pTX Spoke RF Pulses for Cardiac MRI at 7T: a New Design Robust against Respiration Induced Errors, based on a Virtual Simultaneous Exhale-and-Inhale Calilbration Scan

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INTRODUCTION. Cardiac MRI may strongly benefit from high SNR at ultra-high fields (UHF) but is challenged by the short RF wavelength that induces large flip angle variations over the heart. This problem has been successfully addressed in 7T cardiac CINE imaging using parallel transmission (pTX) with 2-spoke pTX RF pulses [1]. Although 2 spokes can provide high contrast uniformity, we sometimes observed significant deviations between measurement and prediction by Bloch simulation as discussed in [1]. Also, at times, the performance changed when using two different 2-spoke trajectories in k-space with similar prediction (Fig1). We suspected motion to be involved (some trajectories may be more prone than others) but subject's bulk motion in the scanner was excluded. All calibrations and acquisitions are performed under breath-hold, assuming that subjects always return to the same exhale position. If, however, the subject's respiratory state (ideally exhaled) during cardiac CINE scans is not the same as during transmit B1 (B1+) and ΔB_0 calibration scans, degradation in the performance of the 2-spoke RF pulse uniformity can be expected. Here we investigate the impact of breath-hold position on cardiac CINE imaging using 2-spoke pTX pulses and we demonstrate an RF pulse design strategy to increase the robustness of 2-spoke pTX RF pulse to variations in breath-hold position. Our findings may also impact free-breathing pTX acquisitions, including at 3T.

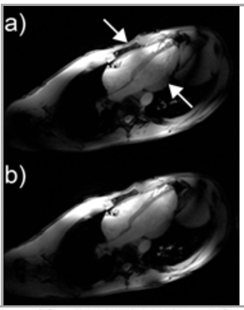

Fig.1: two different 2-spoke solutions with same total energy. Note in (a) a dark area through the heart (arrows), much reduced in (b). Images were not corrected for receive profiles.

METHODS. After obtaining consent, volunteers were imaged at 7T with a 16 channel pTX prototype console (Siemens, Erlangen) using a 16 channel transceiver body coil [2]. The 16 B1+ sensitivity maps were obtained in an axial plane from ECG triggered GRE scans (1 B1+ map per heartbeat) acquired during a single breath-hold using a fast, small flip angle (FA) calibration [1,3]. For each TX map we also acquired within the same heartbeat a sagittal map (16 in total) crossing the diaphragm to monitor breath-hold position during B1+ calibration. A ΔB_0 map, required for 2-spoke RF pulse design, was derived from a dual TE GRE acquisition that also included a diaphragm scan. The B_1^+ and ΔB_0 mapping procedure was repeated 3 times while instructing the subject to hold their breath on 3 different breath-hold positions (POS): I) full exhale, II) half inhale, III) full inhale (POS verified with diaphragm data). With slice selection along the z-axis, gradient blips applied along the x and y axes were used to symmetrically position the 2 spokes about k_x-k_y=0 (see Fig. 2a). In polar coordinates, the radius k_r varied from 0 to $10m^{-1}$ in $1m^{-1}$ steps while the angle φ of the 'spokes axis' (dashed line in Fig2a) to the k_x axis was varied from 0° to 360° (note: *not* 180°) in 10° steps. RF pulses were designed as described in [1] based on B_1^+ and ΔB_0 maps acquired in POS I, using a magnitude least squares solution [4] for each of the 361 different trajectories. We performed Bloch simulations for each solution, first with the original B_1^+ and ΔB_0 maps (obtained at POS I), then after substituting the latter with those obtained at POS II and then at POS III. For each spoke trajectory characterized by (k_r,φ) and each breath-hold position, we calculated the coefficient of variation (CV= std(FA)/mean(FA)) of the simulated FA profile, as well as the total RF energy (E_n) (sum of energy through all channels and spokes) and the maximum energy per channel (E_{max}). This procedure was repeated, but with a modified pulse design based on a virtual 2-slice calibration, including in one slice B1+ and B0 maps from POS-I, *and* in a second slice B_1^+ and B_0 maps obtained in POS-III. In-vivo experiments were conducted in the 3 breath-hold positions using either POS-I based or virtual 2-slice based 2-spoke pTX RF pulse design.

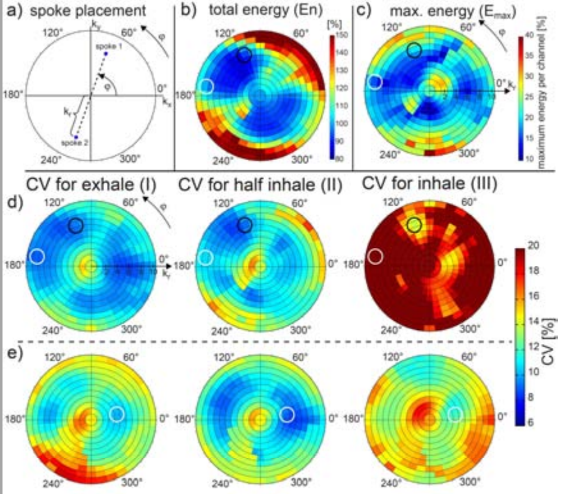

Fig.2: (a) spoke placement, (b) E_n, (c) E_{max} . E_n and E_{max} are normalized to the E_n value of the white circle (a). CV in POS I-III is shown for RF pulse designed for exhale (d) and for RF pulsed designed for both ex- *and* inhale (e).

RESULTS/DISCUSSION. In each chart of Figs.2b-e, the results of CV, E_n, E_{max} for the 361 2-spoke trajectories are shown (color coded) as a function of the k-space trajectory (radius k_r, axis angle φ) as defined in Fig. 2a. Shown results are: E_n (Fig.2b), E_{max} (Fig.2c), CV as a function of POS (Fig.2d&2e). In Fig.2b&2c energy results (E_n, E_{max}) are normalized to E_n of the solution shown in a white circle in b). RF pulses were designed using either B_1^+ and ΔB_0 at POS I (Fig2b-d) or the virtual 2-slice pulse design using POS I *and* III (Fig2e). It was found that: i) CV maps (c,d) are not symmetric about the axes origin, due to non-null ΔB_0 Maps, ii) using different spoke locations can dramatically impact CV (d,e), E_n (b) and E_{max} (c). When RF pulses designed for POS I are applied on POS II or III, CV can greatly increase. For in-vivo CINE acquisition, spoke location at k_r=$9m^{-1}$, φ=170°, (white circle Fig.2a) was chosen as a good tradeoff with low CV (8.9%), acceptable E_n (100% per our Fig.2b definition) and low E_{max}. Corresponding in-vivo images and Bloch-simulations are shown for POS I-III in Fig.3a: CV degrades from 8.9% (POS I) to 10.8% (POS II) and 28.4% (POS III). While POS II shows limited degradation (white arrows), POS III reveals significant artifacts with strongly reduced FA. To find an RF pulse based on POS I but better behaved in POS III, one could chose, e.g., k_r=$7m^{-1}$, φ=110° (black circle Fig.2b-d), which even requires 8% less E_n (Fig2.b). However it requires higher E_{max} (factor 1.26) and, crucially, still increases CV in POS III (13.7%). By contrast, a virtual 2-slice pulse design (Fig. 2e) provides significantly less CV variations between the POS. A solution at (k_r=$4m^{-1}$,φ=10°, white circle Fig2e) yields strongly reduced CV variation between POS (POS I: 10.1%; POS II: 9.0%; POS III: 12.1%), while E_n stays unchanged (100%) and E_{max} increases by only 7%.

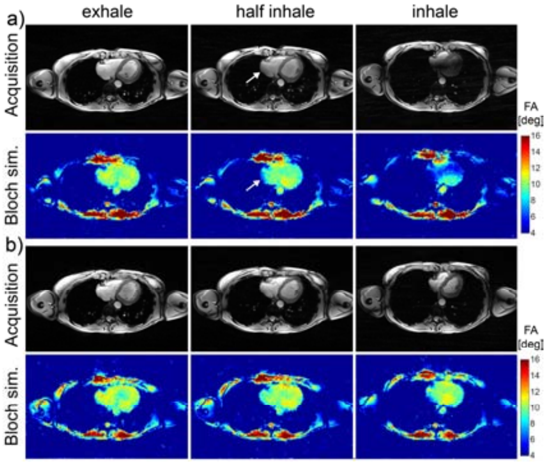

Fig.3: (a) diastolic image of CINE acquisition and Bloch simulation with standard 2-spoke pulse design (white circle trajectory in Fig2d). (b) same acquisition with 2-spoke pulse designed for ex- *and* inhale (white circle trajectory Fig2e).

CONCLUSION. 2-spoke pTX RF pulses are highly sensitive to respiratory position. A modified RF pulse using a virtual 2-position B1/B_0 calibration (ex- *and* inhale) provides solutions robust to the latter. The much greater image quality stability, clearly seen in Fig.3b, could also enable 2-spoke pTX pulses for free-breathing acquisitions.

ACKNOWLEDGMENTS: P41 EB015894, S10 RR026783, KECK Foundation. **REFERENCES** [1] Schmitter et al. MRM 2013 70:1210 [2] Snyder et al. MRM 2012 67:954 [3] Van de Moortele et al. ISMRM 2009:367 [4] Setsompop et al. MRM 2008, 59:908