Comparison of real-time three-dimensional echocardiography with cardiovascular magnetic resonance for left ventricular volumetric assessment in unselected patients

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Aims
To compare left ventricular (LV) volume indices and the ejection fraction (EF) obtained using real-time three-dimensional echocardiography (RT3DE) and cardiovascular magnetic resonance (CMR) in unselected patients representative of ‘real-world’ clinical practice, and to determine the effect of RT3DE image quality on these parameters.

Methods and results
Sixty consecutive patients undergoing CMR underwent same day RT3DE. LV volume and EF measurements were made using both modalities and compared. All scans were independently analysed by a second observer to assess inter-observer variability, and 40% were re-analysed to assess intra-observer variability. RT3DE image quality was graded as good, adequate, and non-analysable. Thirteen (22%) patients had good RT3DE image quality, 29 (48%) had adequate image quality, and 18 (30%) had image quality precluding analysis. Body mass index and arrhythmia frequency were higher in patients with suboptimal image quality. RT3DE significantly underestimated end-diastolic volume (EDV) (–45 ± 35 mL, \(P < 0.001\)), end-systolic volume (ESV) (–11 ± 24 mL, \(P = 0.004\)), and EF (–7 ± 9%, \(P < 0.001\)) compared with CMR although the degree of underestimation was substantially less when image quality was good. Eleven patients (18%) classified as having a normal EF by CMR had a reduced EF according to RT3DE, all but one of which had suboptimal image quality. Observer variability for RT3DE was higher than for CMR for all parameters, however, the difference was not significant when RT3DE image quality was good.

Conclusions
In contrast to previously published data from highly selected patient groups, ‘real-world’ RT3DE substantially underestimates LV volumes and EF. The degree of underestimation is related to image quality.

Keywords
Real time three-dimensional echocardiography • Cardiovascular magnetic resonance • Left ventricle • Image quality • Ejection fraction

Introduction
Assessment of left ventricular (LV) ejection fraction (EF) is the most common indication for cardiac imaging.\(^1\) LV volume indices and EF remain some of the strongest markers of prognosis and their absolute values, as well as their temporal change, are used to guide pharmacotherapy, device implantation, and surgical intervention.\(^2\)–\(^5\) It is important therefore that their measurement is both accurate and reproducible.

By overcoming the need for geometric assumptions and inadvertent use of foreshortened views, real-time three-dimensional echocardiography (RT3DE) is considerably more accurate and reproducible than two-dimensional echocardiography.\(^6\)–\(^10\) Indeed a number of studies have demonstrated RT3DE to have an

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accuracy and reproducibility approaching that of cardiovascular magnetic resonance imaging (CMR), the recognized gold standard technique for the assessment of LV volumes and EF.\textsuperscript{6,11–13} However, such studies have selected patients with optimal echocardiographic windows, sinus rhythm, and good breath-holding ability, and as such have excluded patients in whom RT3DE image quality was not excellent.\textsuperscript{5–19} ‘Real-world’ data reflective of everyday clinical practice are scarce.

The aims of this study were to compare volume indices and the ejection fraction obtained using RT3DE and CMR in an unselected cohort of patients representative of ‘real-world’ clinical practice, and to determine the impact of RT3DE image quality. The inter- and intra-observer variability of RT3DE was also compared with that of CMR.

Methods

Study design

Sixty consecutive consenting patients undergoing clinically indicated CMR scanning at a single institution were enrolled. Patients were recruited prospectively, prior to undergoing imaging. The only exclusion criterion was known complex congenital heart disease. Patients were not excluded on the basis of image quality, arrhythmia, or breath-holding ability. Patients underwent RT3DE either immediately before or immediately after CMR scanning (order determined randomly).

The study was conducted according to the Helsinki Declaration. Ethical approval for the study was given by an Ethics Committee of the UK National Research Ethics Service (reference number 08/H1004/153) and written informed consent was obtained from all participants.

Real-time three-dimensional echocardiography image acquisition and analysis

RT3DE was performed using a commercially available scanner (iE33; Philips Healthcare, The Netherlands) equipped with a 3D matrix array transducer (X3-1) with the patient in the left lateral decubitus position. An experienced operator acquired images from the apical window, during a single breath-hold. A patient specific image sector angle was used; adjusted to the minimal size required in order to encompass the entire ventricle. Image depth and endocardial definition were optimized (temporal resolution 40–50 ms). Subsectors of the image were acquired over four consecutive heartbeats and were subsequently electronically ‘stitched’ together.

Image analysis was performed using QLAB (3DQ-Advanced, Philips) by an investigator blinded to the CMR measurements (Figure 1). At end-diastole, the apical four- and two-chamber cut planes were optimized to avoid foreshortening. Five endocardial reference points were placed manually on the mitral annulus (septal and lateral annulus in the four-chamber view and anterior and inferior annulus in the two-chamber view) and apex. The initial endocardial contour was then manually adjusted. This process was repeated at end-systole, defined as the frame with the smallest LV cavity, as determined visually. Papillary muscles were included in the LV cavity. The voxel count inside the endocardial contours was used to calculate end-diastolic (EDV) and end-systolic (ESV) volumes without any geometric modelling. The EF was derived from EDV and ESV using the standard formula \((\text{EF} = \frac{\text{EDV} - \text{ESV}}{\text{EDV}} \times 100)\).

Cardiovascular magnetic resonance image acquisition and analysis

CMR imaging was performed using a 1.5-Tesla scanner (Avanto; Siemens Medical Imaging, Germany) equipped with a 32-element phased-array coil. Steady-state free precession end-expiratory breath-hold cines were acquired in three long-axis planes (horizontal long axis, vertical long axis, and three-chamber long axis). Subsequently, a series of short-axis cines were acquired from the atrioventricular ring to the apex (short-axis stack). Typical parameters included repetition time 2.9 ms, echo time 1.2 ms, flip angle 80\(\text{o}\), matrix 256 \(\times\) 208, in plane pixel size 1.4 \(\times\) 1.4 mm, slice thickness 8 mm (inter-slice gap 2 mm for the short-axis stack), temporal resolution 30–50 ms, depending on the heart rate. Retrospective gating was used in 57 patients. Prospective gating was required in three patients due to arrhythmia.

Image analysis was performed by a Level 2 accredited operator, blinded to the RT3DE measurements, using CMRtools (Cardiovascular Imaging Solutions, UK) (Figure 2). The epicardial border was manually traced at end-diastole in successive short-axis slices. A second contour was placed within the myocardium on the short-axis slices at end-diastole and systole allowing the signal intensity between the two contours (i.e. the signal intensity of myocardium) to be automatically determined. Detailed, semi-automated tracing of the endocardium at end-diastole and end-systole was then performed using a signal intensity ‘thresholding’ tool, such that papillary muscles and trabeculae were included in mass and excluded from volumetric measurements. The mitral and aortic valve positions at end-diastole and systole were manually identified on the three long-axis images, allowing the valve planes to be tracked through the cardiac cycle. This was integrated into the SA stack analysis allowing automated identification of the LV base and outflow tract. End-systole was automatically determined as being the frame with the smallest cavity volume, by calculating cavity volume at each frame. The EF was derived from EDV and ESV as described previously.

Real-time three-dimensional echocardiography image quality

To allow a pre-specified comparison of RT3DE and CMR according to image quality, RT3DE image quality was prospectively classified as good, adequate, and non-analysable.

Observer variability

To assess inter-observer variability, all RT3DE and CMR scans were independently analysed by a second observer. To assess intra-observer variability, 24 randomly selected scans (40%) were re-analysed by the first observer with a 1-month temporal separation between analyses.

Statistics

Values are expressed as mean \(\pm\) standard deviation (SD) unless stated otherwise. Agreement between RT3DE and CMR was evaluated using the Bland–Altman analysis by calculating mean difference (bias) and 95% limits of agreement (i.e. mean difference \(\pm\) 2 SD). The significance of the differences between each method was assessed using Wilcoxon rank testing. Correlation was assessed using Spearman’s rank correlation coefficient. Inter- and intra-observer agreement were evaluated using the repeatability co-efficient \([\text{defined as } 1.96 \times \sqrt{\text{sum of the squares of the differences between observer measurements divided by } n}])\). The significance of the differences in variability was assessed using a Wilcoxon rank comparison of the squared differences. In a pre-specified subgroup analysis, agreement between RT3DE and CMR, and inter-observer variability, was assessed according to image
quality. P-values < 0.05 were considered significant. Statistical analysis was performed using SPSS Statistics (version 19, IBM).

Results

Patient characteristics

Patient characteristics are displayed in Table 1. Patients exhibited a variety of cardiovascular pathology and a wide range of EDV, ESV, and EF (Table 2). Six patients (10%) had an arrhythmia at the time of scanning (three patients had atrial fibrillation, one had atrial flutter, and two had frequent uni-ventricular ectopic beats).

Image quality

In 13 (22%) patients, RT3DE image quality was classified as good and in a further 29 patients (48%), image quality was deemed adequate. In the remaining 18 (30%) patients, RT3DE image quality was felt too poor for the analysis. In 10 of these patients, poor visualization of the anterior wall alone (i.e. despite other walls being well visualized) was responsible (Figure 3). Three of the remaining eight patients with unanalysable image quality had atrial fibrillation. The two patients with frequent ventricular ectopic beats and the patient with atrial flutter had adequate image quality. All patients with good image quality were in sinus rhythm.

Mean body mass index (BMI) of patients in the good image quality group (24.5 ± 2.6 kg/m²) was significantly lower than patients in the adequate image quality group (28.9 ± 4.2 kg/m²; P < 0.001) and in the poor image quality group (29.2 ± 5.5 kg/m²; P = 0.004), although the difference in BMI between the adequate and poor groups was not significant.

Overall comparison of real-time three-dimensional echocardiography with cardiovascular magnetic resonance

In the 42 patients with analysable image quality, RT3DE significantly underestimated both the EDV and the ESV compared with CMR (EDV: −45 ± 35 mL, P < 0.001; ESV: −11 ± 24 mL, P = 0.004; Tables 2 and 3, Figure 4). However, EDV was underestimated to a greater degree (RT3DE underestimated EDV by 26% of the mean CMR-derived EDV value, and underestimated ESV by 14% of the mean CMR-derived ESV value). As a result, RT3DE significantly underestimated EF (−7 ± 9%, P < 0.001). The Bland–Altman 95% limits of agreement were wide for all parameters, suggesting that the degree of volume underestimation was not consistent between individual patients. Eleven patients
(18%) classified as having a normal EF by CMR (using a nominal normal EF cut-off of ≥55%) were classified as having a reduced EF by RT3DE. However, no patient classified as having moderate LV dysfunction (i.e. EF < 55% but >35%) by CMR was classified as having severe LV dysfunction (EF < 35%) using RT3DE.

Observer agreement is displayed in Table 4. Inter-observer and intra-observer agreement for measurement of all parameters were significantly lower for RT3DE than for CMR.

Analysis time was significantly shorter for RT3DE than for CMR (5.1 ± 1 vs. 7.6 ± 1 min; P < 0.001), although CMR analysis time included measurement of LV mass.

**Comparison of real-time three-dimensional echocardiography with cardiovascular magnetic resonance according to image quality**

RT3DE underestimated volumes to a lesser degree when image quality was good, compared with when image quality was adequate (Table 5, Figure 4). Indeed when image quality was good, RT3DE measurement of ESV was not significantly different from that of CMR, although the limits of agreement remained wide. In keeping with the volume measurements, EF was also underestimated by a lesser degree when image quality was good compared with when it was adequate, although the degree of underestimation remained significant irrespective of image quality.

In the good image quality category, only one patient (8%) classified as having a normal EF by CMR was classified as having a reduced EF by RT3DE. However, when image quality was only adequate, 10 patients (34%) were wrongly classified.

Inter-observer agreement according to image quality is displayed in Table 6. RT3DE inter-observer agreement was higher for all parameters when image quality was good compared with when it was adequate. Indeed when image quality was good, inter-observer agreement for RT3DE-derived EDV and ESV measurements was not significantly different from the inter-observer agreement for CMR-derived values. However, inter-observer agreement for RT3DE-derived measurement of EF remained significantly lower than for CMR-derived EF measurement, even when image quality was good.

**Discussion**

While a number of studies have advocated the use of RT3DE for the assessment of LV volumes and EF, most have used highly selected patient groups with characteristics that are optimal for RT3DE image acquisition. In contrast the present study aimed to evaluate RT3DE in an unselected cohort, and as such provides data directly relevant to the clinical utility of this modality.

Recruitment was prospective and consecutive, without exclusion on grounds of image quality, arrhythmia, or breath-holding ability. Patients exhibited a variety of cardiac pathology causing a
range of regional and global myocardial dysfunction and a wide range of EDV, ESV, and EF values. It is therefore felt justified to consider the present study representative of ‘real-world’, clinical practice.

Most previous studies have reported that RT3DE underestimates LV volumes compared with CMR, although many have found the differences to be small, indeed in some of the earlier comparisons, the differences were non-significant, with narrow limits of agreement. Similarly, a study assessing RT3DE speckle tracking for the quantification of LV volumes found the degree of volume underestimation to be minimal in comparison with CMR. However, most such studies have only included patients with excellent RT3DE image quality. As demonstrated in this study, this represents only a minority of patients in clinical practice (22% of patients in this study). The causes of suboptimal RT3DE image quality are multifactorial, but arrhythmia and raised BMI, both of which were more common in patients with suboptimal image quality in this study, are likely to be major contributing factors.

The degree of volume underestimation in the current study (EDV: –45 ± 35 mL, ESV: –11 ± 24 mL) was larger than in other single-centre studies, but less than in the only multi-centre comparison of RT3DE and CMR (EDV: –67 ± 46 mL, ESV: –41 ± 46 mL). Using interpolated 3D CMR data sets, Mor Avi et al. showed that the main cause of the volume underestimation by RT3DE is its lower spatial resolution, which leads to poorer endocardial border definition and hence, incorrect border tracing. In the current study, the suboptimal image quality in the adequate image quality group would have accentuated the poorer endocardial border definition, thus explaining the greater degree of volume underestimation seen compared with studies that have included only patients with excellent image quality. Indeed in the subgroup with good image quality, RT3DE volumetric measurements were much more in keeping with the published literature and comparable with CMR.

It is likely that the use of intravenous contrast agents would improve RT3DE endocardial definition, and hence its accuracy. However, the use of such agents would potentially diminish some of the advantages that RT3DE has over CMR, including rapidity, portability, and cost.

In the current study, RT3DE underestimated EDV by a greater degree than ESV, which led to a significant underestimation of the EF compared with CMR, which is in keeping with the findings of Chang et al. and Mor Avi et al. It may be that the endocardial border is better defined at end-systole, allowing more accurate tracing. Consequently, in nearly a fifth of patients, RT3DE assessed EF to be abnormal (i.e. <55%) when CMR had determined it to be normal, which could have significant potential clinical implications. Subgroup analysis showed that only one of these cases occurred in patients with optimal image quality, but 10 occurred in the adequate image quality group, suggesting that caution should be applied when RT3DE image quality is not optimal. Interestingly RT3DE and CMR resulted in identical classification with respect to severe LV impairment (EF ≤ 35%).

Nearly a third of patients had RT3DE image quality that was too poor to allow analysis. By recruiting patients who were undergoing CMR there was potential for bias against RT3DE, in that patients could have been referred for CMR following a non-diagnostic echocardiogram; however, this was not mentioned in any of the CMR requests. Furthermore, studies that have screened patients for good image quality have excluded similar proportions. In over half of those with non-analysable images, poor visualization of the anterior wall alone was responsible. This is in keeping with a study by Collins et al. which found that the anterior wall was the most common location for non-analysable segments with RT3DE (45% of 159 non-analysable segments were located in the anterior wall; 936 segments imaged in total), although this difficulty has not been widely reported in the RT3DE literature.
All three patients with atrial fibrillation had poor image quality, and all patients with good image quality were in sinus rhythm. The RT3DE method used involved acquisition of image subsectors over four consecutive heartbeats that were then electronically ‘stitched’ together, thus requiring a constant R–R interval. The variable R–R interval of atrial fibrillation led to stitching artefacts. Newer technology allowing image acquisition over fewer heartbeats, or even in a single heartbeat, may help to overcome this problem, although arrhythmia, particularly atrial or ventricular bigeminy, also impact on CMR image quality and post-processing.\(^{18,19}\)

RT3DE had significantly higher variability than CMR for measurement of all parameters. This is likely to reflect the poorer endocardial definition of RT3DE. Indeed in the subgroup where image quality was good, there was no significant difference in variability between RT3DE and CMR for measurement of LV volumes, but when image quality was suboptimal, RT3DE measurements had considerably higher variability. Nevertheless, measurement of EF showed significantly greater variability with RT3DE compared with CMR, irrespective of image quality.

Many recent studies assessing the variability of RT3DE measurement of LV volumes and EF have calculated variability as the absolute difference of a corresponding pair of repeated measurements expressed as a percentage of their mean in each patient, which is then averaged over the entire study group.\(^{12,13,16–18}\) The limitation of this method is that a large positive difference between observers can be balanced by a large negative difference between observers, resulting in a misleadingly low mean variability value. Using this method, the overall inter-observer (EDV: 6 ± 14%, ESV: 5 ± 17%, and EF: 1 ± 11%) and intra-observer (EDV: 1 ± 8%, ESV: −1 ± 9%, and EF: 1 ± 11%) mean variability values for RT3DE in the current study are comparable with other studies, however, reflecting the wider range of image quality in the current study, the standard deviations are considerably wider. The repeatability co-efficient, which gives the range within which measurements made by two different observers (inter-observer), or two measurements made by the same observer (intra-observer), are expected to lie, is used in the current study as it is considered a fairer measure of variability and more informative to clinical practice.\(^{20,21}\)

The method of CMR image analysis used in the current study was chosen in order to minimize the errors associated with CMR volumetric quantification.\(^{17}\) First, the error associated with inaccurate LV base identification was minimized by incorporating the long-axis images, which allowed straightforward identification of the mitral valve plane (and hence LV base), into the short-axis endocardial contouring (Figure 2). Second, while it is common CMR practice to trace the ‘compacted’ endocardial border, thus including papillary muscles and trabeculae in the LV cavity, this leads to an overestimation of true LV volumes, making the underestimation by RT3DE appear greater than it really is. Furthermore, the more detailed method of endocardial contouring, where papillary muscles and trabeculae are excluded from cavity volumes, as used here, has greater accuracy in comparison with ex vivo validation studies\(^ {25,26}\) and was the technique used to establish normal

**Table 3** Mean difference, significance of the difference, Bland–Altman 95% limits of agreement and correlation coefficient for the comparison of real-time three-dimensional echocardiography and cardiovascular magnetic resonance

<table>
<thead>
<tr>
<th>RT3DE—CMR</th>
<th>Mean difference ± SD</th>
<th>P-value</th>
<th>95% limits of agreement</th>
<th>Correlation coefficient (rs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDV (mL)</td>
<td>−45 ± 35</td>
<td>&lt;0.001</td>
<td>−115 to 24</td>
<td>0.83</td>
</tr>
<tr>
<td>ESV (mL)</td>
<td>−11 ± 24</td>
<td>0.004</td>
<td>−59 to 37</td>
<td>0.84</td>
</tr>
<tr>
<td>EF (%)</td>
<td>−7 ± 9</td>
<td>&lt;0.001</td>
<td>−25 to 10</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Abbreviations as in Table 2.
Figure 4  Bland–Altman comparisons of real-time three-dimensional echocardiography and cardiovascular magnetic resonance for measurement of left ventricular volumes (EDV, end-diastolic volume; ESV, end-systolic volume) and ejection fraction. Overall comparison is shown in the left column. Subgroup analyses according to real-time three-dimensional echocardiography image quality are shown in the centre (good real-time three-dimensional echocardiography image quality) and right (adequate real-time three-dimensional echocardiography image quality) columns.

Table 4  Inter- and intra-observer variability for real-time three-dimensional echocardiography and cardiovascular magnetic resonance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Inter-observer</th>
<th>Intra-observer</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDV (mL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMR</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>RT3DE</td>
<td>34</td>
<td>29</td>
</tr>
<tr>
<td>ESV (mL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMR</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>RT3DE</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>EF (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMR</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>RT3DE</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

Inter- and intra-observer variability of both modalities for measurement of LV volumes and EF, expressed as repeatability coefficients. The repeatability co-efficient is the range within which measurements by two different observers (inter-observer) and two measurements by the same observer (intra-observer) are expected to lie. P-values refer to the significance of the difference in variability. RT3DE had significantly higher variability than CMR for all parameters. Abbreviations as in Table 2.
the frame with the smallest cavity volume. Minimized by automated determination of end-systole as being error associated with inaccurate end-systolic frame selection was for CMR following a non-diagnostic echocardiogram; however, to bias against RT3DE, in that patients could have been referred recruited. As discussed above, this could have theoretically lead Patients planned to undergo a clinically indicated CMR scan were Limitations

Patients planned to undergo a clinically indicated CMR scan were recruited. As discussed above, this could have theoretically lead to bias against RT3DE, in that patients could have been referred for CMR following a non-diagnostic echocardiogram; however, this was not mentioned in any of the CMR requests. Reproducibility of measurements, requiring two separate scans, has not been assessed.

Conclusions

This study assessed the accuracy and variability of RT3DE measurement of LV volumes and the EF in an unselected cohort of patients, and determined the effect of RT3DE image quality on these parameters. In keeping with other published data, RT3DE underestimated LV volumes and EF; however, the degree of underestimation in the current study was substantially larger than in other single-centre studies. This is likely to reflect the unselected, ‘real-world’ cohort of patients involved, and as such the results of this study may be more representative of clinical practice than studies that have used highly selected patient populations. The degree of underestimation was related to image quality; when image quality was good, RT3DE-derived measurements were much closer to CMR-derived measurements; however, this represented only a minority of patients.

Acknowledgements

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References


Table 5

<table>
<thead>
<tr>
<th></th>
<th>Mean difference ± SD</th>
<th>P-value</th>
<th>95% limits of agreement</th>
<th>Correlation coefficient ($r_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDV (mL)</td>
<td>Good</td>
<td>$-28 \pm 35$</td>
<td>0.02</td>
<td>$-97$ to $42$</td>
</tr>
<tr>
<td></td>
<td>Adequate</td>
<td>$-53 \pm 32$</td>
<td>&lt;0.001</td>
<td>$-118$ to $11$</td>
</tr>
<tr>
<td>ESV (mL)</td>
<td>Good</td>
<td>$-4 \pm 23$</td>
<td>0.75</td>
<td>$-50$ to $41$</td>
</tr>
<tr>
<td></td>
<td>Adequate</td>
<td>$-14 \pm 25$</td>
<td>0.002</td>
<td>$-63$ to $35$</td>
</tr>
<tr>
<td>EF (%)</td>
<td>Good</td>
<td>$-5 \pm 5$</td>
<td>0.01</td>
<td>$-16$ to $5$</td>
</tr>
<tr>
<td></td>
<td>Adequate</td>
<td>$-8 \pm 10$</td>
<td>&lt;0.001</td>
<td>$-28$ to $11$</td>
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</table>

Abbreviations as in Table 2.

Table 6

<table>
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<th>Inter-observer</th>
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<tr>
<td></td>
<td></td>
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<tr>
<td>EDV (mL)</td>
<td></td>
</tr>
<tr>
<td>CMR</td>
<td>17</td>
</tr>
<tr>
<td>Good RT3DE</td>
<td>27, 0.249</td>
</tr>
<tr>
<td>Adequate RT3DE</td>
<td>37, 0.005</td>
</tr>
<tr>
<td>ESV (mL)</td>
<td>8</td>
</tr>
<tr>
<td>CMR</td>
<td>12, 0.359</td>
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<tr>
<td>Good RT3DE</td>
<td>16, 0.007</td>
</tr>
<tr>
<td>Adequate RT3DE</td>
<td>12, &lt;0.001</td>
</tr>
<tr>
<td>EF (%)</td>
<td></td>
</tr>
<tr>
<td>CMR</td>
<td>7, 0.03</td>
</tr>
<tr>
<td>Good RT3DE</td>
<td></td>
</tr>
<tr>
<td>Adequate RT3DE</td>
<td>12, &lt;0.001</td>
</tr>
</tbody>
</table>

Inter-observer variability of RT3DE with good image quality, RT3DE with adequate image quality and CMR for measurement of LV volumes and EF, expressed as repeatability coefficients. The repeatability co-efficient is the range within which measurements by two different observers are expected to lie. P-values refer to the significance of the difference in variability. When image quality was good, there was no significant difference in variability between RT3DE and CMR for measurement of LV volumes; however, RT3DE had significantly greater variability when image quality was only adequate. Measurement of EF showed significantly greater variability with RT3DE compared with CMR, irrespective of image quality. Abbreviations as in Table 2.

Finally, the potential error associated with inaccurate end-systolic frame selection was minimized by automated determination of end-systole as being the frame with the smallest cavity volume.

Limitations

Patients planned to undergo a clinically indicated CMR scan were recruited. As discussed above, this could have theoretically lead to bias against RT3DE, in that patients could have been referred for CMR following a non-diagnostic echocardiogram; however, this was not mentioned in any of the CMR requests. Reproducibility of measurements, requiring two separate scans, has not been assessed.

Conclusions

This study assessed the accuracy and variability of RT3DE measurement of LV volumes and the EF in an unselected cohort of patients, and determined the effect of RT3DE image quality on these parameters. In keeping with other published data, RT3DE underestimated LV volumes and EF; however, the degree of underestimation in the current study was substantially larger than in other single-centre studies. This is likely to reflect the unselected, ‘real-world’ cohort of patients involved, and as such the results of this study may be more representative of clinical practice than studies that have used highly selected patient populations. The degree of underestimation was related to image quality; when image quality was good, RT3DE-derived measurements were much closer to CMR-derived measurements; however, this represented only a minority of patients.

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References


