Parallel-transmission-enabled 3D T_2-weighted imaging of the human brain at 7 Tesla

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Purpose: At ultra-high magnetic field, B_1^+ and ΔB_0 non-uniformities cause undesired contrast and signal inhomogeneities. Tailored radiofrequency (RF) pulses exploiting parallel transmission (pTX) have already demonstrated their ability to mitigate these phenomena, especially in the framework of T_1-weighted imaging[1]. Yet the design of refocusing pulses employed in T_2-weighted imaging remains challenging due to the additional demand of a rotation of the magnetization vector[2]. In this work, we use the gradient ascent pulse engineering (GRAPE[3]) combined with the successfully demonstrated k_T-point[4] method to design all the independent yet phase-coherent non-selective refocusing pulses of a variable flip angle turbo spin echo sequence (SPACE[5]). Severe B_1^+ and ΔB_0 inhomogeneities are thus mitigated and whole brain T_2-weighted image quality is improved at 7 T.

Methods: Three healthy subjects, who provided informed consent, were scanned on a 7T Magnetom scanner (Siemens Healthcare, Erlangen, Germany), equipped with parallel transmission capabilities. For both RF transmission and reception, a home-made transceiver-array head coil is used. The eight transmit sensitivity profiles are acquired using the XFL sequence[6] (TA: 4min). The ΔB_0 map and a high-resolution mask of the brain are independently acquired with fast 2D multi-slices sequences. The pulse design procedure described below was implemented in C++ including GPU-enabled CUDA (Nvidia, Santa Clara, CA, USA) extensions and is achieved in about 3 minutes for the design of about 50 different RF pulses. The power of the GRAPE algorithm lays in the optimization of the rotation matrices themselves, which is appealing in the framework of refocusing pulses, as the initial magnetization state before the refocusing train can be arbitrary. Pulse optimization is fulfilled through the maximization of the norm of the projection of a candidate rotation matrix on a desired rotation matrix with prescribed angle and axis of rotation[2]. The gradient of this performance criterion with respect to all control parameters (i.e. real and imaginary parts of RF pulse shapes on all channels) is obtained analytically and incorporated it in a conjugate gradient minimization approach. Gradient blips (i.e. k_T-point positions) likewise are optimized but only at the beginning of the procedure[2]. Replacing the original hard pulses of the SPACE sequence with sets of sub-pulses and gradients blips inevitably increases their durations and SAR contributions. This inherently affects the TR of the sequence, the echo spacing ES and the shape of the RF echo train. The following sequence protocol is therefore adopted: TR: 6s, ES: 10ms, effective TE: 340ms, ETL: 96, resolution: 1mm isotropic, matrix size: 256x224x160, TA: 12min. Receive sensitivity contribution of the coil is removed to focus only on improvements in excitation.

Results and discussion: The use of GRAPE-tailored excitation and refocusing pulses leads to remarkable improvements in both signal and contrast homogeneities, even when compared to a static RF-shim configuration, especially in the cerebellum and in the upper brain region. The GRAPE algorithm presents several advantages compared to other optimization strategies[7], as it makes no linear class of large tip angle (LCTA) approximation and fully takes into account ΔB_0 for each pulse. In addition, relaxation of the phase constraint on the rotation axis, which gives more freedom in the pulse design, is enabled, as the dephased magnetization due to ΔB_0 gradients can be refocused regardless of that phase. Still, all the refocusing pulses must have this same phase pattern to fulfill the CPMG condition. Last, the analytical computation of the derivatives with respect to the control parameters spares the pulse designer many time-consuming elementary calculations necessary to other numerical methods. All 3D TSE-like MRI sequence could benefit from these tailored pulses, starting with the FLAIR sequence, widely used in medical diagnosis (results pending). Future work also includes application of this methodology to the DIR sequence, a less overestimated SAR evaluation, justified by a new real-time SAR monitoring system, and a subsequent improvement of the sequence protocol to further enhance spatial resolution and contrast.

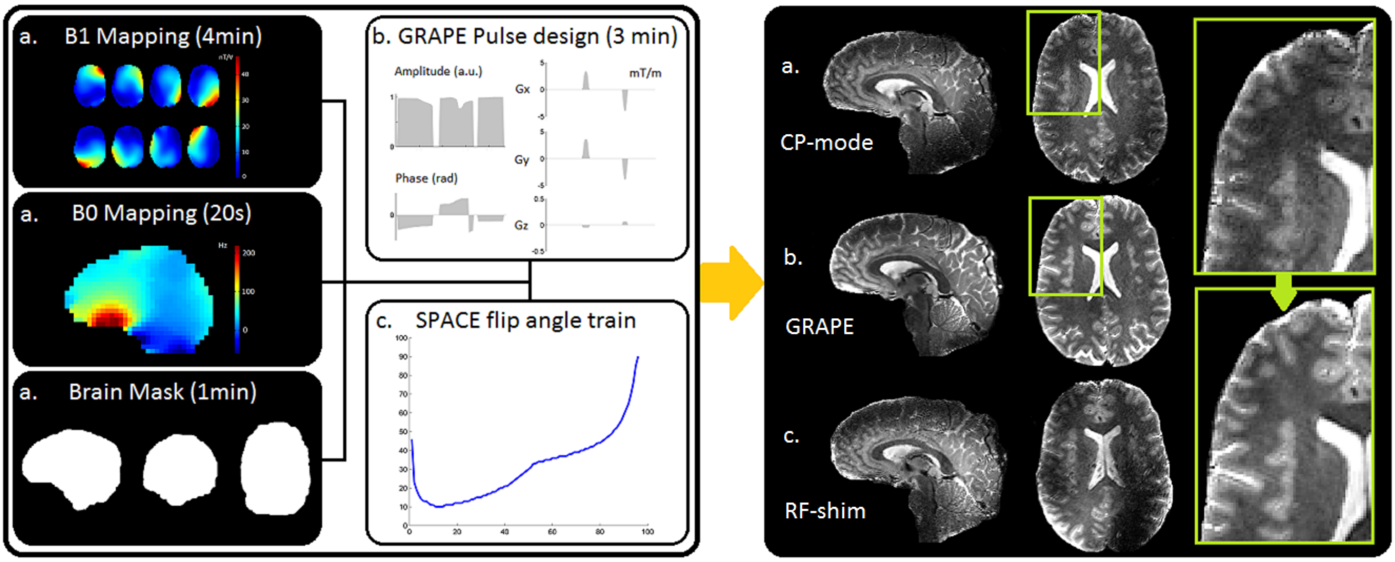

Figure: Step1: Online fast pTX calibration and pulse design: **a.** pTX subject-specific data acquisition, **b.** Example of GRAPE-tailored set of refocusing sub-pulses and gradients (3 k_T-points) used to replace the original hard pulses, **c.** Flip angle train for the SPACE sequence. **Step2:** SPACE images (corrected from coil reception profile): **a.** Conventional hard pulses in a pseudo-Circularly Polarized mode, **b.** Proposed methodology with GRAPE-tailored pulses, **c.** Hard pulses in a static RF-shim configuration*. Last column focuses on contrast enhancement on the cortex brought by GRAPE optimization. *RF-shim signal homogeneity is partially altered because of subject movement (see offset on ventricles).

Conclusion: A novel B_1^+ and ΔB_0 mitigating pulse design algorithm for non-selective phase-coherent refocusing pulses has been investigated in the context of 3D T_2-weighted imaging of the human brain at 7 Tesla. In vivo experiments showed that exploiting the full potential of pTX with the proposed methodology produces high quality T_2-weighted whole brain images with uniform signal and contrast, requiring only 10 preliminary minutes of subject-specific data acquisition and pulse design.

References: [1] Cloos et al, Neuroimage 62, 2012. [2] Massire et al, JMR 230, 2013. [3] Khaneja et al, JMR 172, 2005. [4] Cloos et al, MRM 67, 2012. [5] Mugler, ISMRM, 2000, p.687. [6] Amadon et al, ISMRM, 2012, p.3358. [7] Eggenschwiler et al, MRM, 2013.