Three-Dimensional Mitral Valve Morphology and Age-Related Trends Children and Young Adults with Structurally Normal Hearts Using Transthoracic Echocardiography

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Background: The mitral valve has a complex three-dimensional (3D) morphology that is incompletely described by two-dimensional echocardiography (echo). Three-dimensional echo provides a more robust tool to analyze the mitral valve. The shape of the mitral annulus and leaflets, and differences with age, have not been described by 3D echo in normal children. Our objective was to characterize and quantify the 3D mitral valve morphology in children with normal transthoracic echocardiograms over a broad spectrum of age and to identify differences in valve shape with age.

Methods: Three-dimensional midsystolic mitral valve models were constructed in 100 children and young adults with normal echocardiograms using 3D transthoracic images. Annular and leaflet metrics were quantified and regression equations were prepared. Interuser and intrauser variability was measured.

Results: Two hundred fifty patients, from neonate to young adult, were retrospectively reviewed to obtain 100 evaluable patients (40% evaluable). The annular height to commissural width ratio of the mitral valve ("saddle shape") was preserved across age (median 24.3, IQR 21.8–28.1). Three-dimensional mitral valve area, length, and volume parameters were linearly related to body surface area ($P < .001$). The ratio of anterior to posterior leaflet length and posterior leaflet angle increased with body surface area ($P = .0004$ and .002, respectively) suggesting posterior movement of the coaptation line. Two-dimensional lateral annular diameter underestimated 3D lateral annular metrics ($P < .001$, mean difference 20–22%) but was highly correlated ($R > 0.87$, $P < .001$). Interuser and intrauser variability were acceptable.

Conclusions: Assessment of 3D mitral valve morphology in children is possible in a modern clinical pediatric echocardiography laboratory using transthoracic images, although further optimization of imaging is needed. The saddle shape of the mitral annulus was preserved across age and size. Most mitral valve parameters increased linearly with patient size. Further investigation is warranted to explore changes in valve morphology in the pediatric population in health and with disease. (J Am Soc Echocardiogr 2017;■:■-■.)

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The mitral valve has a complex three-dimensional (3D) morphology that is poorly characterized by two-dimensional (2D) imaging and quantification (Figure 1).[1-3] The normal mitral annulus has a nonplanar saddle shape thought to be important for minimizing mechanical stress on the mitral valve apparatus during ventricular contraction.[1,4-6] The complex 3D geometry of the mitral annulus and leaflet surfaces has also been shown to be critical in valvular function.[7-10]

Linear measurements used to describe the mitral annular geometry using tomographic techniques depend on the correct alignment of imaging planes with anatomic landmarks.[11] Furthermore, it is not possible to properly characterize the nonplanar geometry of the mitral annulus and leaflets by analysis in a single plane. In contrast, 3D echocardiography gives the ability to analyze the geometry and dynamics of the mitral annulus without these assumptions; consequently, these techniques have become commonplace in the adult cardiac operating room[2,8] where resulting analyses are used to help guide intraoperative planning and decision making regarding mitral valve repair.[9,10,12,13] For example, the 3D shape of the valve and specifically the annular height to commissural width ratio (AHCWR) has been shown to be associated with degree of

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Abbreviations

2D = Two-dimensional

3D = Three-dimensional

AHCWR = Annular height to commissural width ratio

BMI = Body mass index

echo = Echocardiography

ICC = Intraclass correlation coefficient

IQR = Interquartile range

LV = Left ventricular

regurgitation and chordal rupture.[4,14] An understanding of the importance of this shape has led to the development of techniques to normalize the shape of the valve surgically, such as use of nonplanar annular rings, with the goal of minimizing stress and increasing the longevity of the repair.[1,15]

To our knowledge, the mitral valve annular shape and leaflet characteristics have not been described in three dimensions, in children with structurally normal hearts. We hypothesized that the 3D morphology of the mitral valve might vary with age, and specifically that the AHCWR of the mitral valve might differ across childhood. The goal of this study, then, was to characterize the 3D morphology of the mitral valve in a pediatric cohort with structurally normal hearts over a broad spectrum of ages and to identify changes in morphology.

METHODS

Subjects

An institutional database was used to retrospectively identify patients with structurally normal hearts and existing 3D left ventricular (LV) volume datasets (in January 2014 our laboratory began acquiring these images as part of routine clinical care). Functional or structural heart disease had been suspected in these children but had been judged to be absent by their treating cardiologists. Specific inclusion criteria were as follows: (1) referral for clinical echocardiogram, (2) no history of congenital or acquired heart disease, (3) no more than trivial valvular regurgitation, (4) no structural defects (patent foramen ovale and trivial branch pulmonary artery stenosis permitted in infants), (5) LV end-diastolic volume Z score > -2.5 and $< +2.5$; and (6) normal LV systolic function (ejection fraction $> 55\%$) on a complete 2D and Doppler echocardiogram. Exclusion criteria included significant stitch artifact, lack of inclusion of the entire mitral annulus in the acquisition, or inability to delineate the mitral valve sufficiently to reliably model the valve. Three-dimensional studies in 250 subjects were reviewed to obtain the 100 patients used in the study. The study was approved by the Committee on Clinical Investigation at Boston Children's Hospital.

Transthoracic Image Acquisition and 2D Echo Data

The 3D images were acquired using full volume or 3D zoom mode, using 4-beat breath-held electrocardiiogram-gated acquisitions when possible (breath holding was not feasible in infants and young children). Transthoracic X7 or X5 probes were used with the Philips IE33 and EPIQ ultrasound systems (Philips Medical, Andover, MA). The 2D volumes and ejection fraction were calculated using the 5/6 area length formula. The 2D mitral annular lateral dimension was recorded from the clinical reports, where available.

3D Mitral Valve Modeling and Analysis

Mitral valve 3D models were constructed using the Tomtec 4D MVA analysis package (version 2.3), running within Image Arena 4.6 software (TomTec Imaging Systems, Unterschleissheim, Germany). Briefly, the mitral valve analysis began with the identification of anatomic landmarks and selection of the early systolic frame (first frame with valve closed) and the end-systolic frames (last frame before the mitral valve starts to open). The single midsystolic frame midway between these two frames was chosen for static modeling and analysis of the valve. This phase allowed direct comparison with multiple adult studies.[4,16] Analysis of the leaflets was based on optical flow and pattern recognition.[17,18] Annular dimensions and characteristics, and leaflet dimensions and characteristics, were automatically generated with manual user correction when needed. Annular dimensions are presented in Figure 2 (height, anterior-posterior diameter, anterolateral-posteromedial diameter, commissural diameter, circumference, and annular nonplanar angle); also recorded were 2D area, 3D area, and sphericity. Mitral valve sphericity was defined as the mitral annular anterior-posterior diameter divided by the anterolateral-posteromedial diameter. The AHCWR was defined as the annular height divided by the commissural width at the annulus, expressed as a percentage. Leaflet characteristics included anterior leaflet area, posterior leaflet area, anterior leaflet length, posterior leaflet length, coaptation length, posterior leaflet bending angle, tenting height, tenting area, and tenting volume (Figure 3). Definitions of all quantities are shown in Table 1.

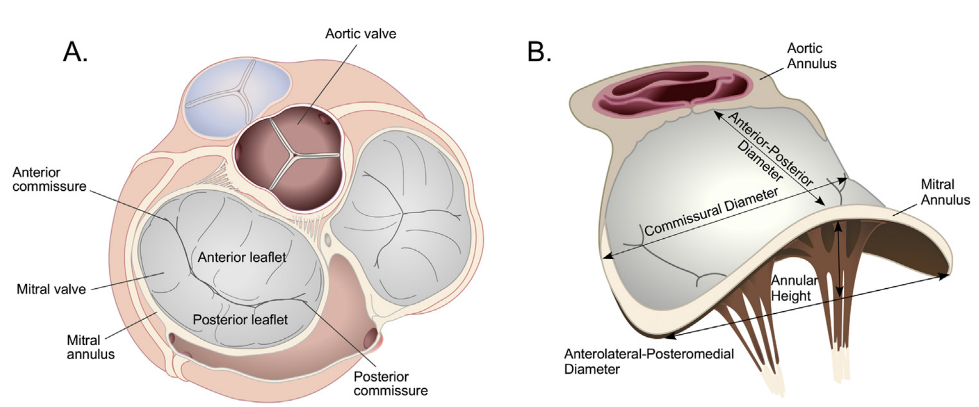

Figure 1 Three-dimensional anatomic relationships of mitral and aortic valves. **(A)** Mitral and aortic valves viewed from above. **(B)** Three-dimensional shape of the mitral valve, with relation to the aortic valve.