Single-Beat Versus Multibeat Real-Time 3D Echocardiography for Assessing Left Ventricular Volumes and Ejection Fraction
A Comparison Study With Cardiac Magnetic Resonance
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**Background**—Real-time 3-dimensional echocardiography (RT3DE) is superior to 2D echocardiography in assessing left ventricular (LV) volumes and ejection fraction (EF), but its feasibility is limited by multibeat acquisition, which requires an optimal breath-hold and a regular heart rhythm. We sought to evaluate the accuracy and feasibility of single- and 2-beat RT3DE for LV volume and EF assessment.

**Methods and Results**—Sixty-six consecutive patients referred for cardiac magnetic resonance (CMR) underwent RT3DE and CMR on the same day. Of the 50 patients (age, 59±18 years; 68% men; 42% coronary artery disease; LVEF=49±14%; limits, 14% to 76%) with an adequate RT3DE image quality, accuracy for LV volumes and EF measurements of single- and 2-beat modalities were compared with the conventional 4-beat acquisition and CMR. Correlations with CMR for LV end-diastolic volume (161±59 mL, r=0.93 to 0.94) and end-systolic volume (86±56 mL, r=0.93 to 0.96) were excellent regardless of the number of cardiac cycles used. However, because of the low temporal resolution (7±2 volumes per second), single-beat underestimated LVEF (bias, −5±8%) with greater bias than 2-beat (bias, 1±6%, P<0.001) and 4-beat (bias, 3±7%, P<0.001) modalities. Interestingly, 2-beat provided accuracy similar to 4-beat for end-diastolic volume (bias, −17±21 mL versus −15±23 mL), end-systolic volume (bias, −9±16 mL versus −12±17 mL), and LVEF (bias, 1±6% versus 3±7%) measurements, but fewer stitching artifacts were observed with 2- than 4-beat modalities (3% versus 30%).

**Conclusions**—Compared with conventional multibeat acquisitions, 2-beat modality provides similar accuracy in LV volume and EF measurements and should be preferred due to fewer stitching artifacts. In contrast, the temporal resolution of single-beat modality appears insufficient to provide an accurate estimation of LVEF. (Circ Cardiovasc Imaging. 2010;3:450-455.)

**Key Words:** real-time 3D echocardiography ■ left ventricular volumes ■ left ventricular ejection fraction
LV volumes have never been evaluated. In the present study, we have compared the accuracy, reproducibility and feasibility of RT3DE using single-beat and multibeat modality (2 and 4 cardiac cycles). Cardiac magnetic resonance (CMR) imaging was used as the gold standard.

Clinical Perspective on p 455

Methods

Study Population
Sixty-six nonselected consecutive patients in sinus rhythm underwent RT3DE and CMR on the same day. Sixteen patients (24%) were excluded because of poor acoustic windows that did not provide adequate echocardiographic image quality for 3D analysis. Of the remaining 50 patients (age, 59±18 years; 68% men) included in the analysis, LV volumes and function assessments were performed in the setting of coronary artery disease (n=21), valvular heart disease (n=5), dilated cardiomyopathy (n=3), hypertrophic cardiomyopathy (n=3), and other heart diseases (n=18).

RT3DE Acquisition
RT3DE acquisitions were performed from the apical window with the patient in the left lateral decubitus position using a commercially available 3D matrix array transducer (Vivid E9 scanner, 3V-D probe (2.5 MHz), GE Vingmed Ultrasound, Horten, Norway). The depth and ultrasound sector size were adjusted to a minimal level still encompassing the entire LV and allowing the highest temporal resolution. In each patient, 3D full-volume data sets were acquired in real time using 1 and several consecutive cardiac cycles (2 and 4 beats). Patients were asked to breathe hold only when 4-beat acquisition was used. RT3DE data sets were stored digitally for off-line analysis.

CMR Acquisition
CMR was performed with a 1.5-T system (Avanto, Siemens Medical Systems, Erlangen, Germany). Patients were positioned in the supine position with a cardiac 6-element phased-array coil placed over the chest. Retrospectively gated and breath-hold LV cine short-axis views were acquired using a steady-state free precession sequence with the following parameters: image matrix, 192×156; field of view, 240 mm; repetition time, 31 ms; echo time, 1.40 ms; flip angle, 81°; slice thickness, 6 mm; no slice gap; and 25 heart phases per cardiac cycle. A stack of LV cine short axes was obtained with the first slice positioned at the LV basis covering the mitral valve and the last slice covering the LV apex.

RT3DE Analysis
Three-dimensional data set analysis was performed off-line on a commercially available workstation (Echo PAC-PC, GE Healthcare, Milwaukee, Wis) using a recently validated semiautomatic software analysis (4DLVQ). The method used to assess LV volumes and systolic function has been previously described. Briefly, cine-loops of 3 apical views (4C, 2C, 3C) and 1 short-axis view derived from the 3D full-volume data set were automatically displayed on a quad-screen with manual alignment when necessary. The end-diastolic frame was automatically defined by R peak on the ECG and the end-systolic frame was estimated from the R-R interval. Both could be manually corrected. Automatic endocardial border delineation of the whole LV volume was processed at end diastole and end systole after positioning 2 landmarks on the mitral annulus and 1 on the LV apex on each apical view. Manual correction was performed at end diastole and end systole to ensure an optimal LV delineation. Eventually, results were expressed as a time-volume curve with the maximum and minimum volumes corresponding to end-diastolic volume (EDV) and end-systolic volume (ESV), respectively. LVEF was computed as following: LVEF (%)=(EDV−ESV)/EDV. Echocardiographic image quality was classified for multibeat acquisitions according to the presence of minor or major stitching artifact. Stitching artifact was defined by a clear visualization of the different acquired subvolumes, with and without discontinuity of endocardial borders over the full cardiac cycle for major and minor stitching, respectively.

CMR Analysis
CMR data were analyzed using commercially available semiautomatic software (Argus, Siemens Medical Systems, Erlangen, Germany). All slices with at least 50% of the LV cavity circumference surrounded by myocardial tissue were included for analysis. End-diastolic and end-systolic LV endocardial borders were automatically traced in every slice and manually adjusted leaving the papillary muscles and the trabeculations within the LV cavity. LVEF was derived from LV volumes as previously described.

Statistical Analysis
Continuous variables are expressed as mean±SD and nominal values as percentages. Comparison among 1-beat, 2-beat, and 4-beat data were performed using repeated-measures ANOVA. Correlation (Pearson) was used to analyze LV volumes estimated by RT3DE and CMR. Agreement between RT3DE and MRI for LV volumes and EF measurements was assessed using Bland-Altman analysis. To test whether bias was zero, a single-sample t test was performed for the difference between RT3DE and CMR. RT3DE reproducibility was assessed in 10 randomly selected patients and expressed as the absolute difference between 2 paired measurements divided by their average. Statistical difference was considered as significant when probability value was <0.05. All analysis was performed using Statview (SAS institute Inc, Version 5).

Results

Population Characteristics
Mean age of the patients was 59±18 years, and 68% were men. LVEDV, LVESV, and LVEF by CMR averaged 161±59 mL (limits, 80 to 360 mL), 86±56 mL (29 to 310 mL), and 49±14% (14% to 76%), respectively.

RT3DE Temporal Resolution and Image Quality
Temporal resolution for LV full-volume data sets acquired using 1, 2, and 4 cardiac cycles was 7±2, 15±5, and 27±8 volumes per second, respectively. RT3DE data sets acquired using 1 or 2 cardiac cycles (without breath-hold) were analyzable in all patients. Minor stitching artifact was reported in 3 (6%) patients for 2-beat data sets. In contrast, for 4-beat datasets, major stitching artifacts preventing adequate delineation of the endocardial border were reported in 3 (6%) patients and minor stitching artifact in 14 (28%) patients.

EDV Assessment
Excellent correlation between RT3DE and CMR was observed for EDV regardless of the number of cardiac cycles used (r limits, 0.92 to 0.94; Figure 1). However, Bland-Altman analysis showed a systematic LVEDV underestimation (Figure 1) by RT3DE with higher bias (−21±25 mL, Figure 1) for single-beat modality. Interestingly, bias for LVED measurement did not differ between 2- and 4-beat modalities.

ESV Assessment
Similarly to EDV, despite excellent correlation between RT3DE and CMR measurements (r=0.93 to 0.96), a systematic underestimation of ESV by RT3DE was observed with multibeat modality. Bias was −9±16 and −12±17 mL for
2-beat and 4-beat acquisitions, respectively (Figure 2). In contrast, no significant bias (−3 mL, \( P=0.31 \)) was observed for single-beat acquisition (Figure 2).

**LVEF Assessment**

Excellent correlations between LVEF by RT3DE and CMR were observed when multibeat modalities were used (\( r=0.89 \) to 0.92, Figure 3) and to a lesser extent for single-beat acquisition (\( r=0.86 \)). RT3DE data sets derived from 2-beat and 4-beat acquisitions provided an accurate assessment of LVEF with small bias (1\( \pm \)6% and 2\( \pm \)7%, respectively). Importantly, bias for LVEF measurement did not differ between 2- and 4-beat acquisitions (Figure 3). In contrast, RT3DE using single-beat acquisition clearly underestimated LVEF (bias \( =-5\pm8\% \)). Underestimation of LVEF measurement >10% was observed in 58%, 63%, 68%, and 75% of patients when temporal resolution was lower than 10, 9, 8, and 7 volumes per cardiac cycle, respectively (Figure 4).

**Impact of RT3DE Image Quality**

Minor stitching artifact did not significantly affect 4-beat accuracy for EDV, ESV, and LVEF assessment (Table 1). However, EDV underestimation tended to be higher when minor stitching artifact was present (bias, \( -18\pm24 \text{ mL vs. } -12\pm21 \text{ mL; } P=0.37 \)).

**RT3DE Reproducibility**

Intraobserver variability ranged from 3\% to 3\%4\% for EDV, 3\%2\% to 8\%5\% for ESV, and 5\%4\% to 7\%4\% for LVEF. Interobserver variability ranged from 5\%4\% to 9\%6\% for EDV, 9\%7\% to 12\%8\% for ESV, and 7\%4\% to 9\%5\% for LVEF. There was no significant difference between single-beat and multibeat modalities for EDV, ESV, and LVEF intraobserver or interobserver reproducibilities (Table 2).

**Discussion**

Several studies have demonstrated that RT3DE provides more accurate and reproducible LV volume and LVEF measurements than 2DE, especially by avoiding the geometric assumption and errors caused by foreshortening.\(^8\)\textsuperscript{–13}\) The accuracy of RT3DE allows the detection of small changes in LV parameters, which can strongly affect medical decisions.\(^15\) However, conventional RT3DE requires at least 3
cardiac cycles for a full LV volume acquisition, which limits its feasibility in patients who cannot perform a breath-hold correctly. To overcome this issue, new 3D echocardiographic systems allow the acquisition of LV volume by using only 1 or 2 cardiac cycles, in contrast to standard multibeat modality acquisitions. In the present study, we demonstrate that the 2-beat modality improves the feasibility of RT3DE acquisition by avoiding breath-hold and then improving image quality. Importantly, the accuracy of LV volumes and EF derived from the 2-beat modality remains similar to standard multibeat modalities over 4 cardiac cycles. In contrast, the temporal resolution of the single-beat approach appears insufficient to provide an accurate estimation of LVEF.

**Accuracy of Single-Beat RT3DE**

Improvement of 3D probe and processing systems in the last decade has brought the technique into current clinical practice. RT3DE provides an accurate and reproducible assessment of LV volumes and function, but its feasibility greatly depends on the image quality. So far, optimal balance between spatial and temporal resolution is conventionally obtained by acquiring LV full volume with multibeat modality (from 3 to 7 cardiac cycles). However, to avoid stitching artifacts, multibeat acquisition requires an experienced operator with stable probe handing, regular cardiac cycle, and a breath-hold during the full-volume acquisition. Consequently, despite its superior accuracy for LV volumes and EF assessment, RT3DE feasibility remained inferior to 2D echocardiography. To avoid breath-hold and extend the use of 3D imaging in patients in arrhythmia, single-beat acquisition has been proposed as an alternative to multibeat modality by several echocardiography systems. However, in the present study, we reported that single-beat acquisition can only provide 7±2 volumes per second (6±2 volumes per cardiac cycles), meaning that the time required to scan 1 volume (143 ms) is longer than isovolumetric contraction and relaxation periods. EDV then would be systematically underestimated and ESV overestimated. This is concordant with our results, which report the highest bias for EDV between RT3DE by single-beat acquisition and CMR. Interestingly, assessment of ESV by single-beat acquisition did not provide a significant difference with CMR. That could be explained by the association of 2 kinds of error. The first error is related to a conventional LV volume underestimation that results from the limited spatial resolution of RT3DE. The second one is a trend toward ESV overestimation because of a low temporal resolution for single-beat acquisition that probably results in missing the real end-systolic timing. Eventually, EDV underestimation and the lack of significant bias for ESV assessment by single-beat acquisition lead to an important underestimation of LVEF. However, because of the limited population sample size, lower accuracy of single-beat acqu
sition for LV volumes and EF measurement may also occur by chance.

Accuracy of RT3DE Multibeat Modalities

Multibeat modality using 4 or more cardiac cycles has been widely used to validate the accuracy of RT3DE. However, the feasibility of LV volume acquisition is limited by the need for a regular heart rhythm and a sustained breath-hold when 4 cardiac cycles are used. In the present study, we demonstrated that stitching artifacts mostly related to incorrect breath-hold may be largely avoided when single-beat or 2-beat acquisition is used. Despite no significant impact of minor stitching artifacts on the accuracy of 4-beat acquisition, the mean difference with CMR due to stitching artifacts tends to be higher in the case of stitching artifacts for LVEDV. Regarding the impact of image quality and spatial resolution on LV volumes and function assessment, minor stitching artifacts should result in less accurate and reproducible measurements.

The main advantage of 2-beat over single-beat modality is the temporal resolution (15±5 volumes per second; scanning time, 67 ms for 1 volume), which ensures a correct scanning of the LV volume during the isovolumetric relaxation and contraction periods. Moreover, 2-beat acquisition provides similar accuracy to the 4-beat modality. These data demonstrate that LV volume acquisition using 2 cardiac cycles should be preferred; RT3DE feasibility is improved without alteration in the accuracy and reproducibility. Future improvement in 3D probe and processing technology should be encouraged to improve the temporal resolution of RT3DE single-beat modality.

Study Limitations

The study was limited to a population with good image quality, which explains the high rate of patients excluded from analysis. We did not evaluate the accuracy of contrast imaging, which is not available on single- and 2-beat acquisitions. Thus, our results cannot be extended to contrast imaging because the acquisition algorithm may reduce the temporal resolution. In addition, this limitation and our results cannot be broadly applied to all echocardiography systems because only 1 system was evaluated in the present study. Moreover, in the present study, temporal resolution was set by default for single beat and multibeat. We did not adjust the volume rate during each acquisition modality (single beat or multibeat) to maintain comparable spatial resolution. Finally, the use of CMR as the gold standard for LV volumes and EF has limitations related to the difficulty in accurately defining the first basal slice and the spatial resolution of apical region.

Conclusion

Compared with conventional multibeat acquisitions, the 2-beat modality provides similar accuracy in LV volumes and EF measurements and should be preferred due to fewer stitching artifacts. The temporal resolution of single-beat imaging appears insufficient to capture end-diastolic and end-systolic volumes.

Disclosures

None.

References


Table 1. Impact of Minor Stitching Artifact on RT3DE 4-Beat Modality for LV Volumes and LVEF Assessment (Bias±SD Versus CMR)

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<thead>
<tr>
<th></th>
<th>Stitch− (n=14)</th>
<th>Stitch+ (n=33)</th>
<th>P Value</th>
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<tr>
<td>Volume rate, per cardiac cycle</td>
<td>21±6</td>
<td>25±6</td>
<td>0.07</td>
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<tr>
<td>EDV, mL</td>
<td>−12±21</td>
<td>−18±24</td>
<td>0.37</td>
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<tr>
<td>ESV, mL</td>
<td>−11±17</td>
<td>−12±18</td>
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<tr>
<td>LVEF, mL</td>
<td>3±7</td>
<td>3±7</td>
<td>0.98</td>
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Table 2. Reproducibility of RT3DE

<table>
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<th></th>
<th>1 Beat</th>
<th>2 Beats</th>
<th>4 Beats</th>
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<tbody>
<tr>
<td>EDV, %</td>
<td>Interobserver</td>
<td>9.2±5.6</td>
<td>4.6±4.2</td>
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<tr>
<td></td>
<td>Intraobserver</td>
<td>3.4±3.7</td>
<td>3.2±3.3</td>
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<tr>
<td>ESV, %</td>
<td>Interobserver</td>
<td>11.9±8.4</td>
<td>9.0±6.9</td>
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<tr>
<td></td>
<td>Intraobserver</td>
<td>8.0±5.1</td>
<td>3.2±2.4</td>
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<tr>
<td>LVEF, %</td>
<td>Interobserver</td>
<td>8.6±11.6</td>
<td>6.6±3.9</td>
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<tr>
<td></td>
<td>Intraobserver</td>
<td>6.8±4.4</td>
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**CLINICAL PERSPECTIVE**

Real-time 3D echocardiography (RT3DE) improves the accuracy of left ventricular volume and ejection fraction measurement. The use of RT3DE is currently limited by the need of acquiring RT3DE data over several cardiac cycles, which requires adequate breath-hold and regular cardiac cycles to avoid stitched artifacts. To overcome this issue, RT3DE data acquisition using only 1 or 2 cardiac cycles has been recently developed. The present study demonstrated that 2-beat acquisition provides similar accuracy to RT3DE data using the conventional 4-beat acquisition. Importantly, stitched artifacts are reduced with 2-beat acquisition because breath-hold is avoided. Improvement in RT3DE technology should be encouraged to facilitate and extend the use of RT3DE in daily practice as to improve the accuracy of left ventricular volumes and ejection fraction assessment.
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