Left ventricular volumetry in healthy children and adolescents: comparison of two different real-time three-dimensional matrix transducers with cardiovascular magnetic resonance

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Aims
To assess the accuracy of different hardware and software settings for left ventricular (LV) volume quantification in children using real-time three-dimensional echocardiography (RT3DE).

Methods and results
The impact of different matrix transducers (IE 33, X3-1 and VIVID 7, V3) and quantification software settings [TOMTEC; contour-finding activity (tCFA) values ranging from 30 to 70 U] on the accuracy of LV indices was tested in 24 healthy children/adolescents (median = 12.6 years) and 25 paediatric patients with Tetralogy-of-Fallot (TOF) (median = 7.3 years) with abnormally shaped ventricles. RT3DE was compared with cardiovascular magnetic resonance (CMR) volumetry as reference. Best agreement (Bland–Altman analysis) was achieved using a tCFA value of 30 U. Applying the V3 device, end-diastolic volume (EDV) and end-systolic volume (ESV) were underestimated by 14.8 ± 10.6% (mean ± SD) and 11.2 ± 16.3%, respectively (r = 0.92, P < 0.001 and r = 0.937, P = 0.003); with the X3-1 system 24.2 ± 11.0 and 14.6 ± 15.2%, respectively (r = 0.951, P < 0.001 and r = 0.912, P = 0.001). Negligible differences <1% (P = n.s.) between both transducers were detected applying a tCFA value of 70 U but with significant underestimation (EDV: ~35%, P < 0.001; ESV: ~26%, P < 0.001) compared with CMR. EDV and ESV of TOF patients were underestimated by 3.2 ± 15.4 and 8.1 ± 22.6%, respectively. Intra- and interobserver variability was <4%.

Conclusion
In contrast to recommendations of the manufacturer, data sets from both RT3DE transducers showed acceptable agreement to CMR for volumetric parameters only for low tCFA. Fine-tuning of software settings is mandatory to improve accuracy.

Keywords
Three-dimensional echocardiography • Magnetic resonance imaging • Cardiac function • Paediatrics

Introduction
Echocardiographic assessment of left ventricular (LV) volumes is essential for cardiac patients with diagnostic and prognostic implications. The paediatric population is characterized by a higher heart rate, greater respiratory variation, and smaller LV volume compared with adults. Two-dimensional echocardiography (2DE) is currently the method most widely used but provides less reliable volumetric data especially in abnormally shaped ventricles as a result of geometric assumptions. Further drawbacks are a poor test–retest reliability, foreshortening, and off-axis views. Nowadays, cardiovascular magnetic resonance (CMR) is regarded as the first-line imaging technique for evaluation of right ventricular (RV) and LV volumes, mass, and function as stated by a consensus panel report because of its high accuracy and reproducibility and independency of geometric assumptions, but it is cost-intensive.

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cannot be used in patients with internal devices, and sedation is often needed in younger children to obtain proper image quality. Cardiac computed tomography (CT) provides highly reproducible measurements of LV volumes, which are significantly larger than CMR with superb spatial and contrast resolution but is not the method of choice in children because of its radiation exposure. With the introduction of second-generation matrix transducers, real-time three-dimensional echocardiography (RT3DE) is becoming a competitive clinical tool that can easily be applied to children and adults with congenital heart disease, allowing rapid volume acquisition and is characterized by greater accuracy and reproducibility than 2DE. Semi-automatic post-processing software has been established with contour-finding algorithms to decrease the time-consuming quantification process without a decrease in accuracy. This software is typically based on a mixture of manual tracing and automatic border detection. RT3DE technology is offered by several manufactures, but up to now, there are no studies about comparisons of the different RT3DE hardware which are prerequisites especially needed for the design of multicentre studies. On the other hand, quantification software has to be harmonized individually for the adequate data set recorded by the different transducers. Thus, the objective of this study was first to investigate the accuracy of volumetric parameters applying two different but technically comparable matrix transducer probes and second to compare the impact of varying contour-finding activities (tCFA) of the RT3DE quantification software with CMR serving as a reference.

Methods

Study population

In March 2008, we prospectively enrolled into the study a total of 24 healthy children/adolescents referred to our institute to collect ventricular CMR and RT3DE reference values. RT3DE and CMR studies were performed from each subject within 45 min in random order to avoid physiologic day-to-day variations in ventricular filling and to ensure identical conditions for both techniques.

To validate usefulness and applicability of the applied model-based RT3DE analysis software regarding abnormally shaped LVs and to assess smaller LV volumes in a younger population, 25 paediatric patients with Tetralogy-of-Fallot (TOF) in the post-operative follow-up were included in the study. The indication for CMR was the assessment of RV pressure and/or volume overload before secondary treatment. RT3DE and CMR examinations were performed within 2 h of time. The study was approved by the institutional review committee and informed written consent was obtained from the parents or caretakers.

Study design

Each healthy subject underwent RT3DE using two different ultrasonic devices: (i) VIVID 7 equipped with a V3 matrix transducer (General Electric, Milwaukee, WI, USA) and (ii) IE 33 equipped with an X3-1 matrix transducer (Philips Medical Systems, Andover, MA, USA), as well as CMR volume measurements to determine the end-diastolic volumes (EDVs), end-systolic volumes (ESVs), stroke volumes (SVs), and ejection fractions (EFs) of the LV. Two additional standard velocity-encoded CMR (phase-contrast CMR, PC-CMR) measurements were added to the CMR protocol to quantitatively assess through-plane flow in the ascending aorta and pulmonary artery for internal cross-check of CMR volume measurements.

TOF patients were examined with the VIVID 7 device equipped with a V3 matrix transducer (General Electric) and accordingly compared with CMR. All CMR and RT3DE scans were obtained by a single expert.

Real-time three-dimensional echocardiography

Children were examined in the left lateral decubitus position. 2DE was performed to rule out heart disease. For RT3DE, the transducer was placed in the apical position with image axis aligned to the LV long axis. The image acquisition of four subvolumes with a maximum field of view (FOV) of 90° and a temporal resolution of 20–26 bp was performed for both systems during a single end-expiratory breathhold to obtain one full volume data set with stable transducer position. The footprint sizes of the transducers were 17 × 26 mm (X3-1) and 21 × 26 mm (V3).

Real-time three-dimensional echocardiography data analysis

Following import of the acquired RT3DE data sets to the Research-Arena platform (TOMTEC, Version 2.0.0 Build 1.29, Unterschleisheim, Germany), quantification of volumes was performed using the 4D LV-Analysis tool (Version 2.5 Build 12). Briefly, a spatio-temporal spline model based on Thin-Plate Splines is initialized. This model ensures both smooth contours in the spatial domain and continuous motion in the temporal domain. In reference to the mode’s surface, the algorithm seeks for those image points which most likely define the endocardium. This is done by finite impulse response and morphological filtering of grey value profiles perpendicular to the current surface estimate. Filter response and distance to the current surface are used to yield a likelihood estimate for each detected image point. All detected image points are now approximated by the same spline model as used in the initials. The approximation considers the derived likelihood measures. The user can determine the minimal sensitivity for contour classification (tCFA) to separate endocardial border from noise. If the approximation step yields a significant change, another iteration is started.

After adjusting of the data set to obtain the largest long-axis dimension, end-diastolic and end-systolic contours were manually traced in four-, two-chamber, and apical long-axis views (Figure 1). Ventricular trabeculae and papillary muscles were included in the LV cavity. EDV, ESV, and EF were calculated semi-automatically by the system.

The intensity of the TOMTEC contour-finding algorithm on ventricular border detection and thus on measurement accuracy was tested by applying 30, 50, and 70 intensity units of the tCFA without altering the manual tracing done before.

Cardiovascular magnetic resonance imaging

CMR was performed on a clinical 1.5 T whole body MR scanner (Philips Medical Systems, Intera, R11, maximum gradient performance 30 mT/m, slew rate 150 T/m/s). The body coil was used for signal transmission and a five-element cardiac phased-array surface coil for signal detection. For determination of ventricular volumes, a multislice multiphase electrocardiographic-triggered balanced gradient-echo sequence (TR/TE/flip = 2.8 ms/1.4 ms/60°) was applied to cover the cardiovascular structures axially between the level of the diaphragm and the aortic arch. Typically, 24–34 slices were obtained during 14 s breathhold manoeuvres (two slices per breathhold, slice
thickness = 6 mm) with 20 heart phases per slice. Matrix size was 156 × 240, FOV 370 mm resulting in an in-plane resolution of 2.3 × 1.5 mm with the higher resolution in the phase-encoding direction, and SENSE-reduction factor of 2 (phase-encode).

Internal cross-check of the LV and RV stroke volumes was performed by two additional PC-CMR measurements angulated orthogonal to the ascending aorta and pulmonary artery, respectively. For this, we used a retrospectively gated gradient-echo sequence with 30–40 heart phases, TR/TE/flip angle of 15 ms/6.5 ms/30°, velocity-encoded value of 150 cm/s, and a spatial resolution of 2.1 × 2.1 × 6 mm.

Cardiovascular magnetic resonance image analysis
Analysis of CMR volume measurements and quantitative flow CMR data sets, respectively, was performed off-line on a workstation using the HDZ MR-Tools software package (Heart and Diabetes Center, Bad Oeynhausen, Germany). Briefly, after defining of the end-systolic and end-diastolic heart phases, an auto-level function is applied for automatic contour detection (threshold = mean value of the signal intensity defined in a region-of-interest in the LV cavity and myocardial septum). If necessary, a manual adaptation of the window/level values is allowed. A separate selection and, if needed, a manual correction of areas belonging to one of the four cardiac chambers can be performed in one step (Figure 2). Although papillary muscles and trabecular structures are typically excluded from the ventricular cavity and added to the myocardial muscle mass by the software, they are included into the ventricular volumes in this study to ensure compatibility to the echocardiographic analysis. No geometric model or assumption is needed for evaluation. LV volumes are calculated by summation of the cavity areas multiplied with the slice thickness in all appropriate slices. For quantitative flow data analysis, a computer algorithm for semi-automatic vessel border detection was used as described elsewhere.

Statistical analysis
Descriptive statistics was performed from all relevant data. Calculation of linear correlation coefficients by Pearson–Bravais and Bland–Altman statistics was obtained to assess intra- and interobserver variability. Therefore, 14 randomly selected subjects were re-evaluated. The RT3DE data sets were evaluated by two experts blinded to each others result and to the CMR data after performing operator trainings before in order to guarantee comparable manual tracing of data sets. CMR data were quantified by a single expert investigator. The analysis of Bland and Altman20 was used to quantify the agreement between CMR and RT3DE LV volumes as well as for comparison of both echocardiographic devices. Significance of the observed differences between the functional ventricular parameters EDV, ESV, SV, and EF was tested with a two-sided paired Student’s t-test. A P-value of ≤0.05 was considered as statistically significant.
Results

Mean age of the study population was 13.6 ± 4.2 years (range 6.4–20.4 years, median 12.6 years, 14 males). Sinus rhythm was present in all participants. Mean heart rate was 81 ± 12 bpm (range 60–104 bpm, median 80 bpm). All scans were completed successfully. CMR volume measurements and quantitative flow studies were finished within 20 min of scan time, whereas RT3DE was completed within 10 min per device. Image quality of all data sets was excellent for post-processing of volume quantification.

Mean age of the patient group was 8.2 ± 3.4 years (range 3.8–17.5 years, median 7.3 years, 13 males) with a mean heart rate of 80 ± 12 bpm (range 60–107 bpm, median 79 bpm).

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Table 1  Bland–Altman statistics: volumetric indices determined by cardiovascular magnetic resonance and real-time three-dimensional echocardiography

<table>
<thead>
<tr>
<th>Healthy subjects</th>
<th>CFA (U)</th>
<th>CMR vs. RT3DE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EDV</td>
</tr>
<tr>
<td>VIVID 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>14.8</td>
</tr>
<tr>
<td>LOA</td>
<td></td>
<td>36.1</td>
</tr>
<tr>
<td>Mean + 2SD</td>
<td></td>
<td>65</td>
</tr>
<tr>
<td>Mean – 2SD</td>
<td></td>
<td>0.942</td>
</tr>
<tr>
<td>r</td>
<td></td>
<td>0.942</td>
</tr>
<tr>
<td>P-value</td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>IE 33</td>
<td></td>
<td>24.2</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>46.3</td>
</tr>
<tr>
<td>Loa</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>Mean + 2SD</td>
<td></td>
<td>0.951</td>
</tr>
<tr>
<td>Mean – 2SD</td>
<td></td>
<td>0.951</td>
</tr>
<tr>
<td>r</td>
<td></td>
<td>0.951</td>
</tr>
<tr>
<td>P-value</td>
<td></td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

RT3DE data were obtained with a VIVID 7 ultrasonic device with a V3/E 33 ultrasonic device with an X3-1 matrix transducer applying a contour-finding activity (CFA) of 30, 50, and 70 U, respectively. Except the correlation coefficient and P-values, all values are given in per cent; mean corresponds to mean difference. EDV, end-diastolic volume; ESV, end-systolic volume; SV, stroke volume; EF, ejection fraction; LOA, limits-of-agreement; r, correlation coefficient.
Figure 3  Bland–Altman plots and linear regression plots. Comparison of end-diastolic cardiovascular magnetic resonance and real-time three-dimensional echocardiography left ventricular volumes. Real-time three-dimensional echocardiography data were acquired with a VIVID 7 ultrasonic device with a V3 matrix transducer.
Patients had dysynchronous septal movement because of right bundle branch block and highly elevated indexed end-diastolic RV volumes [132.7 ± 33.6 (mL/m²) vs. 80.3 ± 14.5 (mL/m²)] in healthy children, P < 0.0001, unpaired Student’s t-test). Mean pulmonary regurgitation was 40 ± 15.7% (range 5.2–58.3%) assessed by flow measurements.

Volumetric data: real-time three-dimensional echocardiography vs. cardiovascular magnetic resonance in healthy subjects

VIVID 7 with V3 matrix transducer

Compared with CMR volume measurements, EDV, ESV, and SV were considerably underestimated (Bland–Altman analysis) by CMR volumetry

Volumetric data: real-time three-dimensional echocardiography vs. cardiovascular magnetic resonance

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Compared with CMR volume measurements, EDV, ESV, and SV were considerably underestimated (Bland–Altman analysis) by CMR volumetry. Mean pulmonary regurgitation was 40 ± 15.7% (range 5.2–58.3%) assessed by flow measurements.

Table 2

Summary of functional cardiovascular magnetic resonance parameters assessed by multislice multiphasic electrocardiographic-triggered balanced gradient-echo technique and stroke volumes determined by phase-contrast cardiovascular magnetic resonance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMR volumetry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left ventricle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDV (mL)</td>
<td>124.8 ± 47.2</td>
<td>65.8–225.8</td>
</tr>
<tr>
<td>ESV (mL)</td>
<td>45.7 ± 21.0</td>
<td>20.7–91.6</td>
</tr>
<tr>
<td>SV (mL)</td>
<td>79.0 ± 26.7</td>
<td>42.5–134.2</td>
</tr>
<tr>
<td>EF (%)</td>
<td>64.2 ± 3.5</td>
<td>57.8–69.8</td>
</tr>
<tr>
<td>Right ventricle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV (mL)</td>
<td>76.5 ± 25.3</td>
<td>41.8–125.6</td>
</tr>
<tr>
<td>EF (%)</td>
<td>63.4 ± 3.7</td>
<td>56.6–72.6</td>
</tr>
<tr>
<td>PC-CMR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ascending aorta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV (mL)</td>
<td>78.8 ± 26.0</td>
<td>41.1–128.6</td>
</tr>
<tr>
<td>Pulmonary artery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV (mL)</td>
<td>78.5 ± 27.2</td>
<td>43.2–129.8</td>
</tr>
</tbody>
</table>

In contrast to the comparisons between CMR and RT3DE data, papillary muscles and trabecular structures were excluded from the ventricular volumes to ensure compatibility to PC-CMR. EDV, end-diastolic volume, ESV, end-systolic volume, SV, stroke volume, EF, ejection fraction.

Table 3

Summary of ejection fractions according to the two ultrasonic systems and contour-finding activity

<table>
<thead>
<tr>
<th>CFA (U)</th>
<th>Ejection fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>VIVID 7</td>
<td>62.6 ± 4.4 (52.2–71.0)</td>
</tr>
<tr>
<td>IE 33</td>
<td>60.3 ± 5.1 (49.9–68.7)</td>
</tr>
</tbody>
</table>

Mean ± SD; ranges in parentheses.
this study with healthy children, we found a yield of comparable values for the LV chamber (SV = 26.7 mL) as well as for the RV chamber (SV = 76.5 ± 25.3 mL).

High correlation was found for EDV and SV (r ≥ 0.92) and a weaker correlation for ESV (r ≥ 0.8).

### Ultrasonic systems: VIVID 7 vs. IE 33

Comparing the two different ultrasonic devices, only negligible mean differences <1% with acceptable scatters ranging between 12.7 and 25.3% (mean ± 2SD) and -13.1 and -26.4% (mean - 2SD) were observed using a tCFA of 70 (Table 5 and Figure 4). Accordingly, high correlation was found for all volumetric indices (r = 0.93–0.97).

By decreasing the contour-finding activity to 50 and 30 U, respectively, higher mean differences were detected using the VIVID 7 ultrasonic system for all volumetric parameters compared with the IE 33 device but statistical significance was only achieved for EDV, SV, and EF applying tCFA 30.

### Cardiovascular magnetic resonance volume measurements and quantitative flow measurements

Although ‘true’ ventricular volumes cannot be assessed in vivo by modalities such as echocardiography, CMR or CT, CMR allows an internal verification of SVs applying different acquisition techniques. As reported by Beerbaum et al., quantitative flow measurements yielded reliable blood flow rates in the great thoracic vessels such as ascending aorta and pulmonary artery, respectively, whereas the ratio of pulmonary to aortic flow (Qp/Qs) should be ~1 in patients with no cardiac shunting. For internal testing, in this study with healthy children, we found a Qp/Qs ratio of 1.0 ± 0.1 (mean ± SD, range: 0.81–1.19), representing almost identical SVs in both arteries (Table 2) applying PC-CMR. Calculation of SVs (difference in EDV and ESV) using the multislice multiphase balanced gradient-echo technique for CMR volume measurements yielded comparable values for the LV chamber (SV = 79.0 ± 26.7 mL) as well as for the RV chamber (SV = 76.5 ± 25.3 mL).
High correlation \( (r = 0.975; \ y = 0.95x + 3.96) \) and high agreement \( (\text{Bland–Altman statistics: mean} \pm SD = 0.1 \pm 8.0\%); \) limits-of-agreement \( = -16.0\%–16.1\% \) were found between both quantitative methods.

**Intra- and interobserver variability**

A subset of 14 randomly selected data sets were used for echocardiographic assessment of intra- and interobserver variability of the LV EDV and LV ESV. Because of the dependence from the applied contour-finding activity with expected increasing variability applying lower contour-finding values \( (\text{higher user control but weaker influence from the assumed model}) \), intra- and interobserver variability was determined with a contour-finding activity of 30 U as the worst case. Intraobserver variability with RT3DE was low \( (<2\%\), Bland–Altman statistics, Table 6 and Figure 4) with a slightly higher scatter for ESVs but comparable to the interobserver variability found for CMR volume measurements. Interobserver variability was acceptable as well \( (<4\%) \) for both ultrasonic systems.

**Discussion**

Due to the fact that follow-up studies are often needed in children with congenital heart disease where remodelling processes are common, techniques without ionizing radiation such as echocardiography or CMR are inevitable to keep radiation exposure in these patients to an absolute minimum. Although CMR is generally accepted as a reference for the assessment of volumetric data,\(^5\) the value of this technique is somewhat reduced by an inferior cost–benefit ratio compared with echocardiography.\(^5\) Reliability of the CMR volume measurements was confirmed by our study where comparable SVs were determined by LV and RV volumetry as well as by performing quantitative flow measurements in the ascending aorta and pulmonary artery, respectively, in healthy subjects with no cardiac shunting (Table 2). The objective of this study was to test two different but technically comparable new generation matrix transducers for 3DE and settings of the quantification software regarding accuracy and reliability of LV volumetry.

Compared with 2DE which is known for less test–retest reliability,\(^7\) higher inter- and intraobserver variability, and greater volume underestimation,\(^21\) RT3DE was found to be superior both in normal and in abnormal LV geometry.\(^22\) Although the examination of younger children is complicated by their greater respiratory variation and higher heart rates, obviously the accuracy of the volumetric indices in the present age groups was not affected and feasibility of volume quantification was 100%. Furthermore, the additional examination of younger patients with TOF demonstrated that abnormal LV shape and mildly impaired LV function due to RV dilatation did not affect accuracy and was comparable to healthy children except of higher scatters. This observation is consistent with studies about assessment of LV volumes by RT3DE in patients with wall motion abnormalities after myocardial infarction.\(^23,24\)

Referring to the healthy children, an underestimation by RT3DE of 10–20% compared with CMR has to be considered, regardless of the applied matrix transducer used for data acquisition. Similar values have been published dealing with comparisons between the two techniques in adults\(^12–14,16,25–31\) with most of these studies showing differences in CMR and 3DE acquisition and evaluation techniques as well as subjects of investigation. Accuracy of RT3DE was further underscored by a low intra- and interobserver variability of \(<4\%\) for all scenarios which was tested at a TCF of 30 U assuming least smoothing by the RT3DE quantification software. Reproducibility as well as the acceptable scatter, reflecting agreement between corresponding measurement results, was comparable to CMR results. Lu et al.\(^12\) found similar values examining a comparable age group with the same quantification software as used in this study demonstrating better reproducibility for RT3DE than for the most other 2D volumetric echocardiographic techniques. However, it should be mentioned that agreement of ESV was considerably reduced. This might be due to the fact that contour-finding algorithms have greater difficulties in differentiating between trabeculae and ventricular cavity in end-systole than in diastole when the endocardial borders are being stretched. Furthermore, it is difficult to reproducibly exclude the papillary muscles at identical positions.

Theoretically, improper definition of the basal portion of the LV may introduce a higher percentage error to the ESV compared with the EDV. But this potential handicap could be easily avoided if CMR volumetric data were gathered axially (=pseudo-four-chamber view) as was done in this study allowing

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**Table 6  Intra- and interobserver variability for real-time three-dimensional echocardiography volumetry**

<table>
<thead>
<tr>
<th>Healthy subjects</th>
<th>3D echocardiography</th>
<th>Interobserver</th>
<th>Interobserver</th>
<th>CMR intraobserver</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VIVID 7 (n = 14)</td>
<td>VIVID 7 (n = 14)</td>
<td>IE 33 (n = 14)</td>
<td>intraobserver (n = 24)</td>
</tr>
<tr>
<td></td>
<td>EDV</td>
<td>ESV</td>
<td>EDV</td>
<td>ESV</td>
</tr>
<tr>
<td>Bland–Altman</td>
<td>Mean</td>
<td>Mean + 2SD</td>
<td>Mean − 2SD</td>
<td>r</td>
</tr>
<tr>
<td>LOA</td>
<td>Mean</td>
<td>Mean + 2SD</td>
<td>Mean − 2SD</td>
<td>Mean</td>
</tr>
<tr>
<td>r</td>
<td>0.991</td>
<td>0.963</td>
<td>0.994</td>
<td>0.953</td>
</tr>
<tr>
<td>P-value</td>
<td>0.012</td>
<td>0.428</td>
<td>0.027</td>
<td>0.401</td>
</tr>
</tbody>
</table>

Assessment of variability was achieved by use of the most user dependent contour-finding activity of 30 U for both ultrasonic systems. For comparison purposes intraobserver variability for CMR volume measurements are shown. Except the correlation coefficient and P-values, all values are given in percent; mean corresponds to mean difference. EDV, end-diastolic volume; ESV, end-systolic volume; LOA, limits-of-agreement; r, correlation coefficient.
accurate delineation between valves, left atrial volume and LV volume areas.

Measurements performed with the V3 and X3-1 matrix transducers revealed good correlations between both transducers with negligible mean differences in volumetric parameters if the same quantification software was used and a high tCFA value of 70 U (= recommendation by the manufacturer) was applied. However, there was only acceptable correlation to CMR data with volume underestimation up to 40%. This might be induced by strong smoothing of the trabecular endocardial borders neglecting cryptic structures belonging to the ventricular cavity which is obviously of greater importance because of a different quantitative relationship between cavity size and folds at the endocardial border in children compared with adults. The calculation algorithm is based on a spatio-temporal spline interpolation model (rotational planes) like a pulsating balloon which is fitted in the myocardial walls in each frame. It seems likely that using high tCFA strong geometric assumptions dominate precise contour tracing. Consequently, lower tCFA values should lead to a more acceptable agreement with CMR data because the priority to manual tracing is elevated. This hypothesis was confirmed in our study for both matrix transducers (Table 1) where lower tCFA values resulted in less underestimation of volumes compared with CMR data. As an example, Figure 5 demonstrates imprecise contour definition introduced by a tCFA of 70 U.

In contrast, greater differences in volumetric indices were observed between the two transducers with reduced tCFA values because quality of the echocardiographic data sets influences more extensively contour definition in this case. In summary, the V3 transducer showed least volume underestimation. These results indicate that comparable to CMR, where no geometric assumptions are needed for evaluation of volumetric indices, reliability of RT3DE might be improved if the application of restrictive models is avoided. Several recent studies have shown that the use of geometric models were at least partly responsible for the different results between both methods. Although an increased user interaction was inevitable to achieve satisfying results well acceptable for clinical routine work, evaluation time could be kept <5 min.

Generally, it should be mentioned that model-based evaluation tools typically include papillary muscles and trabeculae in EDVs but exclude them in ESVs due to closeness and indistinguishableness from myocardium. This may result in a somewhat reduced EF. This is denoted in Tables 2 and 3 where EF determined by CMR (structures excluded from ventricular volumes) is ~3–4% higher compared with EF obtained by RT3DE.

**Study limitations**

No ‘true’ values for LV volumes were available. Thus, accuracy of RT3DE can only be estimated using CMR as a reference. In a recent work by Martensson et al., a higher agreement between measured and true phantom volumes was found for RT3DE and multislice cardiac tomography, whereas large volumetric differences were detected in patients applying both techniques. This raises the question if moving phantoms should be used to identify the appropriate imaging modality for use as the gold standard.

We did not test interstudy variability which would have been of additional value to define differences between two different methods of volume quantification.

No patients with severely compromised cardiac function and dilated LVs were included in this study. Furthermore, the scatters of our patient group are higher than in normally shaped LVs. Thus, it still remains unclear to which extent low tCFA values are sufficient to detect such abnormalities of the LV shape.

Furthermore, a larger study population is needed to estimate the impact of the greater variability in heart rate in children on differences in ventricular volumes between RT3DE and CMR.
Concerning RT3DE technique, higher frame rates and true real-time acquisition as well as higher frequency of the matrix probes would certainly improve the quality of a pediatric examination.

**Conclusions**

RT3DE allows a fast assessment of LV volumes in children with acceptable accuracy which is suitable as an alternative for CMR in the clinical follow-up. It is relatively independent of the acquisition hardware used if comparable probes are used. Restriction of model assumption by high contour-finding activity of the applied semi-automatic evaluation software should be avoided.

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**References**


