Feasibility of Cardiac Fast Spin Echo Imaging at 7.0 T Using a Two-Dimensional 16 Channel Array of Bowtie Transceivers

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Target audience: This work is of interest for clinicians, clinical scientists, basic researchers and engineers interested in transferring cardiac MR (CMR) techniques established in clinical practice at lower fields to ultrahigh fields (UHF).

Purpose: As ultrahigh field (UHF, $B_0 \geq 7.0$ T) cardiac MR (CMR) applications become increasingly used for research, they should help to advance the capabilities of MRI for the assessment of cardiovascular diseases. The signal-to-noise ratio (SNR) gain inherent to UHF CMR holds the promise to enhance spatial and temporal resolution. Such improvements would foster the assessment of cardiac morphology and tissue characterization using fast spin echo (FSE; RARE [1]) imaging. Unfortunately, the image quality achievable at UHF is not always exclusively defined by SNR considerations. As a deep-lying organ surrounded by inhomogeneous tissue structures within the comparatively large volume of the thorax, the heart is particularly susceptible to wavelength-related radio frequency (RF) field focusing and transmission field non-uniformities that accompany UHF MR. Additional RF power deposition constraints render UHF-CMR challenging. In particular, FSE imaging at 7.0 T presents a special challenge due to the train of high peak RF power refocusing pulses ($\alpha \leq 180°$). Notwithstanding its utility for improving B_1^+ uniformity in UHF-FSE imaging, recent studies on using adiabatic pulses [2] for UHF-FSE reported long inter echo times of up to 15 ms; an approach which does not meet the requirements of cardiac MR where the viable window of data acquisition is dictated by physiological motion constraints. Realizing the constraints of FSE together with the opportunities of UHF-MR, this work examines the feasibility of cardiac FSE imaging at 7.0 T. To meet this goal a sixteen channel transceiver array tailored for cardiac imaging that uses bowtie antennas is employed [3,4]. Radiative elements hold the promise of an increase in B_1^+ efficiency and uniformity at deep lying organs like the heart [5].

Methods: Volunteer experiments were performed on a 7.0 T whole body MR system (Magnetom, Siemens Healthcare, Erlangen, Germany). An array consisting of 16 dipole elements, distributed in two rings of eight elements around the upper torso (eight elements posterior, eight elements anterior) was used for signal transmission and reception (Fig.1a). All 16 elements are supplied with equal-intensity signals, while phase adjustments are achieved by inserting phase-shifting coaxial cables into the setup. 2D CINE FLASH imaging with a resolution of (1.4x1.4x4) mm^3 was performed to obtain standard cardiac views (TR = 5.7 ms, TE = 2.7 ms, receiver bandwidth = 454 Hz/Pixel, GRAPPA R=2). For cardiac gated fast spin echo imaging the following parameters were used: TR = 1 R-R interval, TE = 56 ms, echo spacing = 8 ms, echo train length = 12, receiver bandwidth = 781 Hz/Pixel, acquisition matrix = 256x204, spatial resolution = (1.25x1.25x5) mm^3, nominal flip angle = 180°. Gaussian pulses with a duration of 3072 µs and 3000 µs were used for excitation and refocusing. Fast spin echo images were acquired during end-diastole in a single breathhold (duration ≈ 16 s). Three protocols were used: standard FSE, double-inversion recovery FSE (DIR-FSE) for blood suppression and an additional spectral fat saturation preparation pulse.

Results: 2D CINE FLASH images acquired with the 16 channel dipole antenna transceiver array provided a rather uniform signal intensity across the upper torso as demonstrated in Fig.1b. For a midventricular short axis no obvious B_1^+ inhomogeneities are visible across the field of view (FOV). This B_1^+ performance enabled cardiac FSE imaging. Figure 2 shows images derived from FSE imaging for the same midventricular slice (Fig.2a) used for 2D CINE imaging, for an apical short axis view (Fig.2b) and for a four chamber view (Fig2c). The FSE image in Fig.2a properly depicts small anatomic structures like the papillary muscles. The blood suppression inherent to FSE sequences works well in most regions of the heart. Only slow flowing blood in areas close to the endocardium remains visible. This residual signal caused by slow flowing blood is more pronounced in the apical view, since the overall blood flow is reduced. To reduce remaining blood signal a double-inversion recovery preparation was applied for long axis view images of the heart, which are aligned parallel to the blood flow. Fig.2c demonstrates that the B_1^+ uniformity is sufficient to obtain four chamber view (4cv) FSE images. A signal decrease was observed in the anterolateral myocardial segment.

Discussion: This work demonstrates that a dedicated coil array affords uniform transmission fields which enable FSE imaging of the heart at 7.0 T. At UHF implementation of inversion recovery based black blood preparation is challenging because it adds to the RF power deposition. The lack of an extra blood suppression module in Fig.2a and Fig.2b resulted in FSE images showing residual blood flow for slow flow target regions, which could be reduced by incorporating a double-inversion recovery preparation. A modest diffusion weighting could be a valuable alternative for spoiling remaining signal induced by slow flowing blood. Our results indicate that the dynamic range of FSE image contrast at 7.0 T is dominated by subcutaneous fat signal despite the applied spectral preparation pulse, which requires further efforts into fat suppression techniques. Alternatively, reduced field of view acquisition [6] can be exploited to exclude subcutaneous fat of the chest wall from the field of view.

Conclusion: Transfer of FSE imaging – which is very well established for CMR at 1.5 T and 3.0 T – to 7.0 T is of high relevance for advancing the capabilities of UHF-CMR with the ultimate goal to foster explorations into cardiac morphology, myocardial microstructure and myocardial tissue characterization. Our results indicate that FSE imaging of the heart at 7.0 T using a 16 channel transceiver array that uses radiative elements is feasible. Our preliminary results are heartening since numerical EMF simulations using the human voxel model "DUKE" were employed for B_1^+ optimization rather than using time consuming patient specific transmission field optimization. Our preliminary results need to be very carefully validated against cardiac FSE imaging at lower fields. A recognized limitation of this feasibility study is the assessment of a limited number of healthy subjects, but this mandatory precursor was essential before extra variances due to gender and/or pathophysiological conditions are introduced. Therefore, efficacy of the described 16 channel Tx/Rx bowtie antenna approach for FSE imaging in patients awaits further study. Also, the refinement of black blood preparation modules – including double inversion recovery preparation – tailored for 7.0 T is anticipated to further improve FSE image quality at 7.0 T.

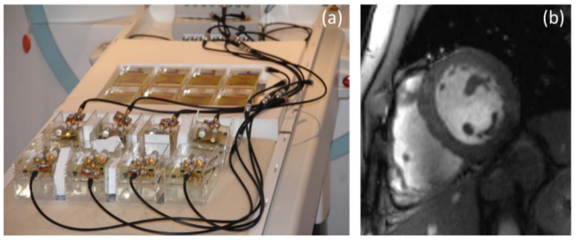

Figure 1. (a) Setup of the 16 element dipole coil array on the patient table, (b) 2D CINE FLASH image for a midventricular short axis view which was acquired using the proposed coil array.

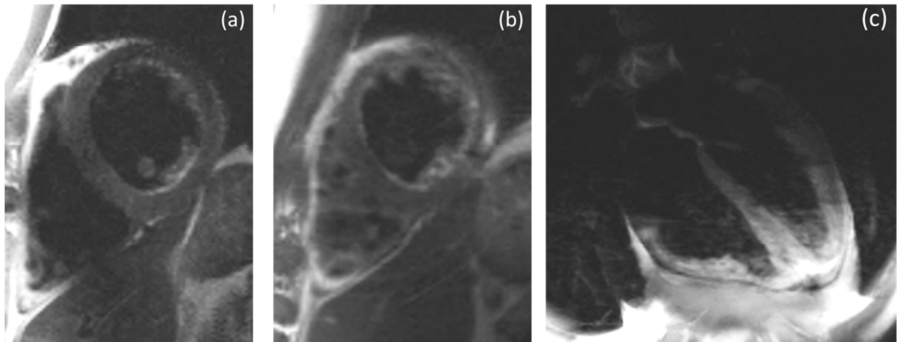

Figure 2. (a) FSE image for the same midventricular slice as in Fig.1b, (b) FSE image for an apical short axis. (c) 4 chamber view FSE image.

References: [1] Hennig et al, *MRM* 1986, 3:823; [2] van Kalleveen et al, *MRM* 2012, 68:580; [3] Winter et al, ISMRM 2012, p. 543; [4] Oezerdem et al, ISMRM 2012, p. 2641; [5] Raaijmakers et al, *MRM* 2011, 66:1488; [6] Feinberg et al, *Radiology* 1985, 156:743