inc, Chicago, IL, USA).

RESULTS

Feasibility

Of the 168 unselected patients referred for routine clinical echocardiography, the indications for echocardiography were categorised and consisted of the following: (1) ischaemic heart disease (20 patients, 12%); (2) valvular heart disease (43 patients, 26%); (3) congestive heart failure (29 patients, 17%); (4) hypertension (15 patients, 9%); (5) pulmonary hypertension (11 patients, 7%); (6) arrhythmia (six patients, 3%) and; (7) other/unknown indications (44 patients, 26%). 3D echocardiography was feasible in 140 patients (83%). Of these, 139 had both 2D and 3D data available for analysis of EF and volumes. The reasons for failure to obtain a 3D dataset included poor image quality in 24 patients (14%), failure of ECG triggering in three (2%) and was unknown in one patient (0.6%). Of the final 220 patients, the increment in time for acquisition and online analysis of 3D LVEF and volumes was available in 184 patients (84%) and was 5.4 (2.0) minutes. There was a difference in 3D acquisition and analysis times between centres (4.1 (1.7) minutes, 5.6 (1.9) minutes and 6.5 (2.1 minutes, $p<0.001$). Patients at the site with lowest acquisition and analysis times had a significantly lower body mass index (22.8 (3.3) kg/m^2) than those in Australia (27.1 (5.3) kg/m^2, $p<0.001$) and Hong Kong (25.2 (2.8) kg/m^2, $p<0.05$).

Volumes and ejection fraction

The differences between 2D and 3D EF and volumes in the 220 patients are illustrated in figure 1. Overall 2D mean EF was 48% (18%), LVEDVi, 70 (34) ml/m^2 and mean LVESVi, 41 (33) ml/m^2. The mean absolute difference in EF was 6% (6%), with a difference in LVESVi of 6 (7) ml/m^2 and LVEDVi of 9 (9) ml/m^2.

Change of ejection fraction thresholds

Of the total study group of 220 patients, 20 (9.1%) and 14 (6.4%) were re-allocated using EF criteria of <40% and <35%, respectively. For a LVEF <40%, the threshold was met by the 2D measure in 81 patients, and 3DE reclassified 13 of these (16.1%). For a LVEF <35%, 3D reclassified 11 of the 63 patients who were measured as below this threshold by 2DE (17.5%).

Figure 2 shows the paired 2D and 3D EF results for each patient. As the proportion of reclassified studies reflects the

Table 1 Re-allocation to above or below ejection fraction (EF) threshold according to 2D EF

2D EF band	No of 2D patients	Re-allocation according to a threshold EF 35% (%)	Re-allocation according to a threshold EF 40% (%)
⩽25%	32	2 (6.3)	1 (3.1)
26–35%	36	14 (38.9)	5 (13.9)
36–40%	13	1 (7.7)	7 (53.9)
41–45%	10	2 (20.0)	5 (50.0)
>45%	129	0 (0)	2 (1.6)

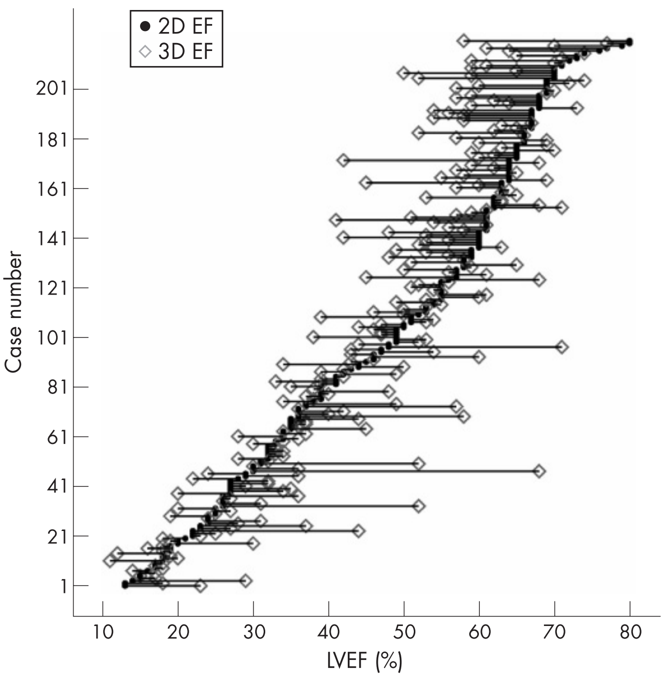

Figure 2 Paired 2D and 3D results for EF (ejection fraction) with patients ranked by 2D value. LVEF, left ventricular ejection fraction.

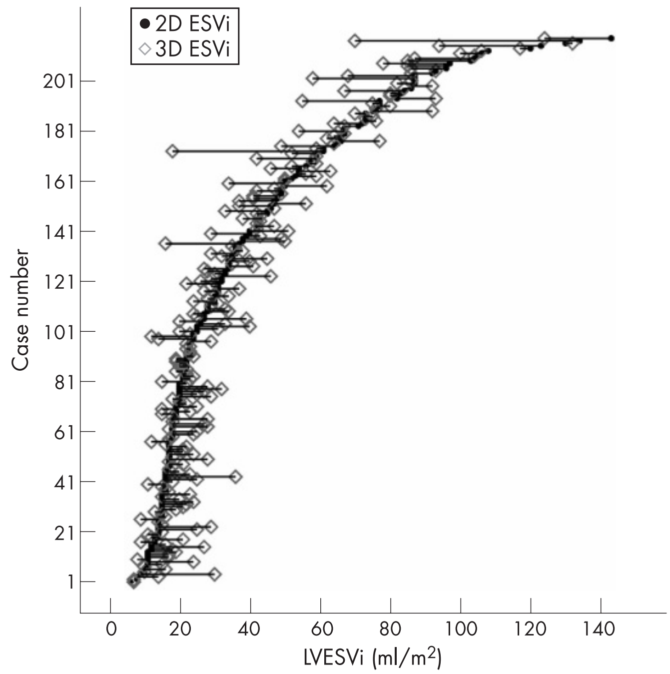

Figure 3 Paired 2D and 3D results for left ventricular end-systolic volume index (LVESVi) with patients ranked by 2D value.

nature of the referral group, we assessed the process of reclassification based on categories of EF and volume. Table 1 shows that it is unusual for patients with 2D-EF >10% away from the EF threshold to be re-allocated. These results imply that 3DE has the greatest impact on re-categorising patients undergoing ICD evaluation with a 2D LVEF ranging between 25–45%, and in deciding about heart failure therapy if the 2D LVEF is 25–50%.

Change of LV volume thresholds

With regard to LV volumes, 23 (10.5%) and eight (3.6%) were re-allocated using the LVESVi criteria of 30 ml/m^2 and >50 ml/m^2, respectively. Figure 3 details the paired 2D and 3D results for LVESVi.

For a LVESVi >30 ml/m^2 the threshold was exceeded by the 2D measure in 105 patients, and 3DE reclassified 13 of these (12.4%). For a LVESVi >50 ml/m^2 3D reclassified five of the 59 patients who were measured as above this threshold by 2DE (8.5%) (table 2). These results imply that 3DE has the greatest impact on recategorising patients after myocardial infarction with a 2D LVESVi from 20–40 ml/m^2 and for patients undergoing evaluation for regurgitant valvular disease with a 2D LVESVi between 30–60 ml/m^2.

Regional wall motion abnormalities

Overall, 46.4% (n = 102) patients had regional wall motion abnormalities (RWMA). However, of those with a 2D left ventricular EF <50%, the proportion of RWMA was significantly higher at 82.7% (n = 86), with only a small proportion of patients having normal wall motion. The presence or absence of RWMA had no significant impact upon the likelihood of re-categorisation of patients categorised by 2D LVEF and LVESVi using 3D results (table 3).

Visual assessment of ejection fraction

In a group of 131 patients (all patients at one hospital), a visual estimation of LVEF was made with the reader blinded to the 2D Simpson's and 3D EF results. There was excellent correlation between the visual EF and the 2D biplane method (R = 0.85) but less than that with 3D (R = 0.68). The frequency with which 2D or 3D EF recategorised a patient classed by visual EF as <40% is shown in table 4.

DISCUSSION

This study shows that the addition of 3DE to routine clinically indicated 2D echocardiography is feasible, with limited costs in terms of time, and has the potential to significantly impact

Table 2 Proportion of patients re-categorised by 3DE around the two selected volume thresholds, according to 2DE volume bands

2D LVESVi band	No of 2D patients	Re-allocation according to a threshold LVESVi 30 ml/m^2 (%)	Re-allocation according to a threshold LVESVi 50 ml/m^2 (%)
⩽20 ml/m^2	80	2 (2.5)	0 (0)
21–30 ml/m^2	35	8 (22.9)	0 (0)
31–40 ml/m^2	26	12 (46.2)	1 (3.9)
41–50 ml/m^2	20	0 (0)	2 (10.0)
51–60 ml/m^2	11	0 (0)	3 (27.3)
>60 ml/m^2	48	1 (2.1)	2 (4.2)

LVESVi, left ventricular end-systolic volume index.

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Table 3 Re-categorisation by 3DE of 2D ejection fraction and volume thresholds, according to the presence or absence of regional wall motion abnormalities (RWMA)

	LVEF<35% (%)	LVEF<40% (%)	LVESVi>30 ml/m² (%)	LVESVi>50 ml/m² (%)
RWMA present	10/57 (17.5)	11/73 (15.1)	9/87 (10.3)	4/54 (7.4)
No RWMA	1/6 (16.7)	2/8 (25.0)	4/18 (22.2)	1/5 (20.0)

LVEF, left ventricular ejection fraction; LVESVi, left ventricular end-systolic volume index.

upon clinical decision-making. In terms of clinically relevant reclassification, this impact appears to be greatest in patients with an EF of 25–50%. For patients in whom accurate measurement of LV end-systolic volumes are important, the major potential impact of 3D assessment appears to be in those whose 2D volumes are between 20 ml/m^2 and 60 ml/m^2. Finally, the results highlight the likelihood of reclassification of visual EF estimations at the critical EF levels where management decisions are made.

Feasibility

Previous work has demonstrated the feasibility of real-time 3DE in selected patients. In this study, we have shown that 3DE has a feasibility of >80% in unselected patients, with only a small increase in the total time taken for the combined 2D and 3D study (5.4 (2.0) minutes). Between-centre differences in 3D acquisition and analysis times may not simply reflect sonographer experience and it is possible that better imaging quality may have been responsible for the significantly faster acquisition and analysis times seen at one centre (Japan)—patients at this site had a significantly lower body mass index than the other sites.

Use of 3D echocardiography

RT-3DE has been well validated against MRI in selected patients, with small systematic biases in assessment of LV volumes (table 5).[20–24]

Common to most of these studies is a (small) underestimation of LV volumes by 3DE when compared to MRI, a result that probably reflects differences in measurement technique between the two modalities. Results for EF measurements show excellent agreement between RT-3DE and MRI. With cardiac MRI still significantly limited in terms of widespread availability and substantial cost and 2DE hampered by issues of foreshortening and geometric assumptions, 3DE techniques offer an accurate, reproducible and affordable tool for LV quantitation.

The influence of the presence or absence of regional wall motion abnormalities upon rates of recategorisation is also of significant interest when making an assessment of the relative benefit of 3D echocardiography. Unfortunately, the high proportion (>80%) of patients with RWMA in those with a reduced EF makes it difficult to draw definitive conclusions in this regard. However, it is interesting to observe that there did not appear to be any increase in the rate of recategorisation in those patients with RWMA when compared to those without.

Accurate 2D quantitation is highly dependent upon adequate image quality and image alignment. For this reason, visual estimations are commonly used in clinical practice in place of quantitative methods. In a subset of 131 patients, the rates of recategorisation by 3D appeared to be similar for visually estimated EF compared to the quantified 2D measure, although the numbers are relatively small. Interestingly, the correlation of visual estimation (blinded) with 2D quantification was better than that with 3D, probably reflecting the importance of observer experience and the learning curve associated with calibration for accurate visual EF assessment.[25]

LV volume thresholds

The presence or absence of left ventricular enlargement is a prognostically important marker of LV dysfunction[15] that is often used in decisions about the timing of surgical intervention in patients with regurgitant valve disease. In current practice, assessment of LV diameter is used for risk stratification, although direct measurement of LV volumes has been advocated as more appropriate, particularly in patients with enlarged

Table 4 Re-allocation of visually estimated LVEF to above or below a threshold of 40% by 2D quantification and 3D

Visual EF band	No of patients	Re-allocation by quantified 2D (%)	Re-allocation by 3D (%)
⩽25%	6	1 (16.7)	1 (16.7)
26–35%	12	2 (16.7)	6 (50.0)
36–40%	3	2 (66.7)	1 (33.3)
41–45%	5	1 (20.0)	2 (40.0)
>45%	105	4 (3.0)	0 (0.0)

Table 5 Previous estimations of the difference in LV volumes and EF by 3DE with magnetic resonance imaging

Study	No of patients	EDV (ml)	ESV (ml)	EF (%)
Caiani *et al*[21]	44	−4.1 (15)	−4 (17)	1 (7)
Jacobs *et al*[20]	50	−14 (17)	−7 (16)	−1 (6)
Kuhl *et al*[23]	24	−14 (19)	−13 (21)	0.9 (4)
Sugeng *et al*[22]	31	−5 (26)	−6 (26)	0.3 (4)
Jenkins *et al*[24]	110	−44 (35)	−21 (28)	−2 (10)

ventricles.[26 27] Borow *et al*[14] showed that in patients with mitral regurgitation, a LVESVi >30 ml/m² predicted a poor postoperative outcome. Similarly, in patients with aortic regurgitation, a LVESVi >60 ml/m² also carried adverse prognostic influence, with LVESVi being a more useful predictor of outcome than preoperative ejection fraction, end-diastolic volume or end-diastolic pressure. Extending these observations in further studies, Starling[16] recommended that in order to maximise postoperative outcomes, surgery for mitral regurgitation should be considered when the LVESVi has increased to between 40 ml/m² and 50 ml/m². In light of these data, a LVESVi of >50 ml/m² was selected for the purpose of this analysis as a clinically relevant threshold to indicate intervention in valvular heart disease.

The value of LVESV as a prognostic marker after myocardial infarction has been demonstrated in several studies,[1] in which ESV has been shown to be the single most important predictor of survival, incremental to measures of EF or diastolic volume. Other work has confirmed the importance of ESV after myocardial infarction[18] and underscores the importance of optimising therapy targeted at the remodelling process.

LV ejection fraction thresholds

Several large clinical trials support the use of EF to target patients at high risk of sudden cardiac death who will gain a mortality benefit from implantable cardiac defibrillators (ICD). An LVEF threshold of less than 30% or 35% has been used in several of these studies[10 28] and society guidelines emphasise the use of LVEF as part of the ICD decision-making process.[11]

Accurate measurement of LVEF is also essential for the diagnosis and ongoing monitoring of systolic heart failure. We selected the threshold LVEF <40% as clinically significant based on a substantial body of work that has utilised a similar threshold for the purposes of diagnosis, prognostication and assessment of heart failure therapy.[12 29]

Limitations

As discussed earlier, previous work has shown that 3DE assessment of LV volumes and LVEF has an accuracy comparable to MRI and that significantly exceeds that of 2DE. Thus, it is reasonable to assume that the accuracy of categorisation for 3D exceeded that of the 2D measures alone, and we do not believe that the lack of a "gold-standard" measure in this study precluded assessment and comparison of the categorisation with the two techniques.

As the majority of patients (63%) were unselected in order to assess feasibility in clinical practice, the number of patients with abnormal LV volumes and EF was proportionally smaller than those with measures in the normal range. However, the inclusion of the unselected patients means that the results are more reflective of real-life referral patterns and therefore have some merit in giving an indication of the potential impact that the introduction of RT-3DE could have on clinical decisions in a hospital-based echo laboratory. As the abnormal patients are those in whom the impact of 3DE may be of most interest, an additional recruitment augmented this group.

Finally, it would have been interesting to assess whether the use of intravenous contrast had any significant impact on the clinical feasibility of 3D echocardiography. However, at the time of the study, these agents were not available for routine clinical use in the participating centres and the analysis was therefore confined to non-contrast studies.

Conclusions

This analysis provides evidence that routine 3D assessment of EF and LV volumes has significant potential to improve clinical decision-making when added to a standard and clinically indicated 2D echocardiogram.

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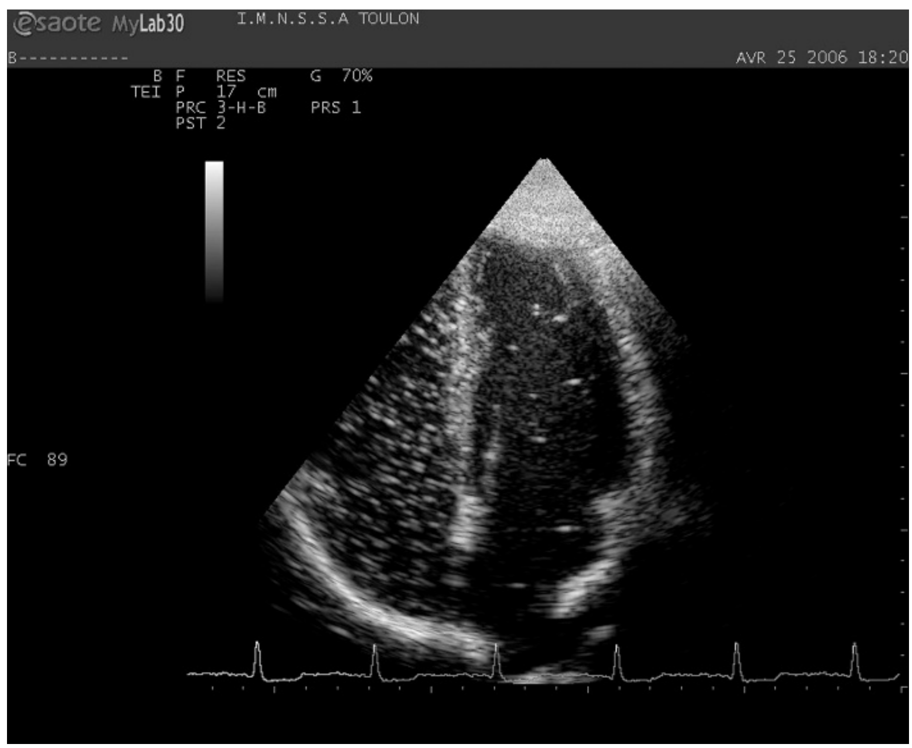
Images in cardiology

Bubbles in the left cardiac cavities after diving

After scuba diving, circulating nitrogen bubbles can be detected in the venous system. In two subjects, we detected circulating bubbles in both right and left cavities of the heart and in the cerebral circulation. Several risk factors of paradoxical gas embolism are suggested here. The two divers developed a high bubble grade after surfacing. The right to left shunting occurred through a large patent foramen ovale (PFO). An increase in bubble grade in right cavities and an increase in arterial passage through the inter-atrial septal defect were observed during isometric contraction of lower limb muscles. Although they remained asymptomatic, our two divers should be considered at high risk of developing neurological decompression sickness (DCS). Indeed, the presence of a PFO has been associated with the risk of developing a DCS[1] and with the incidence of ischaemic brain lesions.[2] Haemodynamic modifications were assessed using Doppler-echocardiography. All the parameter modifications were consistent and suggested a decrease in cardiac preload after the dive. Furthermore, an increase in pulmonary vascular resistance was observed, which could promote the right-to-left shunting. A closure of the PFO could be discussed in these subjects. However, this procedure did not change the high level of venous circulating bubbles and the risk of developing an unrelated interatrial shunt DCS. Consequently, in subjects wishing to pursue their diving activity an appropriate preventive measure could be the use of oxygen-enriched mixture to decrease the nitrogen load and the risk of all types of DCS.



Circulating bubbles in the right and the left cavities of the heart.

A Boussuges, J E Blatteau, J M Pontier

alainboussuges@libertysurf.fr; a.boussuges@imnssa.net

▶ Supplementary figure and video (passage of the circulating bubbles in the left cardiac cavities) available online at http://heart.bmj.com/content/vol94/issue4

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Feasibility and clinical decision-making with 3D echocardiography in routine practice

J L Hare, C Jenkins, S Nakatani, et al.

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