Novel Approach to Three-Dimensional Echocardiographic Quantification of Right Ventricular Volumes and Function from Focused Views

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Background: Echocardiographic assessment of the right ventricle is difficult because of its complex shape. Three-dimensional echocardiographic (3DE) imaging allows more accurate and reproducible analysis of the right ventricle than two-dimensional methodology. However, three-dimensional volumetric analysis has been hampered by difficulties obtaining consistently high-quality coronal views, required by the existing software packages. The aim of this study was to test a new approach for volumetric analysis without coronal views by using instead right ventricle–focused three-dimensional acquisition with multiple short-axis views extracted from the same data set.

Methods: Transthoracic 3DE and cardiovascular magnetic resonance (CMR) images were prospectively obtained on the same day in 147 patients with wide ranges of right ventricular (RV) size and function. RV volumes and ejection fraction were measured from 3DE images using the new software and compared with CMR reference values. Comparisons included linear regression and Bland-Altman analyses. Repeated measurements were performed to assess measurement variability.

Results: Sixteen patients were excluded because of suboptimal image quality (89% feasibility). RV volumes and ejection fraction obtained with the new 3DE technique were in good agreement with CMR (end-diastolic volume, $r = 0.95$; end-systolic volume, $r = 0.96$; ejection fraction, $r = 0.83$). Biases were, respectively, $-6 \pm 11\%$, $0 \pm 15\%$, and $-7 \pm 17\%$ of the mean measured values. In a subset of patients with suboptimal 3DE images, the new analysis resulted in significantly improved accuracy against CMR and reproducibility, compared with previously used coronal view–based techniques. The time required for the 3DE analysis was approximately 4 min.

Conclusions: The new software is fast, reproducible, and accurate compared with CMR over a wide range of RV size and function. Because right ventricle–focused 3DE acquisition is feasible in most patients, this approach may be applicable to a broader population of patients who can benefit from RV volumetric assessment. (J Am Soc Echocardiogr 2015;■:■-■.)

Keywords: Right ventricle, Right ventricular volumes and function, Three-dimensional echocardiography

Echocardiographic assessment of the right ventricle is difficult because of its complex shape. Right ventricular (RV) performance is known to be a major determinant of clinical status and long-term outcomes in patients with pulmonary hypertension, cardiomyopathies, and congenital heart disease.[1-14] Cardiovascular magnetic resonance (CMR) imaging is considered the reference for RV volume and ejection fraction (EF).[15] Because of the complicated structure and geometry of the right ventricle, conventional two-dimensional echocardiography is unable to correctly estimate RV volume using reasonable geometric assumptions. Accordingly, current echocardiographic guidelines[16] recommend the assessment of RV function by surrogate indices that represent RV longitudinal function, including M-mode measurements of tricuspid annular plane systolic excursion and Doppler tissue imaging measurements of peak systolic velocity (S′). However, the accuracy of these surrogate measures against CMR indices of RV function has been modest at best[17,18] because of covariates such as regional abnormalities in the RV free wall, tethering, and tricuspid regurgitation. Another two-dimensional index of RV global systolic function is fractional area change. Its main limitation is the dependence on the specific imaging plane, which causes considerable intermeasurement variability.

Three-dimensional (3D) echocardiographic (3DE) imaging allows direct measurements of RV volume without relying on geometric assumptions regarding RV shape, resulting in more accurate and

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Abbreviations

CMR = Cardiovascular magnetic resonance

EDV = End-diastolic volume

EF = Ejection fraction

ESV = End-systolic volume

RV = Right ventricular

3D = Three-dimensional

3DE = Three-dimensional echocardiographic

reproducible measurements of RV EF.[19-24] The recently published cardiac chamber quantification guidelines included for the first time recommendations for 3D analysis of the right ventricle.[25] However, 3D volumetric analysis has been limited to patients with good images, because of difficulties deriving from 3DE data sets the high-quality coronal views required by existing software packages.[24,26-28] A new approach that allows volumetric analysis of the right ventricle, while eliminating the need for extraction of coronal views, was recently implemented in software. This new software uses instead right ventricle–focused 3D acquisition with multiple short-axis views extracted from the same data set. Our hypothesis was that this new inherently 3D volumetric analysis tool would allow more accurate and more reproducible RV assessment and would be applicable to a higher percentage of patients and thus ultimately be better suited for clinical use. Accordingly, our primary goal was to test the accuracy of this approach against CMR reference and its reproducibility. In addition, we sought to compare the accuracy and reproducibility of these measurements with those obtained using the previous analysis technique in a subset of patients with suboptimal quality of 3DE images.

METHODS

Patient Population

One hundred forty-seven patients in sinus rhythm with wide ranges of RV size and function were prospectively studied. These patients were referred for CMR with clinical indications and agreed to undergo transthoracic 3DE imaging in addition. Both 3DE imaging and CMR were performed on the same day to minimize the impact of changing loading conditions. RV end-diastolic volume (EDV) and end-systolic volume (ESV) and EF were measured from 3DE images using the new software and compared with CMR reference values obtained using the standard disk summation technique. The study was approved by the Institutional Review Board of the University of Chicago Medical Center, and informed consent was obtained from each patient.

CMR Imaging and Analysis

CMR was performed on a 1.5-T scanner (Philips Medical Systems, Best, The Netherlands) with a five-channel cardiac coil. A steady-state free-precision dynamic gradient-echo sequence was used to obtain cine loops, during approximately 5-sec breath holds (repetition time, 2.9 msec; echo time, 1.5 msec; flip angle, 60°; temporal resolution, ∼30–40 msec). In all patients, six to 10 short-axis slices were obtained from the ventricular base to the apex (slice thickness, 6 mm; gap, 4 mm). These images were analyzed offline using commercial software (ViewForum; Philips Medical Systems). In every slice, endocardial contours were manually traced at end-diastole and end-systole by an investigator trained in CMR-based chamber quantification (Society for Cardiovascular Magnetic Resonance level III training) who was blinded to echocardiographic data. Delineation of RV boundaries at end-diastole and end-systole was performed manually for each slice. On the most basal slices, the right ventricle was differentiated from the right atrium by advancing the cine loop frame-by-frame throughout systole. If the cavity was becoming smaller and myocardium thicker, it was included in the RV volume, whereas portions of the cavity that were becoming larger and did not show wall thickening were considered part of the atrium. Endocardial trabeculae were included in the RV cavity. Disk summation was used to calculate EDV and ESV, and EF was calculated using the standard formula.

Transthoracic 3DE Imaging

Right ventricle–focused 3DE data sets that included the entire right ventricle in the pyramidal scan volume were acquired by an experienced sonographer using the iE33 imaging system equipped with an S5 transducer (Philips Medical Systems, Andover, MA). Simultaneous real-time short-axis multiplanar reconstruction was used to ensure optimal visualization of the free wall (Figure 1). Imaging settings were optimized to obtain RV full-volume images with a clear endocardial border and a high frame rate (18 ± 6 Hz). Three-dimensional echocardiographic data sets were stored digitally and used for offline analysis, blinded to CMR data.

Three-Dimensional Echocardiographic Analysis Using the New Software

Quantitative analysis was performed using new dedicated software (4D RV-Function 2.0, a module of TomTec-Arena; TomTec Imaging Systems, Unterschleissheim, Germany) to measure RV volumes and EF using a semiautomated algorithm based on a software platform for data management (Research Arena 2.0; TomTec Imaging Systems). The first steps of analysis involved manual definition of the left ventricular and RV long axes at end-diastole in both apical two- and four-chamber views (Figures 2A and 2B), left ventricular outflow tract diameter in the apical three-chamber view (Figure 2C, top), the anterior and posterior junction points of the RV free wall with the interventricular septum, and the longest dimension of the RV cavity between the septum and the free wall, both in a single short-axis view (Figure 2C, bottom).

These anatomic landmarks were used to automatically extract from the 3DE data set the right ventricle–focused four-chamber view and a series of short-axis views from base to apex for both end-systole and end-diastole (Figures 3A and 3B, top and bottom, respectively) and to generate a 3D model of the right ventricle (Figure 3C). This RV 3D endocardial surface was then tracked throughout the cardiac cycle using speckle-tracking technology (Figure 3D), while fine-tuning was performed interactively to optimize boundary position as necessary. Three-dimensional volumes over time were then numerically computed from the dynamic surface model[29] and used to determine EDV, ESV, and EF.

Intertechnique Comparisons

EDV, ESV, and EF measurements using the new software were compared with the CMR reference values. These intertechnique comparisons included linear regression with Pearson correlation and Bland-Altman analyses to assess the mean intertechnique differences (biases) and limits of agreement (±2 SDs of the mean difference) with the CMR reference.