Design of non-selective refocusing pulses with phase-free rotation axis by gradient ascent algorithm in parallel transmission at 7 T

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Target audience: UHF MRI physicists and engineers.

Purpose: At ultra-high magnetic field, B_1 and ΔB_0 non-uniformities cause undesired contrast and signal inhomogeneities. Tailored radiofrequency pulses exploiting parallel transmission have already demonstrated their ability to mitigate these phenomena. However, the design of large flip angle rotations remains challenging due to the non-linearity of the Bloch equation. In this work, we use gradient ascent pulse engineering (GRAPE[1]) combined with the successfully demonstrated k_T-point[2] method to design non-selective refocusing pulses that mitigate severe B_1 and ΔB_0 inhomogeneities. The novelty of the method lays in the optimization of the rotation matrices themselves as opposed to magnetization states. Consequently, the proposed technique no longer relies on the linear class of large tip angle (LCTA) assumption. Furthermore, this approach allows to compute analytically the gradient of the performance criterion and to relax the phase constraint on the transverse rotation axis, thus speeding up the minimization procedures and providing additional degrees of freedom for pulse design.

Methods: The GRAPE algorithm was adapted to tailor the excitation to approach the target propagator of a 180° rotation about a free but transverse rotation axis, regardless of the initial state of the magnetization. To this end, the desired target and candidate propagators (i.e. the rotation matrices in SU(2)) shall be denoted by U_F and U(T) respectively, T being the time at the end of the RF pulse. Minimizing their $\ell 2$ distance is equivalent to maximizing the norm of the projection[1] of U(T) on U_F: $\varphi=|\langle U_F|U(T)\rangle|^2$. The derivative of this performance criterion with respect to all control parameters (i.e. real and imaginary parts of RF shapes on all channels) is then obtained analytically[1] to finally calculate its gradient and incorporate it in a conjugate gradients minimization approach. The initial guess was computed using an 8 k_T-points RF pulse. The method was experimentally validated on a 7 T scanner (Siemens, Erlangen, Germany) equipped with an 8-channel transmit array, using a water phantom with B_1 and ΔB_0 inhomogeneities similar to those encountered in the human brain in vivo (a ping-pong ball was inserted in the phantom to generate substantial B_0 field inhomogeneities). The rotation matrix itself was measured using Quantum Process Tomography[3] in order to confirm the close to 180° angles and transverse axis of rotation on every voxel. Last, a modified non-selective Spin-Echo sequence was run, replacing the conventional square pulses with the GRAPE-tailored pulses, to evaluate the ability to refocus normally greatly dephased magnetization.

Results: Both experiments confirmed high fidelity of the technique. The experimentally obtained Rotation Angle Normalized Root Mean Square Error (7.14 %) was in excellent agreement with the simulated one (8.07 %) (see Figure). Moreover, the 4.6 ms GRAPE-tailored refocusing pulse in the Spin-Echo sequence clearly outperforms the static hard pulse RF-shim configuration both in signal recovery and uniformity. Last, a BIR-4 adiabatic pulse with the same RF-shim setting but with twice the duration of our GRAPE pulse required three times more energy to obtain comparable refocusing performance, showing a better in vivo applicability of the proposed method at high field.

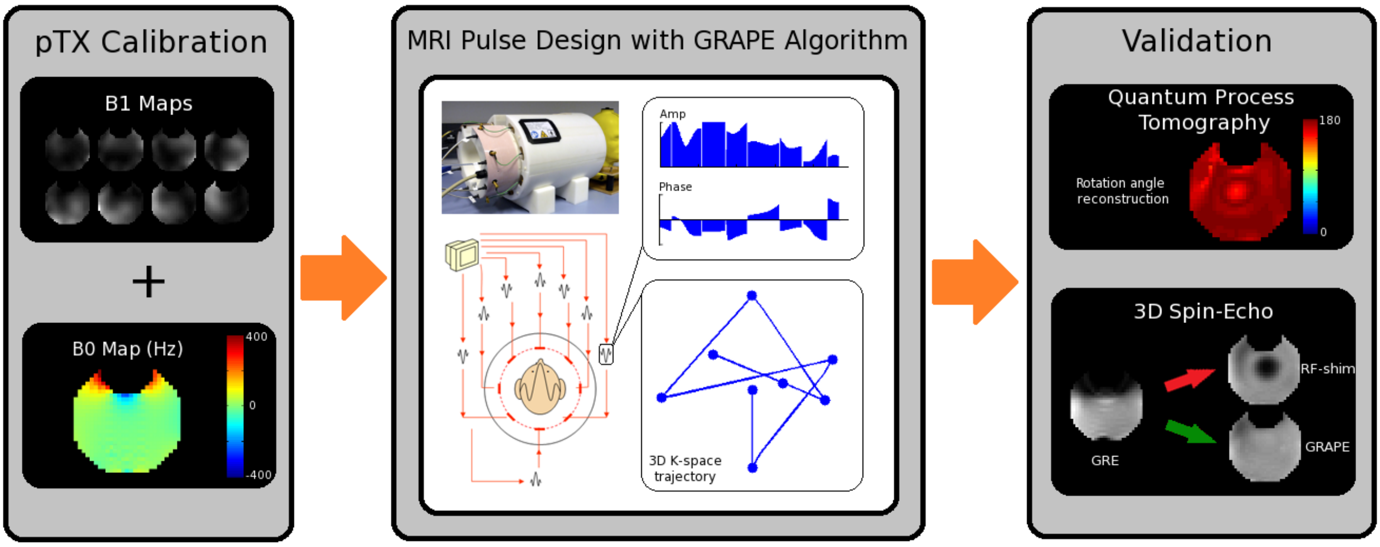

Figure: Step1: pTX Calibration. Step2: Optimization Process. Step3: Experimental Validation (Top: Quantum Process Tomography results: rotation angle. Bottom: Phantom signal with: Excitation only (GRE), modified Spin-echo with RF-shim and GRAPE refocusing pulses).

Discussion: The power of the method lays in the relaxation of the phase constraint on the rotation axis and in the fact that no LCTA assumptions are made. In addition, the analytical computation of the derivatives speeds up the algorithm compared to other numerical methods. Based on the performance of a Xenon 3.2 GHz system with a Tesla 2060C GPU, the final result could be found in less than 5 minutes. This algorithm can moreover be adapted to target arbitrary rotations, i.e. other than 180°, so that many more applications could benefit from it.

Conclusion: A novel B_1 and ΔB_0 mitigating pulse design algorithm for non-selective phase-free refocusing pulses has been investigated in the context of MRI at 7 T. The approach was experimentally validated with the use of Quantum Process Tomography and a Spin-Echo sequence. The GRAPE pulse provided a proper 180° rotation with phase-free transverse axis refocusing and therefore excellent signal uniformity. Virtually all nonselective 3D Spin-Echo-like sequences could benefit from this type of refocusing pulses.

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