Morphologic Analysis of the Normal Right Ventricle Using Three-Dimensional Echocardiography–Derived Curvature Indices

Karima Addetia, MD, Francesco Maffessanti, PhD, Denisa Muraru, MD, PhD, Amita Singh, MD, Elena Surkova, MD, Victor Mor-Avi, PhD, Luigi P. Badano, MD, PhD, and Roberto M. Lang, MD, *Chicago, Illinois; Lugano, Switzerland; and Padua, Italy*

Background: Right ventricular (RV) remodeling involves changes in size, wall thickness, function, and shape. Previous studies have suggested that regional curvature indices (rCI) may be useful for RV shape analysis. The aim of this study was to establish normal three-dimensional echocardiographic values of rCI in a large group of healthy subjects to facilitate future three-dimensional echocardiographic study of adverse RV remodeling.

Methods: RV endocardial surfaces were reconstructed at end-diastole and end-systole in 245 healthy subjects (mean age, 42 ± 12 years) and analyzed using custom software to calculate mean curvature in six regions: RV inflow tract (RVIT) and RV outflow tract, apex, and body (both divided into free wall and septal regions). Associations with age and gender were studied.

Results: The apical free wall was convex, while the septum (apex and body) was more concave than the body free wall. Septal curvature did not change significantly from end-diastole to end-systole. The RV outflow tract and RVIT became flatter from end-diastole to end-systole. In keeping with the "bellows-like" action of RV contraction, the body free wall became flatter, while the apex free wall changed to a more convex surface. There were no intergender differences in rCI. In older subjects (≥55 years of age), the RV free wall and RV outflow tract were flatter, and from end-diastole to end-systole, the RVIT became less flattened and the apex less pointed. These changes suggest that the right ventricle is stiffer in older subjects, with less dynamic contraction of the RVIT and less bellows-like movement.

Conclusions: This study established normal three-dimensional echocardiographic values for RV rCI, which are needed to further study RV diastolic dysfunction and remodeling with disease. (J Am Soc Echocardiogr 2017;■:■-■.)

Keywords: Right ventricle, Normal heart, Curvature, Three-dimensional echocardiography

It has been recognized that the right ventricle alters its shape in response to variations in pressure and volume loading.[1,2] These shape alterations have been shown to be predictive of outcomes in several different clinical situations. Interventricular septal flattening, for instance, has been associated with prognosis in pulmonary hypertension and pulmonary embolism.[3] In addition, less conical right ventricular (RV) remodeling in functional tricuspid regurgitation has been suggested as a potential factor for consideration in the methodology used for tricuspid valve repair.[4] These morphologic changes, however, are difficult to characterize on two-dimensional (2D) echocardiography, because multiple imaging planes need to be integrated to appreciate the complex asymmetric crescent shape of the right ventricle, making quantitative evaluation complex and impractical. Recent advancements in three-dimensional (3D) transthoracic echocardiography allow the entire right ventricle to be contained in a single pyramidal data set lending itself to detailed analysis of RV size and function. After volumetric reconstruction, the endocardial surface of the right ventricle can be extracted and viewed from multiple vantage points, enabling, at least in theory, a description of dynamic changes in RV shape.

The normal left ventricle has a shape that resembles a prolate ellipsoid. In the presence of loading stressors or myocyte damage, the shape of the left ventricle often changes from conical to more spherical. Accordingly, left ventricular (LV) shape alterations have been quantitatively described by the degree of similarity between the left

From the University of Chicago, Chicago, Illinois (K.A., A.S., V.M.-A., R.M.L.); the Center for Computational Medicine in Cardiology, Institute of Computational Science, Universita della Svizzera Italiana, Lugano, Switzerland (F.M.); and the Department of Cardiac, Thoracic and Vascular Sciences, University of Padua, Padua, Italy (D.M., E.S., L.P.B.).

The authors received research grants from Philips Healthcare (Dr. Lang) and Astellas Pharma (Dr. Mor-Avi) for other unrelated studies. Dr. Badano and Dr. Muraru have received equipment grants from GE Vingmed (Horten, N) and TomTec Imaging Systems (Unterschleissen, D), and received Speakers' honoraria from GE Vingmed (Horten, N). Thomas Ryan, MD, FASE, served as guest editor for this report.

Conflicts of Interest: None.

Reprint requests: Karima Addetia, MD, University of Chicago Hospitals, Section of Cardiology, 5758 South Maryland Avenue, MC 9067, D-CAM Room 5501, Chicago, IL 60637 (E-mail: kaddetia@medicine.bsd.uchicago.edu).

0894-7317/$36.00

https://doi.org/10.1016/j.echo.2017.12.009

Abbreviations

2D = Two-dimensional

3D = Three-dimensional

ASD = Atrial septal defect

FAC = Fractional area change

LV = Left ventricular

RV = Right ventricular

RVIT = Right ventricular inflow tract

RVOT = Right ventricular outflow tract

TAPSE = Tricuspid annular plane systolic excursion

ventricle and a reference shape, such as a sphere or a cone.[5] Furthermore, spherical LV shape has been associated with adverse outcomes.[6-8] In contrast, the complex RV shape cannot be easily approximated by a predefined shape, such as a sphere or a cone, and thus RV remodeling has not been systematically studied by means of changes in its global shape. To date, most studies exploring the concept of RV shape have focused on changes in the interventricular septum, with quantification of these changes using 2D-derived eccentricity indices[1,9] or interventricular septal curvature.[10] A small number of studies have focused on changes in RV apical morphology.[11]

In this study, we sought to evaluate the dynamic changes that occur in regional RV curvature in a large population of healthy volunteers over a wide range of ages by generating regional color-coded parametric curvature maps from endocardial surfaces derived from 3D data sets of the right ventricle. This work was aimed at establishing a reference standard against which abnormal right ventricles could be compared and pathologic changes could be detected quantitatively.

METHODS

Patient Population

A total of 245 healthy volunteers (mean age, 42 ± 12 years; 44% men) with adequate image quality were enrolled at two university hospitals (University of Chicago and University of Padua, Italy). Recruited subjects were on no medications and did not have histories of cardiac or lung disease or cardiac risk factors. Inclusion criteria were normal results on 2D transthoracic echocardiography with normal RV and LV chamber size and function and not more than mild valvular regurgitation with normal pulmonary artery pressures (<35 mm Hg). The study was approved by the institutional review boards of both institutions.

Two-Dimensional and 3D Transthoracic Echocardiography

Comprehensive 2D transthoracic echocardiography was performed by an experienced sonographer using the iE33 system equipped with an S5 and X5 transducer (Philips Medical Imaging, Andover, MA) or the Vivid E9 system (GE Vingmed Ultrasound, Horten, Norway) equipped with an M5S transducer. Three-dimensional full-volume RV data sets were obtained from a RV-focused view by stitching together four to six consecutive electrocardiographically gated subvolumes taking care to avoid dropout of the anterior RV free wall and include the entire RV apex in the pyramidal data set. Image depth and sector were optimized to achieve frame rates ≥20 Hz. All images were analyzed offline.

The following 2D parameters were measured using the RV-focused apical four-chamber view in accordance with American Society of Echocardiography and European Association of Cardiovascular Imaging recommendations[12]: (1) basal and midventricular diameters and length; (2) fractional area change (FAC); and (3) maximal tricuspid annular plane systolic excursion (TAPSE) obtained using M-mode imaging from the lateral wall of the tricuspid annulus. Three-dimensional data sets were analyzed using dedicated 3D software to quantify RV end-diastolic and end-systolic volumes and RV ejection fraction and to reconstruct the RV endocardial surface for shape analysis (4D RV-Function 1.1; TomTec Imaging Systems, Unterschleissheim, Germany). RV contours were manually initialized in end-systolic and end-diastolic frames in the short- and long-axis planes, while including the trabeculae in the RV cavity.[13,14] Side-by-side display of dynamic tracking of endocardial borders throughout the cardiac cycle enabled end-diastolic and end-systolic contour adjustments.

RV Shape Analysis

Three-dimensional RV endocardial surfaces were exported as a mesh of connected points and used as input into custom software for analysis of regional RV curvature as previously described.[15] Zero curvature defines a flat surface, while a positive or negative curvature depicts convexity or concavity, respectively. The more positive or negative the curvature, the more convex or concave the surface. The curvature of a region was defined from a reference point outside the right ventricle looking onto the surface being described (Figure 1). To allow comparisons between right ventricles of different shapes, the 3D surface was automatically divided into four parts: one fourth apex, two fourths body, and one fourths RV outflow tract (RVOT) and RV inflow tract (RVIT; Figure 2). The free wall and septal components of both the RV apex and body were reported separately, as these regional curvatures were expected to be facing in opposing directions. Accordingly, the RV surface was divided into six regions: (1) RVIT, (2) RVOT, (3) septal free wall, (4) free wall body, (5) septal apex, and (6) free wall apex (Figure 2). Regional 3D curvature was derived by averaging the local curvature values of all control points within a particular region.

Statistical Analysis

Continuous variables are expressed as mean ± SD. Categorical variables are expressed as numerical values or percentages. *P* values < 0.05 were considered to indicate statistical significance. Subpopulations studied included men and women and age groups (<40, 40–55, and ≥55 years). To study differences between gender and age groups, a two-tailed unpaired Student's *t* test was used for continuous variables. Chi-square analysis was used for categorical variables. When comparing end-diastolic and end-systolic values, paired *t* tests were used.

To determine inter- and intraobserver reproducibility of curvature and volume, RV endocardial surface tracing and shape analysis were repeated in 15 randomly selected patients by two independent observers (K.A. and D.M.), both blinded to prior measurements. The interoperator variability for RV volume and shape indices was computed using percentage variability, defined as the mean of the absolute differences between pairs of repeated measurements divided by their mean.

RESULTS

A total of 348 normal subjects were available for enrollment. Of these, 103 were eliminated because of poor image quality or inadequate attention to RV acquisition. Two hundred forty-five healthy