

A Novel Biventricular Active Mesh Model for Measuring Cardiac Function and Geometry from Cine MRI

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INTRODUCTION

Measurements of cardiac geometry, such as volume and curvature in response to volume or pressure overload are important for clinical decision-making. Despite the promise of magnetic resonance imaging (MRI), approaches for quantifying cardiac geometry remain problematic. First of all, surface models for measuring left ventricular (LV) curvatures are usually based on various coordinate systems, such as cylindrical, spherical and prolate spheroidal [1], which have difficulties in modeling the apex due to the existence of a singularity at the apex. Secondly, these surface models usually require a symmetry that is not applicable in the complex right ventricle (RV). In addition, systolic translocation of the RV atrio-ventricular annulus is greater than that of the LV, resulting in unequal LV and RV stroke volumes (SV) calculated from summated short axis slices. Therefore, to obtain true physiologic geometric and volumetric measurements of the heart, we present a novel biventricular active mesh model that would solve the above mentioned problems and validate it in normal subjects, patients with mitral regurgitation (MR), and patients with pulmonary hypertension (PH).

METHODS

12 normal subjects, 12 MR patients and 12 PH patients were randomly selected. 6 of each group were randomly selected as training sets while the other 6 were used as test sets. MRI was performed on a 1.5-T MRI scanner (Signa, GE Healthcare, Milwaukee, Wisconsin) optimized for cardiac imaging. The electrocardiographically gated breath-hold steady-state free precession technique was used to obtain standard (2-, 3-, and 4-chamber long axis or 360° long axis and serial parallel short-axis) views using the following typical parameters: slice thickness of the imaging planes 8 mm, field of view 40cm, scan matrix 256 × 128, flip angle 45°, repetition/echo times 3.8/1.6 ms.

The biventricular active mesh model was constructed by first fitting a triangulated mesh to each training sample and then constructing a vertex distribution model of the triangulated meshes. A 3D isotropic binary segmentation was constructed utilizing both short and long axis contours that were semi-automatically drawn by experts. A pre-triangulated sphere was mapped to the segmentation using a modified mesh generation algorithm [2]. The surface was smoothed by penalizing the angles among the vertices normals during the mapping. To construct the vertex distribution model, the correspondence among the meshes from the training sets was first performed by aligning their 3D segmentations before triangulation using the Kabsch algorithm. Then a pre-triangulated sphere was used for all segmentations such that the correspondences of resulted triangulated meshes were predefined. The generated triangulated meshes were then aligned using the modified Procrustes procedure. Finally, the active mesh model was constructed as a vertex distribution model. This process was repeated for each myocardium at each time point (ED or ES) for LV and RV, respectively. New triangulated meshes of subjects in the test sets were constructed by deforming the active mesh model to the boundary of its 3D segmentation [3].

To validate the model, LVSV was compared to RVSV in all groups. LVES volume was compared to RVES volume in the PH group (known to have enlarged RVES volume) as well as in the MR group (known to have enlarged LVES volume). A B-spline surface model based on prolate spheroidal coordinate system [4] was used as a "gold standard" to compare the presented method in terms of their LV maximum curvatures using correlation analysis and Bland-Altman plots. Since a gold standard curvature measurement at apex is not available, apex maximum curvatures measured by the presented method was compared using Student's *t*-test in normals vs. in patients with MR (a group known to have reduced apex curvature due to eccentric remodeling).

RESULTS

Figure 1 shows the triangulated surface representations of LV and RV ED endocardium of a normal heart, a MR heart, and a PH heart using color scales of their surface curvedness. The MR heart had an obviously larger LV volume and smaller curvature (dimmer surface color) vs. normal, while the PH heart had an enlarged RV volume vs. normal. There was no significant difference between LVSV and RVSV in normal and PH ($P=0.8$), but LVSV was significantly greater than RVSV in the MR group ($P<0.0001$) due to regurgitant flow into the left atrium. The measured LVES volume was significantly smaller than RVES volume in the PH group ($P=0.01$) resulting from rightward shift of the interventricular septum due to RV pressure overload. LVES volume was smaller than RVES volume in the MR group ($P<0.0001$) due to facilitation of LV ejection into the left atrium in MR. The maximum curvatures of samples from the test sets calculated by the deformed triangulated surfaces and by prolate spheroidal B-spline methods were significantly correlated (correlation coefficient $r = 0.7$ at ED endocardium $P<0.01$). Bland-Altman plots (Figure 2) show that the proposed method had a good agreement with the gold standard at basal, mid and distal LV. As expected, MR hearts had significantly smaller maximum endocardial curvatures at apex compared with normal (0.068 ± 0.004 vs. 0.074 ± 0.002 1/mm, $P=0.01$).

DISCUSSIONS AND CONCLUSIONS

The presented biventricular active mesh model is able to fit smooth surfaces to both the LV and RV including the LV apex and RV base. The computation time for generating mesh for a new subject is less than one minute. Moreover, such new meshes can potentially correct the contour errors near both the LV and RV outflow tract which are usually difficult to determine manually, since the generated new meshes are restricted by the variation from their training sets. Future work includes further improvement of the active mesh models by increasing the training sample size for different pathologies.

REFERENCES

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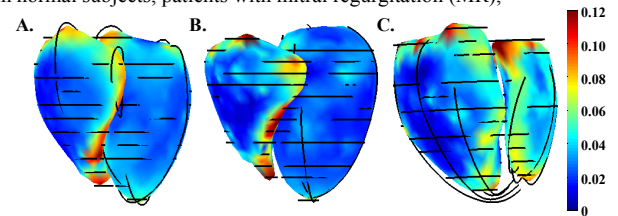


Figure 1. Triangulated surface representations of LV and RV ED endocardium with fitted contours (black lines) of a normal subject (A), a MR patient (B) and a PH patient (C) using color scales of their surface curvedness. The MR heart has a bigger LV chamber with less curvedness at the apex while the PH patient has an enlarged RV chamber.

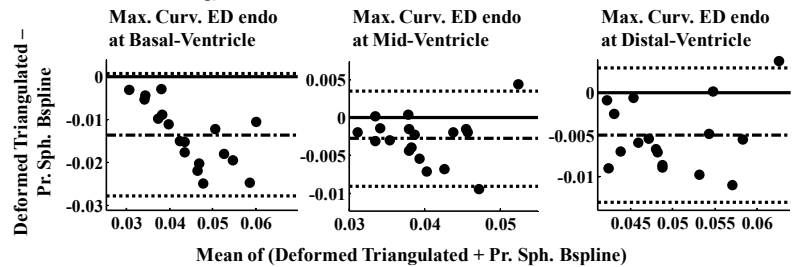


Figure 2. Bland-Altman plots with mean (—), mean \pm 2SD (-----), equal line (.....). (Note: Max. Curv.=Maximum curvature, endo=endocardium)