Self-Navigated 3D Whole Heart Coronary MRI with VARPRO Fat-Water Separation

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TARGET AUDIENCE: Scientists and clinicians interested in coronary MRA, fat-water imaging, and respiratory self-navigation.

PURPOSE: The introduction of respiratory self-navigation (SN) [1] enables the acquisition of whole heart coronary MR angiography (MRA) datasets during free-breathing without the need of a respiratory navigator [2] and with 100% scan efficiency. The SN technique, in combination with a 3D radial trajectory [1,3] has successfully been tested for the acquisition of non-contrast and post-contrast whole-heart coronary MRA datasets in both volunteers [3] and patients [4]. The standard CHEmical Shift Selective (CHESS) pulses [5], commonly used for suppressing the fat signal which surrounds the coronary arteries, rely on a specific timing for the acquisition of the center of k-space that coincides with the longitudinal fat magnetization crossing the nulling point. However, in 3D radial imaging, each readout equally contributes to the signal of k-space center, and, therefore, such an acquisition technique intrinsically exhibits a compromised fat suppression performance due to fat magnetization recovery during the acquisition window. Alternative approaches for Dixon-like [6] fat-water signal separation, that can be used with flexible echo times (TE) (e.g. when acquisition is performed with a bSSFP imaging sequence, and TEs must be minimized) have recently been described in the literature. In particular, the VARiable PROjection method (VARPRO) [7] shows high robustness in 2D and 3D cardiac applications with large background field variation and low SNR. In the present work, a multiecho version or the 3D radial SN sequence described in [3] was implemented. The VARPRO method was then applied to the acquired multiecho 3D volumes. In this study, the SN-VARPRO approach was compared to the standard CHESS fat saturation technique.

METHODS: The prototype 3D radial multi-echo acquisition was combined with the VARPRO method for 3D fat-water separation, while the SN algorithm [4] extracted the superior-inferior readouts of the first echo and used them for respiratory motion correction. SN-VARPRO was tested first on two home-built 2- and 3-compartments agar-$NiCl_2$ phantoms [8] that approximate the relaxation times of blood (inner compartment), fat (middle compartment – with paraffinum liquidum – only right-hand phantom) and healthy myocardium (outer compartment). The 3D radial SN-VARPRO technique was then applied in n=5 healthy adult volunteers for free-breathing whole-heart coronary imaging and the results were compared to those obtained with the standard CHESS saturation pulse applied to a single-echo 3D radial SN acquisition (SN-CHESS). All measurements were performed on a 1.5T clinical MRI scanner (MAGNETOM Aera, Siemens AG, Erlangen, Germany). In vivo data acquisition was performed ECG triggered and segmented during the most quiescent diastolic phase. A T_2-preparation pulse (TE T_2Prep = 40ms) was added prior to each acquired k-space segment to both ECG-triggered bSSFP imaging sequences. Acquisition parameters were: TR=10.6 and TEs=1.52/4.06/6.60/9.14ms for the multi-echo version (4 echoes with monopolar gradients) and TR/TE 3.1/1.56ms for the single-echo, FOV $(220mm)^3$, matrix 192^3, voxel size $(1.15mm)^3$, radio frequency (RF) excitation angle 115°, and receiver bandwidth maximized to 1150 Hz/Px for all echoes of the multi-echo acquisition and set to 898 Hz/px for the single-echo. A total of ca. 12000 radial readouts were acquired for each dataset. While ~30 radial readouts per heartbeat were acquired in the single-echo version, only 10-14 fit in the quiescent diastolic phase in the multi-echo acquisitions. Fat-water images were reconstructed from the multi-echo datasets using a 3D version of the VARPRO algorithm in Matlab (The MathWorks, Natick, MA, USA). The water/fat SN-VARPRO and SN-CHESS phantom results were qualitatively compared and profiles of fat-water signal were plotted and visually analyzed. In vivo SN-VARPRO and SN-CHESS whole-heart coronary datasets were qualitatively compared in terms of fat suppression around the coronary arteries. Quantitative values of visible vessel length and sharpness [9] of the proximal right coronary artery (RCA) and left anterior descending artery (LAD) were compared. Acquisition times were also recorded and compared.

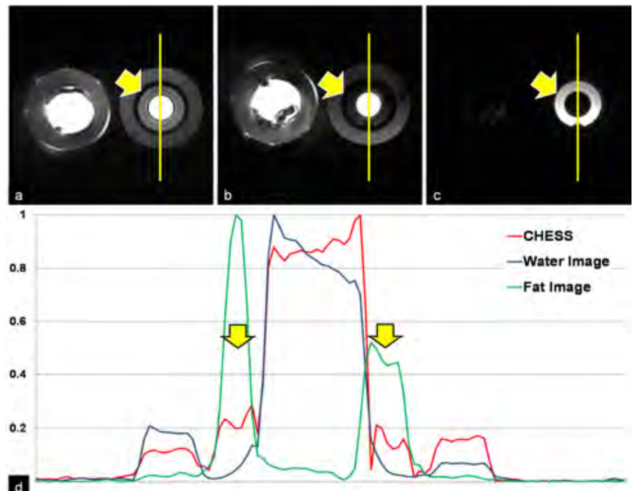

Fig. 1: Results of the phantom experiments. A transversal view of the CHESS fat suppressed volume (a) can be visually compared to the corresponding VARPRO water (b) and fat (c) images. The yellow lines indicate the location of the normalized image profiles plotted in (d). It is clear how the fat signal from the intermediate compartment (arrows) is not completely suppressed by the CHESS pulse, but almost completely disappears in the VARPRO water image.

RESULTS: The phantom results are displayed in Fig.1. While some residual fat signal can still be seen in the SN-CHESS dataset (a,d - arrows), the same region in the SN-VARPRO water image (b,d - arrows) displays a much reduced fat component. The fat signal is almost exclusively shifted to the SN-VARPRO fat dataset (c,d - arrows). The inhomogeneities in the left phantom (myocardium and blood only) are due to air-water interfaces to which the multi-echo bSSFP acquisition is more sensitive. The increased effectiveness of the SN-VARPRO fat suppression in vivo could be qualitatively assessed in all volunteer datasets (example in Fig.2). For the single-echo SN-CHESS measurement, percentage vessel sharpness and visible lengths of LAD and RCA were, respectively, 40.8±8.3% / 104±22mm and 44.8±8.4% / 116±8.8mm. For the SN-VARPRO water image the corresponding values were 48.3±3.1% / 96±25mm for the LAD, and 44.9±7.8% / 107±14mm for the RCA. Although a trend of increased vessel sharpness of the LAD can be noticed in the SN-VARPRO datasets, none of the values were statistically significant ($p>0.05$). The acquisition time of the single-echo SN-CHESS datasets was 7 minutes on average, while the multiecho approach required an average of 15 minutes ($p<0.05$).

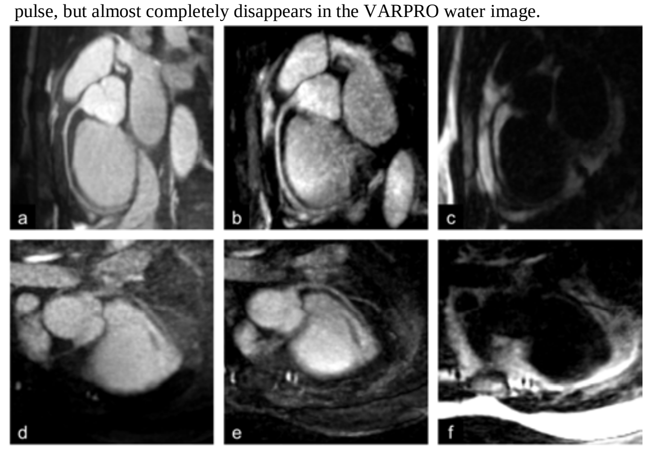

Fig. 2: Example of multiplanar reformats for one RCA (a,b,c) and an LAD (d,e,f). The results obtained with the CHESS pulse (a,d) can be directly compared to those obtained with the VARPRO method in both water (b,e) and fat (c,f) images.

DISCUSSION AND CONCLUSIONS: The multiecho version of the SN 3D radial acquisition sequence allows high spatial resolution whole-heart coronary MRA where fat/water separation can be achieved using the VARPRO algorithm. A similar vessel length and trend for superior vessel sharpness was obtained with the proposed SN-VARPRO methodology in comparison to the standard CHESS pulse. Moreover, it can be noticed that most of the artifacts derived from the radial undersampling are shifted to the SN-VARPRO fat image (Fig.2, c,f), while unsuppressed fat signal from spatially varying off-resonance frequencies due to shim imperfections (e.g: in the chest wall) are taken into account by the VARPRO reconstruction. However, the longer TRs needed for the acquisition of the 4 bSSFP monopolar echoes force to decrease the number of k-space readouts that can be acquired during a single heartbeat, resulting in a substantial increase of the total acquisition time. The use of iterative reconstruction algorithms such as compressed sensing that could take advantage of both the incoherent sampling pattern of the trajectory as well as of the echo dimension might be one possible solution to this problem.

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