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Towards Realistic Cardiac MR Image Simulation; Inclusion of the Endocardial Trabeculae in the XCAT Heart Anatomy

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Synopsis

The importance of realistic cardiac MR simulation has been realized over the past decade. For this application, XCAT phantom provides realistic highly detailed whole body anatomical models including the heart and respiratory motion. Although the current XCAT heart model is complete in terms of substructures, the trabeculae structure of the endocardium, which is geometrically complex, is lacking. Based on a high-resolution ex-vivo cardiac image data, we modeled and incorporated the irregularity of the trabeculae into the existing XCAT model. We demonstrated that greater realism in cardiac MRI simulation can be achieved by including the trabeculae anatomy into the heart.

Introduction

Magnetic resonance (MR) image simulation plays a crucial role in optimization, benchmarking and validation of medical image analysis algorithms, particularly segmentation methods. Having realistic numerical anatomical models of human organs is one of the essential ingredients of generating realistic simulated MR images. Especially for cardiac application, a highly detailed anatomical model comprising both the heart itself, its substructures, and the surrounding organs with motion functionality needs to be employed. The eXtended CArdiac and Torso (XCAT) phantom¹ developed based on Visible Human Project image dataset² provides a realistic four-dimensional human anatomical model with ability to include cardiac and respiratory motion. The XCAT phantom comprises a high level of anatomical details for the various heart compartments. To improve the phantom realism, the papillary muscles of the left myocardium were included into the XCAT heart phantom. However, the anatomy of myocardial trabeculae for the inner layer of the right and left ventricle of the heart is still lacking in XCAT. The effect of including and excluding these anatomies on the left ventricular quantitative measurements has been assessed^{3, 4}.

From the simulation perspective, the importance of the trabeculae inclusion in the appearance of simulated images was previously highlighted by C. Tobon-Gomez et al.⁵. However, they simulated the presence of the trabeculae by allocating randomly a 3-pixels wide disc to the inner layer of the heart wall and assigning a calculated trabeculae density value rather than modeling the real anatomy. The purpose of this study is to modify the XCAT heart anatomy to increase the realism for simulating cardiac MR images by including realistic trabeculae. To resemble the real anatomy, the trabeculae were precisely modelled based on high spatial resolution cardiac MR image data and integrated into the XCAT. Thereafter, the MR extension to XCAT phantom (MRXCAT⁶) was utilized to synthesize realistic simulated cardiac MRI. To achieve even more realism, we further extended the MRXCAT to include more than 15 organs around the heart visible in the simulation field of view.

Methods

Modeling of trabeculae: To model the trabeculae of the myocardium, open access ex-vivo high-resolution 3D MRI data of a normal human heart⁷ were utilized. This whole heart image data was suitable to capture the irregularity of the trabeculae muscular geometry. The trabeculae for right and left ventricle of the heart were manually segmented slice-by-slice using ITK-SNAP software⁸. A polygon mesh model was exported to be incorporated into the inner surfaces of the XCAT heart chambers. The polygon model for heart's right ventricle (RV) and left ventricle (LV) was precisely aligned with the heart using Rhinoceros software⁹.

Creation of voxelized phantom: To perform MRI simulation, the creation of a voxelized phantom was performed with XCAT, which includes variable anatomical parameters to generate patient specific anatomical models. The parameters for the torso dimensions in lateral and anterior-posterior directions and the heart orientation within the ribcage were specified based on normal values provided⁵. The short axis (SA) and 4-chamber (4CH) views of the heart were obtained according to cardiovascular magnetic resonance pocket guide¹⁰ by using the rotating and re-slicing functionality of the ImageJ¹¹ processing software tool.

MR simulation: The signal equations based simulation approach of MRXCAT was exploited as the framework of CMR simulation. Cardiac cine MR images were simulated with balanced steady state free precession (b-SSFP) signal model for sequence parameters TR/TE=2.78/1.39, flip angle= 60, 0.5x0.5x4 mm³ voxel size, and 460x460x19 matrix size. To simulate more realistically, we increased the number of structures in MRXCAT by defining additional organ labels available from the voxelized XCAT. MR tissue properties such as T1, T2 and proton density for a normal subject were assigned from literature¹².

Results

Myocardial trabeculae: Figure 1 shows the manual segmentations of the LV (red) and RV (blue) chambers. A 3D model corresponding to segmented labels is demonstrated such that the tiny jagged-like muscular structure of the trabeculae anatomy is visible. Figure 2 schematically illustrates how the polygon surface mesh model is 3D-aligned with the heart model embedded into the whole XCAT phantom surfaces.

MR simulation: The modified version of the XCAT heart clearly improves the anatomical realism of the simulated images. MR simulated images of short axis view and 4-chamber view at end diastolic and end systolic phase of the heart cycle are displayed in Figure 3. To visualize sharply the myocardial trabeculae anatomy, simulation was performed with high spatial resolution.

Discussion

This paper has proposed a step towards more realistic cardiac MRI simulation by modifying the detailed anatomy of the XCAT heart phantom. Particular attention has been paid to model accurately the anatomy of the myocardial trabeculae. To the best of our knowledge, this is the first time that the spatial distribution of the trabeculae has been modeled accurately.

Conclusion

We demonstrated that greater realism in cardiac MRI simulation can be achieved by including the trabeculae anatomy into the myocardial wall. In pursuit of generating a database of realistic simulated MR image for medical image analysis research, in our future research we will concentrate on further improving

the realism of the MR simulation (including realistic noise, partial volume, tissue texture, etc.).

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Figures

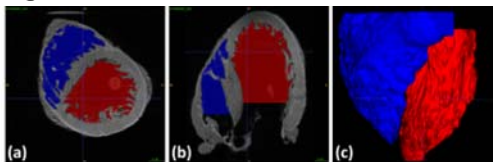


Figure 1 Create an anatomy-based model for trabeculation of LV and RV myocardium. We performed manual slice-by-slice segmentation of the myocardial trabeculae for the LV (red) and for the RV (blue) in the ITK-SNAP software (a,b) and exported the labels as 3D surface meshes (c).

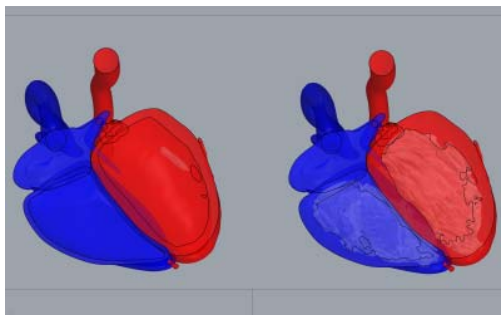


Figure 2 Alignment of the trabeculae model of the LV (red) and the RV (blue) within the inner layer of the original XCAT heart using Rhinoceros surface modelling software. The procedure involves 3D nonlinear transformation and rotation of the trabeculae model to have it incorporated into the LV and RV surfaces.

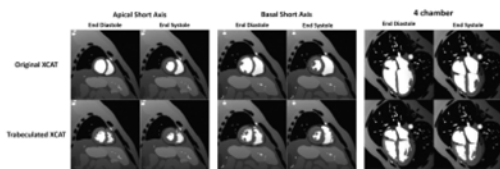


Figure 3 Simulation of MR images. The short axis view at apical and basal slices and 4-chamber view of the original XCAT heart (top row) and the same views for trabeculated XCAT (bottom row) were simulated at end diastolic and end systolic of heart.