Multi-Band-Multi-Spoke pTX RF Pulse Design in the Heart at 7 Tesla: towards Faster, Uniform Contrast Cardiac CINE Imaging

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INTRODUCTION. Cardiac MRI has been shown to be feasible at ultra high field (UHF) (i.e.≥7T) [1] and may benefit from higher SNR and increased intrinsic contrast [2,3]. However, UHF cardiac MRI is particularly challenging because, in addition to cardiac and respiratory motions that confront cardiac studies at any field strength, the short RF wavelengths associated with UHF lead to highly heterogeneous flip angle through the heart. The former problem is normally addressed by imaging under breath-hold (~20 seconds), which strongly limits spatial coverage. The latter problem has been addressed using multi-channel transmit RF coils that allow for B1 shimming techniques [2,3] and using more advanced parallel transmission (pTX) RF pulse design with 3D tailored RF excitation ('spokes') [4]. In this work, we address the needs for larger spatial coverage *and* improved excitation homogeneity concurrently by designing spoke pTX RF pulses to simultaneously excite (and acquire) multiple slices [5,6] (equivalently labeled Simultaneous Multislice Excitation (SMS)' or 'Multi-Band (MB)') using a 16 channel (ch) pTX system. We demonstrate successful cardiac multiband acquisitions for 2 slices (MB2) at 7T and further compare 1-spoke (equivalent to B1+ shimming) and 2-spoke RF pulse performances.

METHODS. Healthy volunteers were imaged, after obtaining consent, on a 7T system (Siemens, Erlangen) equipped with a prototype 16-ch pTX system using a 16-ch transceiver body coil. Transmit B1 (B1+) sensitivity maps of each transmit (TX) channel were sequentially obtained in two parallel slices, 25 mm apart, with a fast, small-flip-angle estimation technique [4,7], using an ECG-triggered gradient echo (GRE) sequence. For each slice, a single breath-hold was sufficient to collect the 16-ch B1 calibration. B0 maps were obtained (dual echo, gated GRE sequence) in the same slices for RF pulse design. Band-specific 1-spoke and 2-spoke RF pulses were designed according to [6], using the magnitude-least-squares optimization [8]. Resulting RF pulses shapes for both bands were added channel-wise to perform MB2 excitations. Acquisitions were performed with and without CAIPIRINHA [9]. When CAIPIRINHA was enabled, an additional 180˚ RF pulse phase was added for all even lines of the second slice. The same RF pulse shape (filtered SINC with BWTP=4) was used in 1-spoke pulses with a pulse duration of 1600us, and in 2-spoke pulses with a pulse duration of 800 us per spoke (same total duration 2x800=1600us). MB2 and Single-Band (SB) acquisitions of two 25mm distant slices were performed in axial and short-axis views using a GRE sequence in CINE mode (192x120 matrix, resolution 2.3x2.3x5 mm^3; TR/TE = 42/2.5ms, up to 30 cardiac phases, no in-plane GRAPPA). The first cardiac phase of the SB acquisitions was used as a calibration dataset to reconstruct each cardiac phase of the MB2 data using a slice GRAPPA algorithm [10,11]. 1- and 2-spoke excitations were designed with same total RF energy and same flip angle (approximately 10˚). Heterogeneity was quantified by computing a coefficient of variation (CV= std/mean) over the Region of Interest (over the heart) used for RF pulse design.

RESULTS. Fig.1 displays short-axis views of a MB2 dataset with 1-spoke excitation showing original (aliased, left column) and corresponding reconstructed images (center & right columns) without and with CAIPIRINHA. In both cases, successful reconstruction was obtained with effective separation of the 2 slices and strong correlation to the SB data utilized as a reference (top row, Fig 1). However, when scaling the reconstructed image of slice 1 (Fig.2, center & center-bottom) to the noise level (Fig.2a), a strong noise increase (x 2.9) is clearly seen *without* versus *with* CAIPRINHA, associated with higher g-factors. Similarly, the strong reduction of signal leakage [12] from slice 2 into slice 1 (Fig.2b) with CAIPIRINHA demonstrates the positive impact of aliasing reduction. The leakage ratio averaged over the heart in short axis view, shown in Fig.2c (Fig.2b divided by SB data of slice 2), drops from 14.3% without to 3.8% with CAIPIRINHA. A common challenge with MB pulses is a higher RF energy demand. Constraining 1-spoke solutions to lower RF energy can lead to increased flip angle inhomogeneity and to lower flip angle, especially in posterior heart areas (Fig.3, left columns). A 2-spoke RF pulse with same total energy, however, can improve the CV from 16.2% for 1-spoke to 11.8% for 2-spokes as seen in the Bloch simulation in the bottom row. Moreover the 2-spokes can remarkably recover signals in the posterior areas of the heart (see white arrows) that were lost with 1-spoke RF pulses.

DISCUSSION. In this work 1-spoke and 2-spoke pTX MB RF pulses with/without CAIPIRINHA were applied to cardiac imaging at 7T. Although successful reconstruction was achieved in both cases, significant improvement was obtained using CAIPIRINHA. In agreement with previous findings with SB pTX pulses [4], 2-spoke pTX MB excitation significantly improved cardiac image quality over 1-spoke pTX MB, particularly in the posterior area of the heart.

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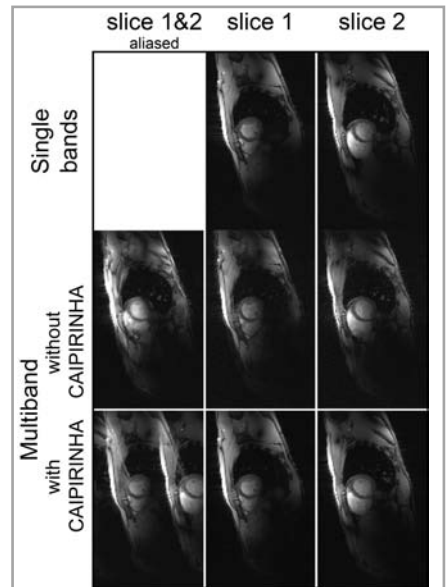
Fig.1: *aliased and reconstructed images of MB 2 data in short axis view with/without using a CAIPIRINHA reconstruction. The top row shows single band data for comparison.*
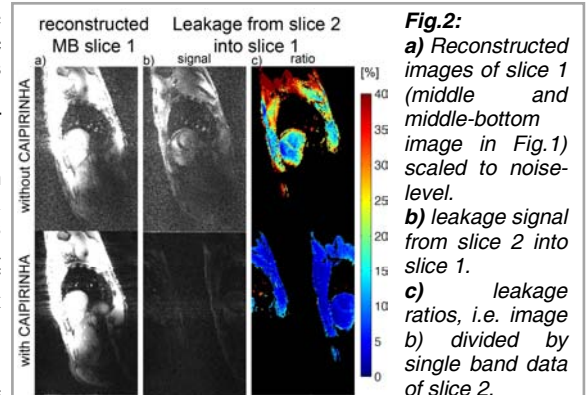
Fig.2:
a) Reconstructed images of slice 1 (middle and middle-bottom image in Fig.1) scaled to noise-level.
b) leakage signal from slice 2 into slice 1.
c) leakage ratios, i.e. image b) divided by single band data of slice 2.
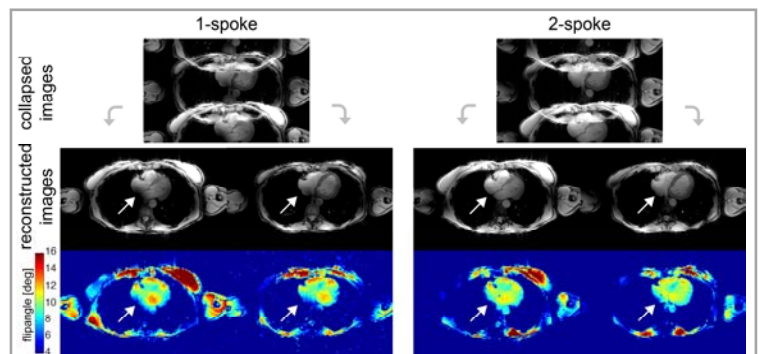
Fig.3: Top: *aliased MB2 data with CAIPIRINHA and 1-spoke (left) and 2-spoke RF excitation (right).* **Middle:** *reconstructed data.* **Bottom:** *flip angle maps obtained from Bloch simulations.*