A Novel System for the Assessment of Mitral Annular Geometry and Analysis of 3D Motion of the Mitral Annulus from 3D Echocardiography

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Abstract

Real-time 3D echocardiography (RT3DE) allows noninvasive evaluation of mitral annular 3D geometry. In this study, we propose a novel computerized method for the assessment of mitral annular (MA) geometry and analysis of MA motion through the cardiac cycle. We applied this technique to examine differences between normal subjects and patients with ischemic mitral regurgitation (IMR). The algorithm was evaluated using five saddle-shaped MA phantoms and then applied to both normal subjects and patients with IMR. Strong agreement between the estimated and actual angle of the MA phantoms was observed (y=0.99x+1.5, r=0.87, p<0.001, mean difference 2.66±10.9). In the clinical study, non-planarity angle at end-systole (ES) was significantly greater in IMR vs normal subjects (135±9.2 vs. 129.3±3.1, p<0.03). In all cases, MA was less planar at ES than ED. In IMR, MA was dilated (943±83 vs. 769±34 mm^2, p<0.005) and motion of posterolateral MA was significantly reduced (7.3±1.3 vs 16.0±1.1 mm p<0.001). This approach can determine unique 3D descriptors of MA geometry that may provide information about pathophysiologic changes in patients with IMR.

1. Introduction

Real-time 3D dimensional echocardiography (RT3DE) is emerging as the ideal modality of imaging the heart. Its non-invasive, easy-to-use characteristics combined with a satisfactory time-resolution (< 40 ms) render RT3DE a very effective tool able to acquire in one view the complex geometry of cardiac structures such as the mitral annulus (MA).

Two-dimensional imaging modalities, such as conventional echocardiography, are unable to disclose information regarding the curved shape of the MA [1][2]. A fast rotating probe was utilized to overcome this limitation, and enable off-line reconstruction of the MA. Unfortunately, the reconstruction of the MA required imaging of several synchronized cardiac cycles. The process was not only troublesome, but also subject to severe approximations and errors. Today, real time 3D echocardiography allows non-invasive, same-beat evaluation of 3D MA geometry.

The mitral annulus has a complex geometry, which can be characterized by asymmetric elliptic shape with a saddle 3-dimensional structure [2][3]. Although the complex 3D geometry of mitral annulus (MA) is known to relate to valve function, it has not been fully investigated. In depth analysis of the 3D geometry of the mitral annulus and its dynamic motion throughout the cardiac cycle might be important for better understanding of mitral valve dysfunction and, consequently, improve mitral valve repair and/or design of prosthetic valves [4][5][6].

In this study, we propose a novel computerized method for the assessment of MA geometry and analysis of motion of mitral annulus through the cardiac cycle from real-time 3D echocardiography. We applied this technique to examine differences between normal subjects and patients with ischemic mitral regurgitation (IMR).

2. Methods

2.1. In-vitro study

Five phantoms mimicking saddle shaped mitral annuli were built. In order to simulate the physiological anatomical shape, the geometrical structure of the mimicked mitral annuli was not planar. The mimicked MA shape ranged from almost planar to saddle shape, and the non-planarity angle α of each phantom was known and ranged from 85 to 160 degrees.

Each phantom was imaged by RT3DE. In this study, we employed both the RT3DE system produced by Volumetrics (Durham, DC) and the Sonos 7500 more recently introduced by Philips (Andover, MA). Both systems used a matrix array transducer operating at 3.5 MHz. After acquisition, images were digitally transferred to a personal computer (P3 800 MHz, 256 MB ram) and analyzed using visualization and analysis software designed in our lab [3].

For each phantom, the operator identified eight points along the mimicked saddle shaped mitral annuli. An automated algorithm based on Fourier analysis reconstructed the shape of the entire curved mitral annuli and superimposed the 3D reconstruction on the original dataset. The operator was able to quickly create a 3D reconstruction of the simulated mitral annuli by locating the 3D mitral annular location. The accuracy of the tracing was evaluated by superimposing the reconstructed 3D annuli on the original 3D data. Once the tracing was completed, parameters including the curved length of the reconstructed mitral annuli, the projected area and the non-planarity angle, curvature, and regional velocity were numerically derived.

2.1.1. Projected mitral annular area

Since reconstructed mitral annuli are not planar curves, the mitral annular area is not defined. In fact, there is more than the one 3D surface whose border coincides with a given 3D mitral annular curve. The projected mitral annular area has been defined as the area of the closed planar curve that is the projection of the 3D saddle shaped mitral annulus on best fitting MA plane. Best fitting plane was obtained using the least square method.

2.1.2. Non-planarity angle α

The non-planarity angle α is defined as the angle between the vectors from septal and lateral points to the center of the inter-commissural line (Figure 1). Previous studies have shown that this parameter might be related to valve function.

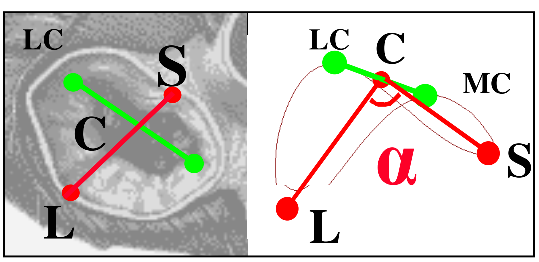

Figure 1: Measurement of the non-planarity angle α

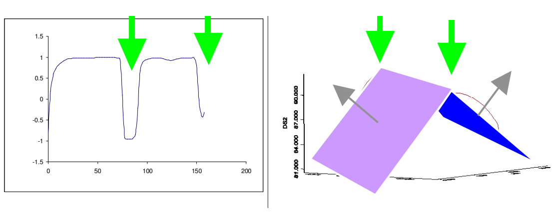

Figure 2: Automatic calculation of non-planarity angle α

Since manual assessment of this angle could be time consuming, we propose an alternative method in this study for the automatic assessment of the non-planarity angle α. The first step of the algorithm divides the saddle shaped mitral annulus into two open curves: the postero-lateral and the antero-medial portions of the mitral annulus. The algorithm is based on the assumption that the portions of the mitral annulus between the two commissural points of the mitral valve can be approximated to planar curves that lay, generally, on two different planes. The change of planarity occurs in proximity to the commissural points. We used this property to automatically detect the commissural points and assess the non-planarity angle α.

To observe the change in planarity, we traverse the reconstructed mitral annular points and locally calculate the plane defined by three consecutive mitral annular points. Observing brisk changes in this local plane (Figure 2), we detect the regions where the commissural points are located, and divide the mitral annular curve into the postero-lateral and anterior-medial portions.

The second step of the algorithm involves finding the best fitting plane for each portion of the mitral annulus. The non-planarity angle α of the mitral annulus is finally assessed as the angle between the two best fitting planes.

2.2. In-vivo study

In this study we included twelve normal subjects, and seven patients with IMR. Each patient was imaged by RT3DE and each phase of the cardiac cycle was visualized and analyzed using our customized software.

For each phase the operator selected eight mitral annular points. Similarly to the in-vitro study, the 3D mitral annuli were reconstructed and parameters including the angle between the vectors from septal and lateral points to the center of the inter-commissural line, projected area, curvature, and regional velocity were numerically derived for each cardiac phase.

2.2.1. Regional velocity

The regional velocity of each mitral annular point can be numerically derived, as the displacements of each mitral annular point are known for each time frame acquired by RT3DE. Velocities obtained are 3D vectorial quantities that change over time. Their representation would require the use of interactive software and the comparison between different cases would not be immediate. To simplify analysis of local mitral annular velocity, we extrapolated the vertical and radial components of velocities. Changes in these local scalar quantities over time can be represented in 2-dimensional graphs that are able to capture contraction, expansion and vertical translation of the mitral annulus.

2.3. Statistical Analysis

Linear regression and Bland-Altman analysis were used to evaluate correlation and agreement between measured and actual parameters. Variables are expressed as mean±SD.

3. Results

In the in-vitro study, a strong agreement between the estimated and actual angle of the MA phantoms studied in vitro was observed as shown in Figure 3 ($y=0.99x+1.5$, $r=0.87$, $p<0.001$, mean difference = 2.66±10.9).

In the clinical study, the non-planarity angle at end-systole (ES) was significantly greater than normal (135±9.2 vs. 129.3±3.1, $p<0.03$). In all cases, MA was less planar at ES than ED (Table1). In IMR patients, the MA was dilated (area = 943±83 vs. 769±34 mm^2, $p<0.005$) and motion of posterolateral MA was significantly reduced (Table 2, local displacement between ES and ED = 7.3±1.3 vs 16.0±1.1 mm $p<0.001$). In patients with IMR, regional MA velocity presented a more irregular pattern than controls (Figure 4).

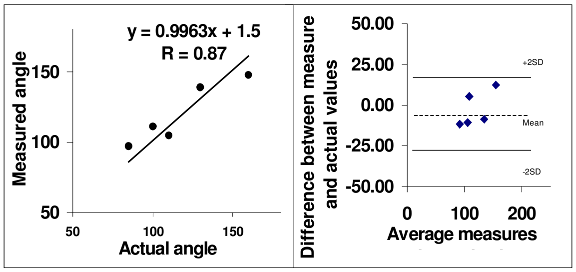

Figure 3: Results of *in vitro* study

	ES	ED	
IMR (n=7)	136 ± 10 °	144 ± 13°	p >0.05
Normals (n=12)	122 ± 3°	129 ± 3°	p < 0.001
	p < 0.03	p > 0.05	

Table 1: Automatic MA angle measurements

	Anterior anteromedial	Anteromedial-medial	Medial-posteromedial	Posteromedial-posterior	Posterior-posterolateral	Posterolateral-lateral	Lateral-anterolateral	Anterolateral-Anterior
IMR (n=7)	10 ± 2	12 ± 3	13 ± 3	6 ± 2	5 ± 1	7 ± 2	13 ± 2	12 ± 1
Normals (n=12)	13 ± 2	13 ± 2	13 ± 2	13 ± 2	13 ± 1	16 ± 1	17 ± 1	14 ± 1

Table 2: MA regional displacement (mm) between ED and ES

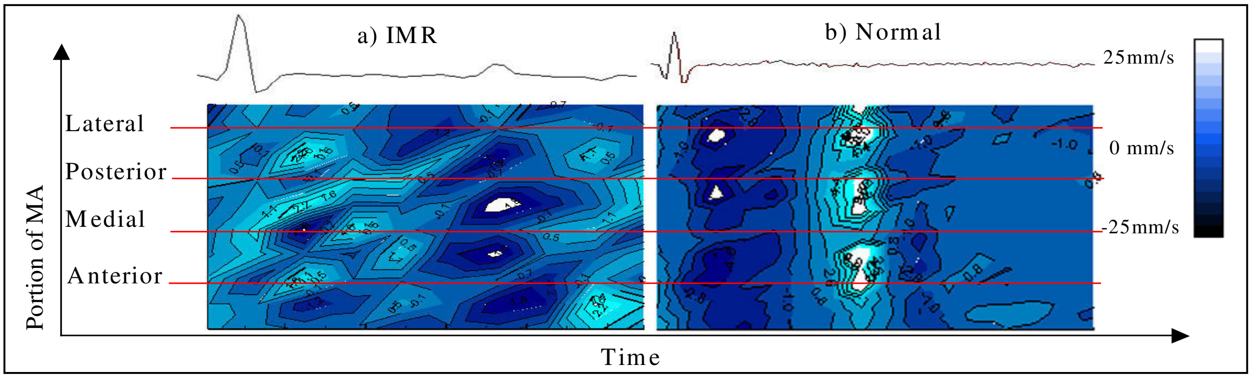

Figure 4: Regional MA velocity maps demonstrating more irregular motion in (a) IMR vs. (b) normals

4. Discussion and conclusions

Real-time three-dimensional echocardiography introduced the feasibility of non-invasive 3D geometric and motion analysis of the mitral annulus. Exhaustive characterization of physiologic and pathologic changes of MA geometry and dynamics has not been attained maybe because of the low diffusion of this imaging modality in the clinical environment and the lack of appropriate 3D analysis tools. Understanding MA 3D geometry and dynamics may aid the design of surgical procedure or prosthetic mitral valve and/or improve the outcome of problematic mitral valve repairs such as MA with ischemic MR. In fact, a durable solution to IMR is not yet available, since the surgical repair of IMR has an unsatisfactory low success rate [4][7]. RT3DE combined with appropriate analysis software may provide the missing link to attain the goal of characterization patho-physiologic changes of MA, and provide the needed knowledge to improve outcome in mitral valve repair.

In this study, we show that 3D motion of the MA can be accurately analyzed from RT3DE. In contrast to techniques previously used in other studies [2], RT3DE enabled us to avoid dangerous radio-opaque markers, or other implanted device, which, besides being risky, may indeed change the dynamics of the MA itself. We brought to focus techniques that can be used to accurately characterize 3D motion of the MA from RT3DE. This study also shows that reliable automatic algorithm can be developed in order to accelerate time consuming tasks in the 3D analysis of the MA and to acquire needed knowledge in shorter time.

We developed computer software to apply the described techniques in all the phases of the cardiac cycle in both controls and patients with IMR and we were able to quantify differences in 3D geometry and dynamics of the MA between the two groups.

The increased planarity we found at ES in the shape of the MA with IMR combined with an increased variability throughout the cardiac cycle might be one of the reasons why surgical repair of MA with IMR is still challenging.

Although we demonstrated a more irregular pattern of MA motion in IMR subjects, the size of the patient groups studied is a limitation of this study. Clearly, larger and more diverse patient populations should be examined.

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