Sub-minute 3D black-blood imaging of the whole heart with isotropic spatial resolution

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Introduction

Evaluation of cardiac morphology is an important part of routine diagnostic applications of cardiac MRI in various pathological conditions, such as congenital abnormalities, myocardial infarction, cardiomyopathies, and tumors. A previous technical approach for morphological cardiac MRI is based on a 2D black-blood fast spin-echo sequence with double inversion-recovery (DIR) blood suppression [1]. The major drawbacks of 2D DIR imaging are the prohibitively long scan time and inability of multiplanar image presentation. Rapid STEAM technique was recently revisited as a black-blood imaging technique for human heart [2], but the sequence has been known to cause myocardial signal loss in certain conditions [3]. A new blood suppression iMSDE (improved motion-sensitized driven equilibrium) method based on the flow dephasing effect has been recently proposed for vascular applications [4]. In this study we aim to develop a novel reliable and time-efficient cardiac black-blood imaging method based on the iMSDE principle.

Methods

Human subjects: Six healthy volunteers (4 males 2 females, age range 30-59) without clinically diagnosed cardiac disease were recruited in this study. This study has been approved by the local Institutional Review Board. Sequence parameters were optimized on one subject. The settings determined as a result of optimization were used for other subjects to test the sequence performance.

Sequence design and optimization: As a blood-suppression technique for the proposed sequence, we have chosen an improved MSDE (iMSDE) design [4] (Fig. 1), which, when compared to regular MSDE, allows for efficient compensation of B1 and B0 field inhomogeneities [4]. Of note, the benefits of iMSDE design are critical for cardiac imaging at 3T, where large B1 and B0 non-uniformities typically occur [5]. The iMSDE preparation was combined with the TFE (turbo-field-echo) readout sequence due to its proper balance between fast acquisition and robust image quality. The first gradient moment of the iMSDE sequence was optimized to balance the blood suppression capability and overall image quality. A series of images with 1.5 ms dephasing gradient duration were acquired at the same location of one volunteer while varying the gradient strength, and correspondingly, the first gradient moment. The contrast-to-noise ratio (CNR) between the left ventricle chamber wall and ventricle lumen, as well as lumen/muscle SNR were used as the optimization criteria.

Imaging parameters: All MRI scans were conducted on a clinical 3T scanner (Philips Achieva R2.5.3, Best, the Netherland) with a standard manufacturer's six-channel phased array cardiac coil. The iMSDE prepulse was applied with the optimized parameters obtained in the optimization experiment. The parameters for the 3D TFE sequence were: TR: 1 R-R, TFE TR/TE 3.4/1.0ms, FA 15°, FOV 340×240×80 mm, voxel size 2×2×2 mm, TFE factor 37, cardiac triggering with trigger delay 550-750ms, respiratory navigator, parallel imaging factor 3. The total imaging time was 56 seconds without navigator efficiency (calculated for the heart rate of 60 beats/min).

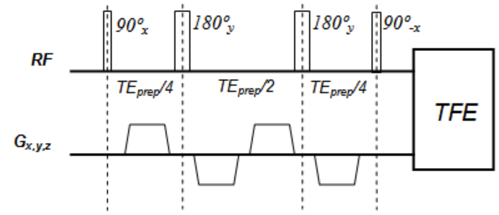

Fig. 1 iMSDE-TFE sequence used for fast whole heart black-blood imaging. The gradient parameters were optimized in the *sequence optimization* section and the optimized values used in the following study.

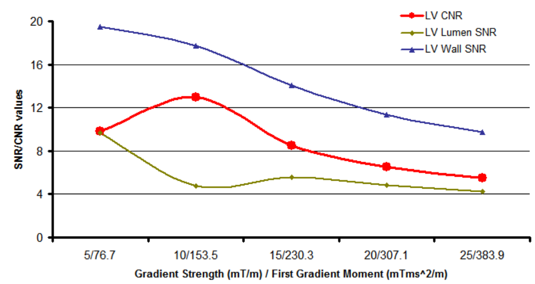

Fig. 2 iMSDE sequence parameter optimization for fast human heart imaging. The CNR of LV chamber (red line) maximizes when the first gradient moment is 153.5 mTms^2/m.

Results

Sequence Optimization: Lumen SNR demonstrated monotonic decrease with an increase of the dephasing gradient strengths (Fig 2). At the same time, the CNR between blood and cardiac muscle was maximized when the first gradient moment was 153.5 mTms^2/m as seen in Fig 2. With a further increase of the gradient strength, the loss of the cardiac muscle signal becomes apparent, while no improvement in blood suppression is achieved. Correspondingly, the optimal value of the first gradient moment based on CNR consideration (153.5 mTms^2/m) was used in the following experiments.

In vivo imaging: In all subjects, the images presented diagnostic quality and excellent blood suppression with the mean CNR between blood and cardiac muscle of 18.1±5.9. Actual acquisition time varied as the actual respiratory navigator efficiency ranges from 35-55%. Fig. 3 shows a typical image set reformatted to the short axis view. Due to 3D isotropic acquisition, each image set can be presented in an arbitrary chosen plane thus enabling comprehensive diagnostic evaluation. Fig. 4 represents three basic cardiac imaging projections (short axis, 4-chamber, and 2-chamber views) obtained from a single image set of another volunteer.

Discussion and Conclusions

This study demonstrates the feasibility of a principally new approach in cardiac MRI based on the iMSDE flow suppression technique. The major advantage of of this method is directionally-independent blood suppression, which is not subjected to the outflow requirement in contrast to the standard DIR method. The iMSDE-TFE sequence enables large-volume reliable black-blood imaging in the presence of complex flow patterns and provides very high imaging speed and robustness. Using this method, high-resolution human whole heart 3D image set can be acquired within 2-3 minutes with diagnostic image quality.

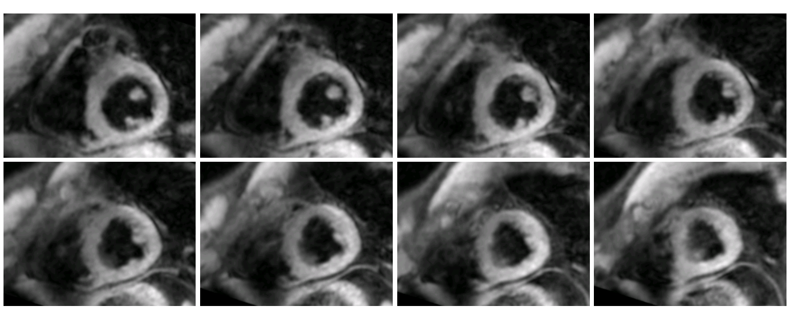

Fig. 3 Reconstructed whole heart image set for short-axis view acquired with iMSDE-TFE sequence within 1 minute. The voxel size is 2×2×2 mm.

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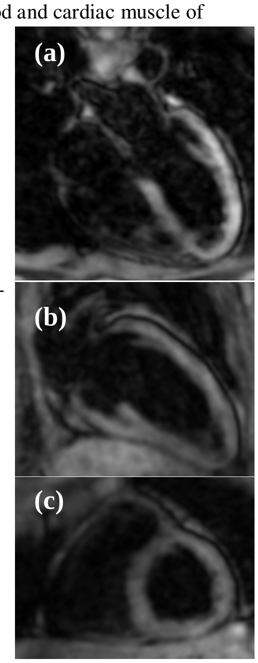

Fig. 3 different views of heart anatomy reconstructed from the 3D whole heart imaging dataset: (a) 4 chamber, (b) 2 chamber and (c) short-axis. Reconstruction resolution: 2×2×4 mm.