3D Reproducing Kernel Hilbert Spaces for reconstruction of Heart rate modulated cardio-respiratory magnetic resonance imaging

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INTRODUCTION: Usually MRI uses ECG information to acquire an image over multiple cardiac cycles by collecting segments of k-space at the same delay in the cycle, assuming that cardiac position over several ECG cycles is reproducible. Unfortunately, in clinical situations many subjects are unable to hold their breath. High resolution MRI acquisition in free-breathing is of real clinical relevance, as hemodynamic parameters may differ between breath-holding and free-breathing. It has been shown that heart motion during respiration has a different pattern during inspiration and expiration.

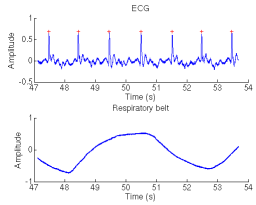

Fig. 1 : Zoom on physiological signal

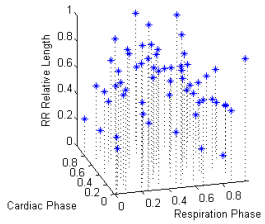

Fig. 2 : Location of the acquisition of one k-space point in the normalized 3D space (cardiac phase, respiratory phase and instantaneous heart rate).

These physiological aspects emphasize the need for the development of an MRI for cardiovascular function across the breathing cycle. A segmented imaging technique that can resolve motion across both the cardiac and respiratory cycle, have been proposed and recently extended using cardiac- and respiratory-resolved imaging [1]. These different approaches, for both artifact reduction in high resolution acquisition and physiological interaction of cardiac and respiratory cycles, require a more general method. The aim of our work is to provide a method for cardiac imaging reconstruction at each cardio-respiratory phase and for every instantaneous heart rate. We propose a generalized method, based on the results obtained by Zwaan [2]. In his method, heart motion during breath-hold was studied with the assumption that each heartbeat is a rescaled copy of a standard heartbeat. Here, the same assumption is extended to respiratory motion and heart rate modification. Similarly to the algorithm presented by Zwaan [2], our method [3] is based on the properties of the Reproducing Kernel Hilbert Spaces (RKHS), which provide a general and rigorous framework for handling interpolation problems, and have been widely used in signal and image processing. This framework is of particular relevance here, as retrospective gating can be reformulated as a scattered data interpolation in a 3D space.

METHODS: MR examination was performed on a 1.5 T SIGNA Excite HD MR system (General Electric, Milwaukee,WI). Physiological signals, collected using a modified version of the Maglife (Schiller Medical, Wissembourg, France) patient monitoring system, were converted into optical signals, transmitted outside the MR bore, and then recorded on the signal analyzer and event controller (SAEC) computer. Pneumatic belt was used to monitor respiration, and ECG sensors provided information about the cardiac phase (Fig. 1). Healthy volunteer underwent fast MR imaging sequences (60 full k-spaces, 2D FIESTA, TE=1.8 ms, TR=4.08 ms, k-space dimension 256^2, FOV 36cm, 10 mm slice thickness, Flip angle 45° and 8 element cardiac coils, phase order linear modulo 8, full acquisition length 64s). The imaging plane was chosen in cardiac transmittal short axis. Data were acquired with feedback in free-breathing. The subject was instructed to maintain the respiratory curve between two predetermined limits. We normalized the acquisition times to obtain a cardiac phase in the interval *[0, 1]* with a diastole/systole method. For the respiratory phase, linear rescaling has been used, with end inspiration corresponding to 0. For instantaneous heart rate we normalized the interval between the minimal (808ms) and maximal (1100ms) RR length during the acquisition (Fig.2). The reconstruction method presented in [3] was extended using 3D RKHS basis : splines or Sobolev. Contrary to standard method, which requires, for every case of the cardio-respiratory phases, a complete k-space acquisition, our method is such that for each position in the Fourier space, we have a fixed number of snapshots at different cardo-respiratory phases and instantaneous heart rate. For reconstruction, we use data from all acquisition times to obtain an image at the desired cardio-respiratory phase and instantaneous heart rate.

RESULTS: Cardiac images, with a fixed cardio-respiratory phase, were reconstructed from the data acquired in free-breathing in the subject. It is possible to obtain images from different cardiac phases in any respiratory phase, such as end expiration (phase = 0.8). On the other hand, it is also possible to select a precise cardiac phase (like end-diastole, phase = 0.9) and to reconstruct cardiac images at different respiratory phases. Since heart rate is physiologically correlated with the respiratory phase and diastole length the 3D space (Fig.2) is not homogeneously populated, therefore even if technically any point in this 3D cube could be reconstructed, care to the choice of meaning full physiological combination of cardio-respiratory phase and heart rate should be taken. With this precaution, it is possible to chose a fixed RR value and to reconstruct cardiac images at different cardio-respiratory trajectory to study the respiratory modulation of heart rate and diastolic filling. Two images from end-diastole cardiac phase in end expiration, for two different heart rates are presented (Fig.3).

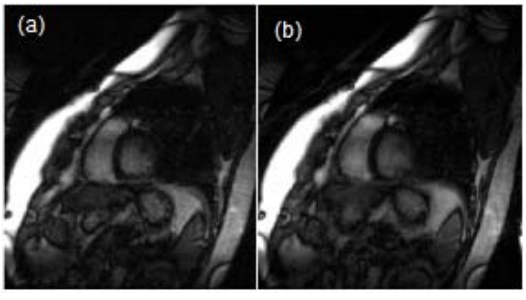

Fig. 3 : Reconstructed images using RHKS interpolation at cardiac phase 0.9, respiratory phase 0.8. (a) for a RR relative lenght equal to 0, and (b) for a RR relative lenght equal to 0.5.

DISCUSSION: In this paper a method for cardiac-respiratory MRI acquisition and reconstruction in free-breathing was presented. This method is based on the use of retrospective gating and the fact that the image has been searched in a RKHS. Our work shows that it is possible, with a comparatively short acquisition time in free-breathing, to obtain heart images from a subject at different cardiac or respiratory phases. This may be particularly important in clinical situations where apnea is impossible. Another interesting aspect of the method is that it is possible to study the cardiac and respiratory interactions which is clinically relevant. These preliminary data should be confirmed by a clinical study.

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