Standardized Delineation of Endocardial Boundaries in Three-Dimensional Left Ventricular Echocardiograms

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Background: Three-dimensional (3D) echocardiography is fundamental for left ventricular (LV) assessment. The aim of this study was to determine discrepancies in 3D LV endocardial tracings and suggest tracing guidance.

Methods: Forty-five 3D LV echocardiographic data sets were traced by three experienced operators, from different centers, according to predefined guidelines. The 3D meshes were compared with one another, and the endocardial areas of discrepancies were identified. A discussion and retracing protocol was used to reduce discrepancies. For each data set, an average 3D mesh was produced (reference mesh). Subsequently, four novice operators, divided into two groups, traced 20 of the data sets. Two operators followed the tracing protocol and two did not.

Results: The intraclass correlation coefficients among the three experienced operators for end-diastolic volume, end-systolic volume, and ejection fraction were 0.952, 0.955, and 0.932. The absolute distances between tracings were 1.11 ± 0.45 mm. The highest tracing discrepancies were at the apical cap and anterior and anterolateral walls in end-diastole and end-systole and also at the basal anteroseptum in end-systole. Agreement with the reference meshes was better for the novice operators who followed the guidance (10.9 ± 17.3 mL, 10.2 ± 14.7 mL, and −2.2 ± 4.1% for end-diastolic volume, end-systolic volume, and ejection fraction) compared with those who did not (16.3 ± 16.4 mL, 17.0 ± 16.0 mL, and −4.2 ± 4.1%, respectively).

Conclusions: Comparing 3D LV tracings, the endocardial areas that are the most difficult to delineate were identified. The suggested protocol for LV tracing resulted in very good agreement among operators. The reference 3D meshes are available for online testing and ranking of LV tracing algorithms. (J Am Soc Echocardiogr 2017;■:■-■.)

Keywords: 3D echocardiography, Left ventricular segmentation, Endocardial tracing

Three-dimensional (3D) echocardiography provides significant advantages over two-dimensional (2D) echocardiography and is currently applied in several aspects of cardiology.[1,2] The most common indication for performing echocardiography in adults is the evaluation of left ventricular (LV) size and function.[3] The use of 3D echocardiographic imaging eliminates geometric assumptions and misinterpretation errors caused by foreshortened views in 2D mode.[2,4] Several trials have demonstrated the reproducibility of 3D-derived LV measurements.[5-7] At present there are no clear standards or guidelines available for 3D LV endocardial border tracing, and there is no direct comparison of actual tracings among different operators.

Automated tracing of the left ventricle in 3D cardiac ultrasound data sets has been a subject of scientific research for the past 20 years,[8] but there has hardly been any comparison of different methods on the same data sets.[6]

In this study, we aimed to address these issues by suggesting a protocol for LV endocardial tracing in 3D echocardiographic data sets and

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Abbreviations
2D = Two-dimensional
3D = Three-dimensional
ED = End-diastolic
EDV = End-diastolic volume
ES = End-systolic
ESV = End-systolic volume
ICC = Intraclass correlation coefficient
LV = Left ventricular
LVEF = Left ventricular ejection fraction
LVOT = Left ventricular outflow tract

creating a series of clinically realistic data sets with well-established reference tracings on the basis of manual tracings from three expert echocardiography centers. On the basis of this standard set, a competition for automated tracing methods was organized, associated with the Medical Image Computing and Computed Assisted Interventions 2014 symposium, which has been published previously.[9] The purpose of this competition was to provide reference 3D LV meshes for testing LV endocardial tracing algorithms. The reference meshes remain available online for continuous testing and ranking of fully automated or semiautomated algorithms.

Finally, we evaluated the usefulness of our tracing protocol in a clinically relevant setting, in which commercially available software was used by novice operators.

METHODS

Acquisition Protocol

We included 45 individuals: 15 healthy individuals, 15 patients with previous myocardial infarction at least 3 months before the time of echocardiography, and 15 patients with nonischemic dilated cardiomyopathy. The patients were recruited at three different institutions (Rennes University Hospital, Rennes, France; University Hospital Leuven, Leuven, Belgium; and Thoraxcenter, Erasmus MC, Rotterdam, The Netherlands). Fifteen patients undergoing echocardiography and meeting the inclusion criteria were recruited at each institution. Exclusion criteria were left bundle branch block, visually dyssynchronous left ventricle, and unacceptable image quality. Unacceptable image quality was defined as (1) significant stitching or other types of artifacts affecting the tracking of endocardium or (2) poor visualization of the LV wall or wall out of the image sector to an extent that the image could no longer be manually analyzed with good confidence in multiple segments. The image quality of the accepted data sets was graded as good, fair, or poor (Figure 1). Good quality was defined when the endocardium was visible in end-diastolic (ED) and end-systolic (ES) instances in all 17 segments throughout the cardiac cycle, fair quality if the endocardium was not clearly seen in one or two segments, and poor quality when the endocardial border was not clearly distinguished in ES or ED frames in more than two segments, but the operator could still define the border with confidence by tracking the endocardium throughout the cardiac cycle and also by considering adjacent segments. The variation in image quality was a result of recruitment of cases in a real-life setting and was not intentional. The image quality variation was similar in all three hospitals' data sets.

We used echocardiography machines from three different vendors: Vivid E9 with a 4V probe (GE Vingmed Ultrasound, Horten, Norway), iE33 with an X3-1 or X5-1 probe (Philips Medical Systems, Andover, MA), and SC2000 with a 4Z1c probe (Siemens Healthcare, Erlangen, Germany). Machine settings were optimized to achieve maximum image quality while keeping the volume rate above 16 Hz. The mean number of frames per cardiac cycle was 25.7 ± 8.5. Acquired data were fully anonymized and handled within the regulations set by the local ethical committee of each hospital.

Endocardial Tracing Procedure

ED and ES frames were identified. Nine standard anatomic planes were defined: four longitudinal planes through the long axis under 45° angles and five transverse (short-axis) planes divided equally along the long axis. For the tracings, a custom noncommercial tracing package for 3D echocardiograms (Speqle3D) was used, developed at the University of Leuven.[10] A single experienced operator from each center (A.P., M.L.G., E.G.) with experience of >300 3D LV tracing analyses was appointed to perform the tracings. Each operator independently traced the endocardial border in the nine predefined planes, in both ED and ES instances. To guarantee direct comparisons, the operators were only allowed to contour in the nine predefined slices and in the allocated ED and ES frames. All 45 data sets were traced by all three operators.

A set of guidelines for performing the LV tracing was defined at the beginning of the project and revised subsequently by comparing the tracing conventions of the different centers. Basic aims were as follows:

Include trabeculae and papillary muscles in the LV cavity (Figure 2). A suggestion was for the operator to take as a reference point the endocardial border that is free of papillary muscle and then trace "outside" the papillary muscle to meet the endocardium at the other edge of the muscle (i.e., from the basal to the apical segment or vice versa). Also, we suggested tracing at the level of the trough of endocardial creases to include trabeculations in the LV cavity.

Keep tissue consistency between end-diastole and end-systole and between adjacent and intersecting planes. The operator was asked to play the cine loop forward and backward to ensure that the traced endocardial border in end-diastole was corresponding to the same tissue line in end-systole by tracking the endocardium throughout the cardiac cycle. During this process, special consideration was taken with regard to elevation plane artifacts. Also, the prototype software showed the projection of the intersection points between tracings of orthogonal planes (Figure 3). The operator therefore ensured tissue consistency between transverse and longitudinal planes.

In long-axis views, draw up to the mitral valve annulus on the inside of the bright ridge up to the point at which the valve leaflet is hinging. The mitral valve annulus is sometimes quite difficult to trace with consistency. For this reason, we suggested that the operator should trace at the ventricular side of the annulus and pay special attention to identify the leaflet hinge point by reviewing the cine loop instead of judging on the basis of a single frame (Figure 4).

Partly exclude the LV outflow tract (LVOT) from the cavity by drawing from the septal mitral valve hinge point to the septal wall to create a smooth shape (Figure 5). The LVOT is one of the most challenging parts of LV endocardial tracing. We proposed to trace in a way that partially excludes the LVOT and provides a smooth shape of the basal anteroseptal wall segment to keep the LV shape symmetric and also avoid giving the impression of a dyskinetic segment as the LVOT expands during systole.

Draw the apex high up near the epicardium in both end-diastole and end-systole, taking into consideration that there should be