Impact of RF-shimming on the uniformity and specific absorption rate of spin-echo imaging at 7 Tesla

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Target Audience: MR physicists, ultra-high field practitioners.

Purpose: High resolution T_2-weighted imaging, commonly implemented with a turbo spin echo (TSE) sequence, is compromised by the non-uniform flip angle distribution due to transmit field inhomogeneity at high field. Additionally, TSE is usually severely SAR-limited at high fields due to the rapid succession of 180° refocusing RF pulses. The additional transmit degrees-of-freedom provided by parallel transmission (pTx) coils and pTx pulse design can be used to improve excitation uniformity [1] as well as to reduce SAR [2]. Several authors have suggested using pTx to address these challenges, however published results have so far overly constrained RF power as a proxy for SAR thus resulting in sub-optimal pulses [3,4]. Boulant et al have successfully incorporated SAR constraints in the design of excitation and refocusing pulses for TSE but their work was limited to non-selective (3D) imaging [5,6]. In this work, we study the impact of slice-selective pTx RF-shimming on the image uniformity and SAR of spin-echo experiments at 7 T.

Methods: *Pulse design:* We design large tip angle radiofrequency (RF) pulses (excitation and refocusing) in two steps [7]. First, we compute a preliminary pulse using the Linear Class of Large Tip Angle (LCLTA) approach [8]. Second, we refine this initial guess by full optimization of the Bloch equation in the spinor domain [4,5,9] using a flip angle target (excitation) or, in the notation of Pauly et al [9], a β^2 target (β^2=1 for an ideal refocusing pulse, see Fig. 1). We minimize a magnitude least-squares objective function subject to peak voltage and local SAR and global SAR constraints [6,10]. To decrease computation time, we provide fast analytical expressions of the Jacobian of both the objective function and SAR constraints to the optimizer (fmincon, Matlab 8, Natick MA). *Simulations*: We evaluated the simultaneous optimization of excitation fidelity and SAR (excitation and refocusing pulses individually) on electromagnetic simulations of a 7 T, 8-channel transmit array loaded with a 33 tissue types body model [10]. The SAR matrices were compressed into a smaller set of virtual observation points for faster optimization [11]. *Experiments*: We played single echo spin echo (SE) pulses on a 7 T head 8-channel pTx system (pTx "Step 2", Magnetom 7 T, Siemens, Erlangen) using the following parameters: 1.6x1.6x5 mm^3 pixel size, FOV = 20x20 cm^2, TE = 18 ms and TA = 130 s. All experiments were performed using a realistic 3D-printed head phantom with three agar-filled compartments (bone, brain and everything else). Only peak voltage constraints were enforced in these experiments (no SAR constraints).

Results/Discussion: Application of RF-shimming to the excitation and refocusing parts of the SE pulse improved the SE image uniformity significantly (Fig.2, top-right, green) compared to the conventional birdcage pulses (Fig.2, top-left, red). These images correlated closely with the simulated flip angle and β^2 maps shown in Fig.1. Also shown in Fig.2 is the incremental improvement due to applying RF-shimming to the excitation OR the refocusing parts of the pulse. The L-curves of Fig.3 show that, at constant flip angle error, RF-shimming reduced local SAR by 55% for the excitation and 48% for the refocusing pulses individually (compared to the BC mode) for the simulated dataset. Future work includes in-vivo validation as well as extension to multiple spokes.

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References: [1] Grissom et al. 2006;56:620–629 [2] Guerin et al. MRM 2014;71(4):1446–1457 [3] Setsompop et al. 2009;195(1):76–84 [4] Grissom et al. IEEE Trans Med Imaging 2009;28(10):1548-59 [5] Boulant et al. MRM 2014 doi:10.1002/mrm.25353 [6] Hoyos-Idrobo et al. IEEE Trans Med Imaging 2013 doi: 10.1109/TMI.2013.2295465 [7] Yetisir et al. ISMRM 2014 Abstract 1454 [8] Pauly et al. JMR 1989;82:571-587 [9] Pauly et al. 1991;10(1):53-65. [10] Kozlov et al. JMR 2009;200(1):147-152. [11] Eichfelder et al. MRM 2011;66:1468-1476

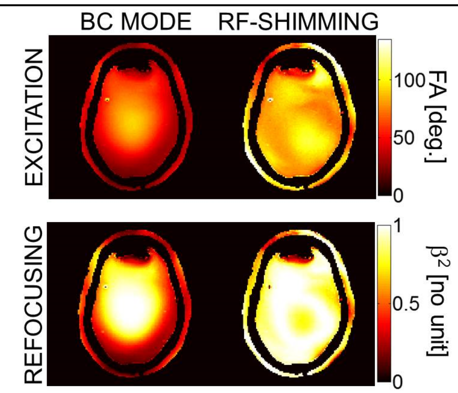

Fig.1. Flip-angle and β^2 maps of the designed excitation (90˚) and refocusing (180˚) pulses (Bloch simulation). Pulses were designed only for brain.

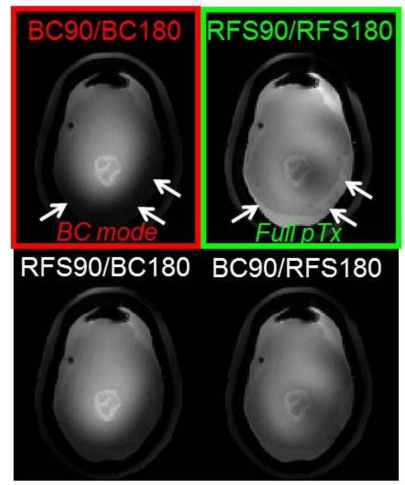

Fig.2. Spin echo images obtained with four methods combining RF-shimming/BC mode excitation and refocusing pulses. The white arrows point to regions where RF-shimming significantly improved the excitation uniformity compared to the BC mode.

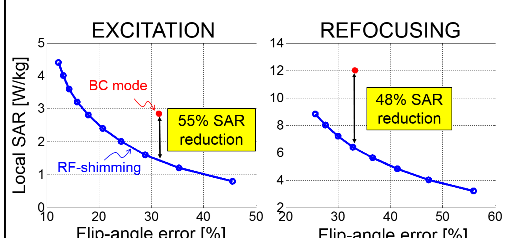

Fig. 3. L-curves showing the tradeoff between local SAR and the flip-angle uniformity for excitation and refocusing pulses on a simulated dataset. Global SAR limit is 3 W/kg, peak RF voltage limit is 150 V for all pulses.