PHYSIOLOGICALLY IMPROVED NCAT PHANTOM (PINCAT) ENABLES IN-SILICO STUDY OF THE EFFECTS OF BEAT-TO-BEAT VARIABILITY ON CARDIAC MR

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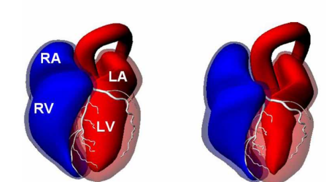
INTRODUCTION

With the ongoing improvement of the temporal and spatial resolution of advanced cardiac MR imaging techniques, it has become important to understand and quantify the complex motion effects limiting further improvement of the accuracy and diagnostic value of the images produced. Cardiovascular variables such as heart rate (HR), arterial blood pressure, stroke volume and the shape of electrocardiographic complexes all vary beat-by-beat [1]. These further interact with respiration. This variability reflects the dynamic response of the cardiovascular (CV) regulatory systems to perturbations in the CV function. Because of the difficulty to control and isolate these physiological variability effects, and their complex interaction with the specific pulse sequence and imaging protocol, it is difficult to study their effects on image accuracy and quality in-vivo. Instead, we propose the use of a versatile and physiologically realistic phantom. NCAT [2] is a numerical spatial and temporal (4D) cardiac-torso phantom extensively used for CT/PET studies. We propose an adaptation of the NCAT phantom to MR applications. We also incorporate a CV system simulator to account for the natural beat-to-beat variability in cardiac motion and HR. The proposed phantom is useful for evaluating cardiac MR imaging schemes including novel data acquisition and reconstruction methods. We demonstrate this by studying the effect of beat-to-beat HR and volume variability on coronary vessel-wall MR angiography.

THEORY

The 4D Nonuniform rational B-spline based Cardiac-Torso (NCAT) phantom [2] was developed to provide an accurate and flexible model of human anatomy and physiology. It includes a realistic model for the cardiac and respiratory motions based on tagged MRI data and respiratory-gated CT data respectively. The NCAT phantom models the main coronary arteries based on 3D angiogram data and also cardiac twisting and lateral motions. The NCAT phantom allows specifications of anatomic and physiological parameters such as HR, respiratory rate, LV volume etc. The adjoining figure shows a top view of the heart chambers and coronary artery branches at end-diastole and end-systole (courtesy W. P. Segars, PhD). Combined with models of the imaging process, the NCAT phantom is used to generate simulated imaging data and reconstructions. The tissue contrast parameters in the NCAT phantom were modified in this study for MR imaging applications. Note that this contrast depends on the MR pulse sequence and the sequence parameters. With this modification, the NCAT phantom can be used to simulate cardiac MR imaging applications. However, the NCAT phantom assumes periodic cardiac and respiratory motion which is not physiologically realistic especially for cardiac-compromised subjects. Therefore, we combined the MR NCAT phantom with a the Research CV Simulator (RCVSIM) [3] that models the beat-to-beat variation in morphology and timing of the human CV system. The model is based on an extensive list of heart and circulatory parameters that characterize the intact circulation. The proposed Physiologically Improved NCAT (PINCAT) phantom post-processes the NCAT-generated image sequence such that it matches the beat-to-beat changes predicted by the CV simulator. The processing ensures that we match (1) the cardiac aperiodicity modeled due to the various physiological effects including hemodynamic response to respiration and baroreflex control; (2) beat-to-beat variation in cardiac motion reflected, for instance, in changes in the end-diastolic volume from beat-to-beat. This is achieved by appropriate processing of the image sequence generated by the NCAT phantom and time-warping the resulting sequence.



End-diastole **End-systole**

METHOD

We studied the application of the PINCAT phantom in an MR vessel-wall imaging experiment, which is of great current interest [4], using a gated imaging scheme. An advantage of the incorporated CV simulator was that it provided the needed cardiac gating (QRS complex) information. The simulation corresponded to imaging of 6 transverse 3mm-thick slices with resolution of 384x384 and FOV of 38.4cm. The simulated phantom modeled the presence of plaque (thickness=1mm, width=2mm and length=5mm) located half way between the base and apex of the left circumflex (LCX) coronary artery. A transverse maximum intensity projection (MIP) image generated by NCAT (Fig. 1) shows the location of the plaque. To separate the effects of cardiac and respiratory motion, we simulated data corresponding to a breathhold of 4 minutes. Note that this is infeasible for a human subject and therefore these effects cannot be clearly isolated in an in-vivo experiment. This capability of the phantom is very useful in the evaluation of novel imaging schemes. MR data corresponding to a prospectively-gated 3D segmented k-space imaging scheme was generated and 6 slice images were reconstructed.

RESULTS AND CONCLUSION

Figure 2 shows a 1-D cut (marked by dashed line in Fig. 1) through the MIP reformatted reconstructions for two different physiological scenarios (a) assuming perfectly periodic cardiac motion (b) incorporating beat-to-beat variation in HR (65-80bpm) and end-diastolic and end-systolic ventricular volume. The figure shows that the variability causes an error in the plaque intensity estimate and hence the atherosclerosis may be underestimated. One can use these results to optimize the imaging parameters and comparatively evaluate novel imaging ideas such as adaptive triggering or navigator-based methods [4-6]. The PINCAT phantom allows variation of anatomical and physiological parameters to simulate different disease states to test the robustness of an imaging scheme. Another advantage of computer-generated phantoms is that the exact anatomy and physiological functions of the phantom are known, thus providing a gold standard from which to evaluate and improve the imaging techniques. In conclusion, we have described a physiologically-improved, realistic and flexible 4D cardiac-torso phantom, which is a promising tool to fully characterize and quantify the effect of beat-to-beat motion variability in MR imaging and angiography.

Fig. 1

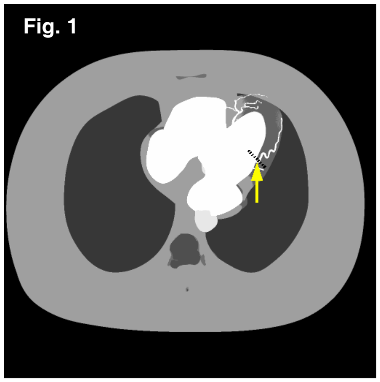
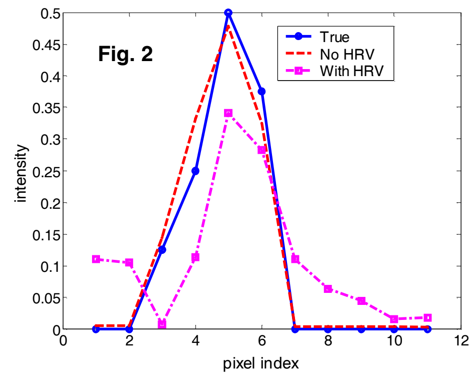


Fig. 2



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