Left ventricular volume and ejection fraction assessment with transoesophageal echocardiography: 2D vs 3D imaging

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Editor’s key points
- MRI is the gold standard technique for left ventricular (LV) volume measurement.
- With transthoracic echocardiography, 3D measurements correlate better with MRI assessments of LV volume than 2D measurements.
- Transoesophageal echocardiography (TOE) is routinely used to measure LV and ejection fraction during cardiac surgery.
- The current study showed that measurements with 3D TOE correlated well with 2D TOE, but offered no advantage over 2D TOE.

Background. Developments in transducer technology have enabled the use of three-dimensional transoesophageal echocardiography (3D TOE) in the operating theatre. Transthoracic echocardiography (TTE) 3D left ventricular (LV) volumes and ejection fraction (EF) agree better with magnetic resonance imaging (MRI) measurements, with less intra- and inter-observer variability compared with 2D. This has not been validated with 3D TOE. The aim of this study was to assess the bias, limits of agreement, and reproducibility of 3D TOE and 2D TOE LV volumes and EF in cardiac surgical patients.

Methods. Sixty-three patients having cardiac surgery with TOE were evaluated. LV volumes and EF were calculated using modified Simpson’s method on 2D mid-oesophageal four- and two-chamber views, xPlane, and from a 3D full-volume data set. Intra- and inter-observer variability were assessed in a subset of 17 patients.

Results. Real-time 3D TOE volume and EF assessment was possible in 59 of the 63 patients. Median end-diastolic volumes (EDVs) as measured by 2D, xPlane, and 3D techniques were 98.5, 94, and 97 ml. Median ESVs were 38.5, 40 and 35.6 ml. Median EFs were 58, 54 and 62.2%. There were no significant pairwise differences between these measurements. The limits of agreement for all comparisons were wide, and there were no statistically significant differences between the three methods in intra- or inter-observer variability.

Conclusion. The intraoperative use of 3D TOE to estimate LV volumes and EF has small bias compared with 2D assessments, wide limits of agreement, and no clear advantages compared with standard 2D TOE imaging in terms of LV volume and EF assessment.

Keywords: cardiac surgery; echocardiography, transoesophageal; 2D echocardiography; 3D echocardiography

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Calculation of left ventricular (LV) volumes and ejection fraction (EF) is a routine part of perioperative transoesophageal echocardiography (TOE). In the operating theatre, this is often performed qualitatively with ‘eye ball’ or visual estimation, but this has significant interobserver variability and requires experience. American and European echocardiography consensus groups recommend the biplane method of discs (modified Simpson’s rule) and area length methods for LV chamber quantification with 2D echocardiography. These rely on adequate endocardial border definition, orthogonal image alignment, and geometric assumptions to convert manually traced areas into volumes. With TOE, the apex of the left ventricle is furthest from the transducer, thus it can be difficult to visualize. If the imaging plane misses, the true apex foreshortening of the ventricle results and volumes are underestimated.

Current matrix array TOE transducers have 2500 imaging elements and allow acquisition of three-dimensional (3D) full-volume data sets in real-time. LV volumes can be determined from these data sets without relying on geometric assumptions and may be less prone to errors because of foreshortening and thus underestimation of LV volume. Endocardial position is automatically measured off line at hundreds of points over the LV surface, so the calculation of LV volumes can theoretically be performed with greater accuracy than when using 2D echocardiography in one or two planes. These transducers also allow simultaneous orthogonal plane imaging (biplane or triplane), which could also potentially minimize foreshortening.

Three-dimensional transthoracic echocardiography (TTE) volumes show better agreement with cardiac magnetic resonance imaging (MRI) (considered to be a gold standard
for LV volume estimates) and tend to be greater with less
inter- and intraobserver variability than 2D TTE volumes.\textsuperscript{5} To date there is limited data comparing 3D and 2D TOE LV volume measurements. The TOE probe is relatively fixed in the oesophagus, with the apex in the far sector field, unlike the mobile probe in TTE with its proximity to the apex. Calcification of the mitral apparatus can cause image drop out of LV endocardial borders with TOE. Intraoperative TOE involves additional challenges such as mechanical ventilation, diathermy interference, direct cardiac manipulation, and rapidly changing loading conditions.

The aim of this study was to assess the bias, limits of agreement, and reproducibility of simultaneously acquired 3D TOE and 2D TOE LV volumes and EF in patients undergoing cardiac surgery.

**Methods**

After Human Research and Ethics Committee (HREC) approval, we studied 63 unselected patients undergoing cardiac surgery having TOE where there was no contraindication to TOE. Requirements for written informed consent were waived from HREC for this project as real-time 3D TOE is routine during open heart surgery in our institution.

Patients who were in atrial fibrillation were excluded from the study because of difficulties acquiring 3D full-volume data sets over four beats without ‘stitching’ artifacts attributable to unequal cardiac cycle durations.\textsuperscript{5}

Patients were selected when either of the investigators was the echocardiographer for the case. All images were acquired after induction of general anaesthesia and tracheal intubation and before pericardiotomy, cardiac surgical manipulation, and cardiopulmonary bypass. The patient was disconnected from the ventilator during image acquisition to minimize motion artifact and all electrical diathermy was withheld to minimize the ECG disruption. Images were acquired sequentially over a few minutes during a period of haemodynamic stability. All images were acquired on an iE33 echocardiography platform (Philips Medical Systems, Vision 2007 software, Andover, MA, USA) using a real-time 3D matrix array transducer (X7-2t).

The following images were acquired sequentially after optimization of machine settings:

1. 2D mid-oesophageal four- and two-chamber images, each over one representative cardiac cycle.
2. Simultaneous mid-oesophageal four- and two-chamber images using the xPlane mode during one representative cardiac cycle.
3. A 3D full-volume data set over four cardiac cycles.

The orthogonal xPlane was selected by placing a line passing through the midpoint of the mitral annulus to the apex in four-chamber (4C) view to, where possible, maximize both 4C and two-chamber (2C) volumes and minimize foreshortening.

All measurements were performed intraoperatively at a later stage using the software on the iE33. LV end-diastolic volume (EDV), LV end-systolic volume (ESV) and EF were obtained using the modified Simpson’s method on the standard 2D mid-oesophageal four- and two-chamber images and the xPlane on simultaneous four- and two-chamber images, according to American Society of Echocardiography chamber quantification guidelines.\textsuperscript{6}

Three-dimensional LV volumes and EF were measured from the 3D full-volume data set. Using the on board QLab software (Version 6.0, Philips Medical Systems, Andover, MA, USA), the full-volume data of the LV was organized into orthogonal four-, two-chamber, and short-axis views. End-diastolic and end-systolic frames were selected. Mitral annular and apical points were placed on these images. Semi-automated LV endocardial border detection software on QLab outlined the endocardial borders in these three planes. The software then used sequence analysis to track the endocardium in all frames and then automatically calculate a true 3D EDV, ESV, and EF from the moving 3D endocardial shell. The endocardial borders could be adjusted manually if the endocardial border tracking was deemed inadequate, and the sequence analysis repeated.

All measurements were performed by an experienced cardiac anaesthetist (B.C.) with TOE qualifications and additional training in 3D echocardiography and use of QLab software. A subgroup of 17 patients was randomly selected for assessment of intra-observer variability (at a later stage by B.C. who was blinded to the initial measurements) and inter-observer variability by a second cardiac anaesthetist (M.K.) with TOE qualifications and 3D/QLab training, who was also blinded to the initial assessments.

**Statistics**

* A priori sample size determination was not possible as we had no reliable estimates of the variability of the differences in measurements between 2D and 3D TOE methods. We performed a post hoc power estimation of our data to detect a 10% difference in EDV, ESV, and EF.

The bias and precision (limits of agreement) of the three methods of measurements were compared using Bland–Altman analysis on a pairwise basis (i.e. 2D vs xPlane, 2D vs 3D, xPlane vs 3D). The methods were compared with pairwise Wilcoxon signed-rank tests.

Reproducibility was assessed by calculating the intra- and inter-observer variability. This was expressed as the mean (plus 95% confidence limits from a $t$ distribution with $n - 1$ degrees of freedom) and limits of agreement of the difference between the two measurements. Pairwise comparisons of the mean differences (intra- and inter-observer) in EDV, ESV, and EF between the three methods of measurement were assessed with $t$-tests and differences in the standard deviation (i.e. a measure of variability) of the intra- and inter-observer differences between the three methods of measurement were assessed with $F$ tests.
The Holm–Sidak procedure was used to correct for multiple comparisons.7

All statistical analysis was performed using Stata™ 11 (Stata Corp LP, College Station, TX, USA).

Results

Of the 63 patients in sinus rhythm studied, suitable images were obtained in 59 patients with inadequate image quality in three patients (4.7%) in both 2D and 3D imaging, with failure of ECG triggering in a remaining patient.

Manual adjustment of the 3D endocardial tracking software was required in 50% of patients.

The mean (so) age of the patients was 65 (11.3) and there were 45 males and 18 females.

Patients were having cardiac revascularization and valvular surgery, or a combination of the two (Table 1).

Fifteen patients had impairment of LVEF (LVEF <50%) with four of these patients having LVEF <30%. Eleven of these patients with impaired LVEF had segmental wall motion abnormalities, but no patients had LV aneurysms. Overall, six patients (10%) had LV volumes over 150 ml.

Figure 1 shows the volumes and EFs as measured by the three methods. There were no significant pairwise differences between EDV, ESV, and EF as assessed by the three methods (Wilcoxon signed-rank test).

Figure 2 shows the pairwise Bland–Altman plots (and 95% confidence intervals for the bias) for EDV, ESV, and EF by the different techniques.

Post hoc power analysis indicated our study had over 90% power to detect a 10% difference in EDVs and EFs and over 80% power to detect a 10% difference in ESVs (two-sided analysis and alpha value of 0.05).

The middle two columns of Table 2 show the mean difference, its 95% confidence interval, and the limits of agreement for the intra-observer differences between measurements for the three methods of assessing EDV, ESV, and EF. There were no significant pairwise differences (i.e. 2D vs xPlane, 2D vs 3D, and xPlane vs 3D) between the three methods in mean difference (EDV P > 0.96, ESV > 0.93, EF > 0.89, t-tests) or standard deviation (EDV P > 0.10, ESV > 0.14, EF > 0.63, F tests).

The right two columns of Table 2 show the mean difference, its 95% confidence interval, and the limits of agreement for the inter-observer differences between the measurements for the three methods of assessing EDV, ESV, and EF. There were no significant pairwise differences between the three methods (i.e. 2D vs xPlane, 2D vs 3D, and xPlane vs 3D) in mean difference (EDV P > 0.22, ESV > 0.90, EF > 0.80, t-tests) or standard deviation (EDV P > 0.18, ESV > 0.55, EF > 0.30, F tests).

Discussion

Almost all of the experience on 3D LV volumes and EF has been with TTE with little validation using TOE. Although this finding has not been universal,8 most of the TTE studies have shown that 2D echocardiographic measures of LV volume have tended to underestimate those obtained with 3D echocardiography and cardiac MRI, particularly in

Table 1 Surgery. CAGS, coronary artery graft surgery; AVR, aortic valve replacement; MV, mitral valve

<table>
<thead>
<tr>
<th>Surgery</th>
<th>Number</th>
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<tbody>
<tr>
<td>CAGS</td>
<td>37</td>
</tr>
<tr>
<td>CAGS/valve</td>
<td>7</td>
</tr>
<tr>
<td>AVR/aortic surgery</td>
<td>12</td>
</tr>
<tr>
<td>MV repair/replacement</td>
<td>4</td>
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<tr>
<td>Double valve</td>
<td>3</td>
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Fig 1 Box plots of EDV, ESV, and EF measured by the three techniques. The middle lines represent medians and boxes represent the 25th to 75th percentile. All outliers are shown as points. EDV, end-diastolic volume; ESV, end-systolic volume; EF, ejection fraction.
Fig 2 Bland–Altman plots of EDV, ESV, and EF by the three techniques: 2D, xPlane, and 3D. The numbers in brackets beneath the biases are the 95% confidence intervals for the biases. EDV, end-diastolic volume; ESV, end-systolic volume; EF, ejection fraction.
patients with cardiac disease. They have also suggested that intra- and inter-observer variability are greater with 2D compared with 3D volumes and EF.

This study confirms that the use of 3D TOE for perioperative LV volume and EF assessment in cardiac surgery is achievable in most patients, has small bias compared with 2D assessment, but has wide limits of agreement. However, in contrast to most of the TTE studies, 2D volumes were not smaller than LV volumes estimated by xPlane and full-volume 3D techniques. In the absence of a gold standard such as MRI and studies comparing simultaneously acquired 2D and 3D TTE and TOE measurements, whether this is because 2D TOE volumes are greater than 2D TTE volumes or 3D TOE volumes are smaller than 3D TTE volumes, is unclear. Furthermore, in contrast to most TTE studies, 2D intra- and inter-observer variability were not significantly greater than with xPlane and full-volume 3D techniques.

There are differences between TTE and TOE which may explain our results. The LV is relatively distant, particularly the apex, in TOE windows compared with TTE and often the semi-automated border detection software on QLab had difficulty tracking the endocardium, despite clear endocardial border definition to the naked eye. This required manual adjustment of the border detection software, potentially introducing errors in volume and EF measurement.

In the case of large ventricles (especially in transversely oriented hearts), it may be difficult to capture the entire base of the left ventricle in the image sector with TOE and hence difficulty in accurately positioning the mitral annular points on which the 3D endocardial tracking is dependent.

In our four patients where accurate 2D and 3D volumes could not reliably be measured, three had severe mitral annular calcification with dropout of the septal and lateral walls and poor image quality in both 2D and 3D imaging. TTE avoids this problem because of the apical as opposed to transoesophageal window.

Simultaneous orthogonal image planes obtained with xPlane could potentially minimize foreshortening. However, sometimes compromises in image quality in one of these planes are required for both to have acceptable quality simultaneously. This may explain why xPlane imaging produced similar volumes to 2D imaging.

Despite the small biases, we found wide limits of agreement between the three methods and in intra- and interobserver variability. However, our findings are consistent with the TTE literature. In the few studies that actually compared 2D TTE volumes and EFs with 2D TTE with 3D TTE measurements, there is a similarly wide dispersion of data. Despite advances in the imaging technology, problems unique to echocardiography still occur. Apical foreshortening, acoustic shadowing, suboptimal endocardial border definition, inadequate image resolution, translational cardiac motion, and problems identifying phases of the cardiac cycle such as end systole and end diastole result in quantitative echocardiography having limitations, even in experienced hands. The measurement of volumes from the 3D full-volume data set adds additional subjective elements such as the choice of orthogonal planes, positioning mitral annular and apical points, and manual adjustment of endocardial tracing.

**Limitations**

We studied no patients with very asymmetrical ventricular chambers, e.g. ventricular aneurysms. It is possible that 3D TOE would be more accurate (compared with 2D and xPlane) in assessing the volume of such ventricles as the geometrical assumptions of Simpson’s method are likely grossly violated. One would expect 3D TOE may have a role in LV evaluation after infarct exclusion surgery in patients with ischaemic cardiomyopathy for this reason; however, direct comparison with 2D in such patients has not been

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Intra- and interobserver variability (n=17). EDV and ESV in millilitres, and EF as percentage. EDV, end-diastolic volume; ESV, end-systolic volume; EF, ejection fraction</th>
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<tbody>
<tr>
<td><strong>Mean difference (95% CI) Limits of agreement</strong></td>
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<tr>
<td><strong>EDV</strong></td>
<td><strong>ESV</strong></td>
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<tr>
<td>2D</td>
<td>-3.76 (-8.23 to 0.70)</td>
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<tr>
<td>xPlane</td>
<td>-2.82 (-10.57 to 4.92)</td>
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<tr>
<td>3D</td>
<td>-5.08 (-12.59 to 2.42)</td>
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<tr>
<td><strong>EF</strong></td>
<td><strong>Mean difference (95% CI) Limits of agreement</strong></td>
</tr>
<tr>
<td>2D</td>
<td>-0.18 (-3.18 to 2.83)</td>
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<tr>
<td>xPlane</td>
<td>-0.65 (-3.93 to 2.64)</td>
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<tr>
<td>3D</td>
<td>-1.74 (-5.70 to 2.23)</td>
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performed. Our small number of patients with large dilated ventricles and severe LV dysfunction does not allow generalizability of these results to this population and additional study is required in this patient subgroup.

We studied patients with sinus rhythm as a regular rhythm is required for full-volume 3D acquisition over a number of cycles. However, xPlane imaging may be particularly useful in situations of variable R–R interval or gross haemodynamic instability. With xPlane the 4C and 2C images are acquired in the same cardiac cycle, as opposed to using Simpson’s method in the standard way. The four- and two-chamber images acquired on different cycles may have very different volumes and EFs.

**Conclusion**

In our group of patients undergoing cardiac surgery, the use of 3D TOE for LV volume and EF assessment had small bias compared with 2D assessment, but wide limits of agreement. However, in contrast to most TTE studies, 2D volumes were not smaller than LV volumes estimated by xPlane and full-volume 3D techniques. Furthermore, 2D intra- and inter-observer variability were not significantly greater than with xPlane and full-volume 3D techniques. Three-dimensional TOE offered no clear advantages compared with standard 2D TOE alone in terms of LV volume and EF measurements.

**Declaration of interest**

None declared.

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