Parallel Transmit using 3D Spokes RF Pulses for Improved B_1^+ Homogeneity over 3D Volumes

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Purpose: B_1^+ uniformity is a major issue in high field MRI due to short RF wavelengths in tissue. Various methods have been proposed to mitigate B_1^+ inhomogeneity including RF shimming and fully independent parallel transmit (pTx) using 2D spokes pulses [1-2]. 2D spokes pulses are designed to optimize B_1^+ over a single 2D slice, and therefore when applied to a single slab are not expected to achieve optimal B_1^+ uniformity over the full 3D volume; furthermore, multi-slice 2D spokes pulse design is time-consuming and complex, as different spokes pulses have to be designed for each slice. We propose a new method to improve the B_1^+ homogeneity in single-slab 3D imaging using 3D spokes parallel transmit RF pulses. This generalizes the approach in [1-2] with the addition of phase encoding blips along the z-axis to address the B_1^+ inhomogeneity not only in-plane but also through-slab.

Methods: Figure 1 shows the new concept by focusing on one spoke out of a multi-spoke 3D pTx RF pulse, showing particularly the variable offset of the center of the spoke, Δk_z, created by the addition of a z-gradient blip in addition to the conventional x- and y-gradient blips. A conjugate gradient algorithm was used to derive the optimal sub-pulse amplitudes, phases and spokes locations, including Δk_z offsets. A new matrix formulation was used to optimize the speed of the algorithm to achieve practical convergence times of ~10s for a typical whole-brain single-slab prescription. A multi-resolution scheme with optimal choice of initial conditions minimized the likelihood of trapping in local minima, while ensuring fast convergence. B_1^+ maps were collected using a Bloch-Siegert (BS) B_1^+ method [3] with an optimized off-resonant pulse (offset frequency $\Delta\omega_{BS}$=1940 Hz, width =4 ms) [4]. The B_0 and B_1^+ maps of 2 channels for all slices in a 9-slice slab were collected in a single 2:40 minute scan. These maps were then fed to the 3D spokes pulse design script to design x, y and z gradient waveforms as well as amplitude and phase waveforms for channels 1 and 2. Pulse design was accomplished using a MATLAB script and typical computation time was 30s. A 0.75 ms SLR pulse shape with time-bandwidth product of 8 was chosen as the sub-pulse shape. The resulting 5-spoke RF pulse width was 5.4 ms. Figure 2 shows the gradient and RF waveforms for that pulse (z-gradient phase encoding blips shown although these are easily consolidated into slice-select gradients)

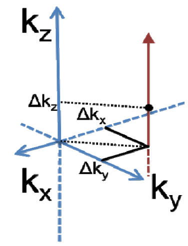

Fig. 1) A typical 3D spoke in k-space

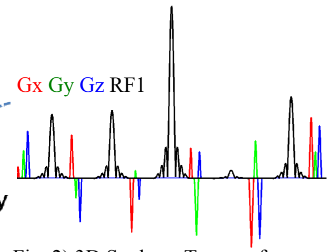

Fig. 2) 3D Spokes pTx waveforms.

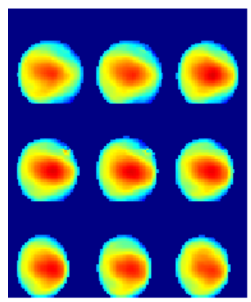
Fig. 3) qTx B_1^+ maps

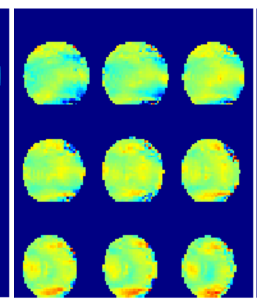
Fig. 4) central-slice-designed 2D pTx B_1^+ maps

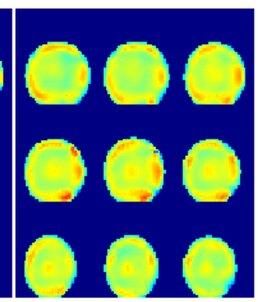
Fig. 5) 3D Spokes pTx Design B_1^+ maps

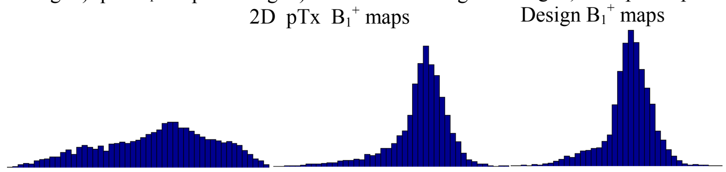
qTx std: 32.4% 2D pTx std: 18.2% 3D pTx std: 16.0%

Fig. 6) B_1^+ histogram of qTx, central-slice-designed 2D pTx & 3D spokes pTx .

Results: We scanned a volunteer on a 2-ch pTx 7.0T scanner (GE Healthcare, Waukesha) and designed a 3D spokes pulse parallel transmit pair, intended to optimize B_1^+ uniformity over a 45 mm thick coronal slab (spatially resolved into 20 slices). Fig. 3 shows the conventional quadrature transmit (qTx) B_1^+ maps measured by the Bloch-Siegert B_1^+ mapping method. Fig. 5 shows the predicted B_1^+ maps resulting from application of the 3D spokes pTx RF pulse. Fig. 4 shows the same maps resulting from application of a 2D spokes pulse, designed to optimize B_1^+ uniformity over a single central 2D slice and then applied to the whole slab. Fig. 6 shows the measured B_1^+ histograms over the full slab, comparing qTx, 3D spokes pTx, and central-thin-slice-designed 2D spokes pTx applied to the whole slab. Fig. 7 shows a comparison between images acquired following qTx and 3D spokes pTx RF pulses. The imaging parameters where 256×256 matrix, 26 cm FOV, thickness=5 mm, TE=7 ms, TR=13 ms, and FA=3 deg.

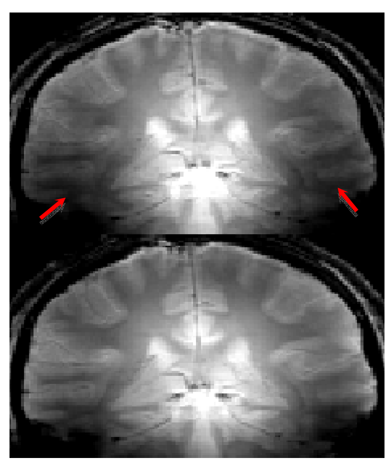
Fig. 7) qTx (Top) vs. pTx (Bottom) images

Discussion: Figures 3 and 5 show predicted pTx B_1^+ maps over the whole 9-slice slab, for qTx versus 3D pTx, respectively, showing the marked improvement of B_1^+ uniformity provided by the 3D spokes pulses. Fig. 4 shows that B_1^+ uniformity is not as good using 2D spokes pulses designed from central 2D slice data but applied to the whole slab. Fig. 6 shows that the width of the whole-slab B_1^+ histogram is improved by a factor of 2 using 3D pTx compared to qTx. It also shows that central-slice-designed 2D pTx does not produce as much uniformity gain. Fig 7 shows the improvement in the gradient echo image quality prior to any receive sensitivity correction. The high flip angle in the center of images in qTx mode is corrected in the 3D pTx images. In addition, the signal loss in the temporal lobes in the qTx scan (shown by red arrows) is improved in the pTx scan. 3D pTx pulse design is faster than designing separate 2D pTx pulses for each individual slice, and at the same time produces improved B_1^+ uniformity over a thick slab in a 3D acquisition scan. 3D spokes pTx pulses are generally shorter and more practical than 2D spokes pulses; this is especially relevant in the case of thin slices (e.g. < 3mm) where 2D spokes pulse implementation is challenging even for high performance whole-body gradient systems. 3D spokes pTx improves B_1^+ uniformity over a volume without performing a full 3D pulse design, which makes practical implementation more feasible.

References: [1] Grissom et al., MRM 56:620-629, 2006. [2] Setsompop et al., MRM 60(6):1422-1432, 2008. [3] Sacolick et al., MRM 63:1315:1322, 2010. [4] Khalighi et al., Proc. ISMRM 18:2842 (2010). **Acknowledgement:** Research support from GE Healthcare.