Application of k_T-points to human brain imaging at 7 Tesla

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Introduction: Transmit-SENSE [1] gives the opportunity to implement short excitation pulses with good flip-angle (FA) homogeneity at high field. Recently, a novel non-selective pulse design, referred to as k_T-points, was presented which enables sub-millisecond pulses with excellent spatially uniform excitation properties over an extended volume [2]. Up until now, this was only demonstrated in phantoms. In this abstract, for the first time, application of this novel pulse design to human brain imaging at 7 Tesla is presented.

Methods: Experimental verification was performed on a Siemens 7T Magnetom scanner (Erlangen, Germany), equipped with an 8-channel transceiver-array. The AC84 gradient head coil allowed gradient amplitudes up to of 50mT/m and slew rate of 333T/m/s. A home-made transceiver-array head coil was used, which consists of 8 stripline dipoles distributed every 42.5° on a cylindrical surface of 27.6-cm diameter, leaving an open space in front of the subject's eyes. Both the 10-sec- and 6-min-averaged RF powers were monitored in real time for each transmit-channel. To account for the plethora of possible E-field interference patterns, a conservative approach based on finite-element simulations was adopted to ensure patient safety and compliance with the SAR guidelines [3]. Three subjects were scanned, and informed consent was obtained from them in accordance with guidelines of our institutional review board.
First an in house developed B0-mapping and shimming procedure was run. Then a set of relative B1-maps [4,5] was obtained from spoiled Fast Low Angle Shot (FLASH) images (mean-FA: 3°, max-FA: 6°, sequence parameters: TR = 50ms, 5-mm isotropic resolution with a 48x48x36 matrix). In order to increase the overall accuracy, this was implemented in the framework of the matrix-based B_1^+-mapping method [6]. Furthermore, actual FA-maps were obtained for two approximately orthogonal phase combinations contained in the set of FLASH acquisitions. To this end, the AFI sequence [7] was used with TR1/TR2 = 40/200ms, and the same acquisition matrix as for the FLASH sequence. Small non-linearities in the relative B1-mapping procedure due to T1-effects were corrected based on the spoiled GRE signal equation. FA-maps were thus obtained in every human head, allowing the design of k_T-point-based excitation pulses targeting a uniform excitation profile (FA = 5°) throughout each brain. The inverse Fourier method was used to determine the k_T-point locations, ordered by solving the associated traveling salesman problem [8]. Subsequently, excitation pulses were designed using the spatial domain method [9] in combination with the MLS approach [10]. Optimized sub-pulse durations were found with an iterative approach [2]. Obtained tailored pulses were inserted into the FLASH sequence for quantitative analysis. In addition, higher-resolution FLASH images were acquired with proton-density- (sequence parameters: TR = 50ms, TE = 1ms, 2-mm isotropic resolution with a 128x128x80 matrix) and $T2^*$-weighting (sequence parameters: TR = 75ms, TE = 25ms, same matrix as for the proton-density weighted images). To emphasize the effect of the excitation uniformity, receive-sensitivity corrections were applied during post-processing [11].

Results: FA distributions obtained with different excitation pulses are shown in Fig. 1. In addition to the central brightening effect, the synthesized Circularly-Polarized (CP) mode demonstrated low FA's in the frontal lobe and cerebellum (Fig. 1**a** - 32% FA variation across the whole brain). As expected, the static-shim (a single k_T-point optimized at the center of k-space) produced a significant improvement over the synthesized CP-mode (Fig. 1**b**). Still, considerable spatial variations remain in the excitation profile (17% FA variation). Using 5 k_T-points (440-µs, 90-V peak amplitude), good FA homogenization was achieved throughout the volume of the brain (Fig. 1**c** - 7.8% FA spread). The impact of the excitation uniformity on the image can clearly be seen in the proton-density-weighted FLASH images (Fig. 2). The low FA's produced by the CP-mode in the cerebellum, occipital, frontal and temporal lobes are manifested in the lack of signal in these regions (Fig. 2**a**). With 5 k_T-points, the signal in these areas is completely recovered (Fig. 2**b**). Most dramatic is the improvement obtained in the cerebellum, which is now clearly visible with the same uniform excitation as throughout the rest of the brain (Fig. 3). Comparing the total incident energy of the pulses demonstrated in Fig. 1, both the CP-mode (100-µs, 68 mJ) and static-shim (100-µs, 65 mJ) require similar amounts of energy. The further reduction in FA-spread obtained with 5 k_T-points was produced at the expense of a moderate increased total energy (440-µs, 90 mJ). Focusing on the maximum energy per transmit-channel, the CP-mode (8.5 mJ) and static shim (21 mJ) are no longer comparable. Although the total energy used by the 5 k_T–point-based excitation was nearly double that of the static-shim, the energy is more evenly distributed among transmit-channels (maximum: 18 mJ).

Discussion & conclusion: Spatially uniform excitation throughout the volume of the human brain by means of Transmit-SENSE has been demonstrated in 3 healthy human volunteers at 7 Tesla thanks to an original minimalist k-space coverage, the k_T-points. This limited number of k-space locations where RF energy is deposited to counteract B1-inhomogeneities leads to short non-selective excitation pulses with good FA uniformity over extended volumes. Thus a whole range of 3D sequences with short TR can be targeted for applications at high fields, with less SAR limitations than energy-consuming pulses such as adiabatic or strongly-modulating [12] pulses. Currently, work is in progress to also demonstrate the application of k_T-points in the large flip-angle regime. Specifically, a low SAR implementation of the MP-RAGE sequence fully benefiting from power-efficient uniform excitations provided by the k_T-points method is underway.

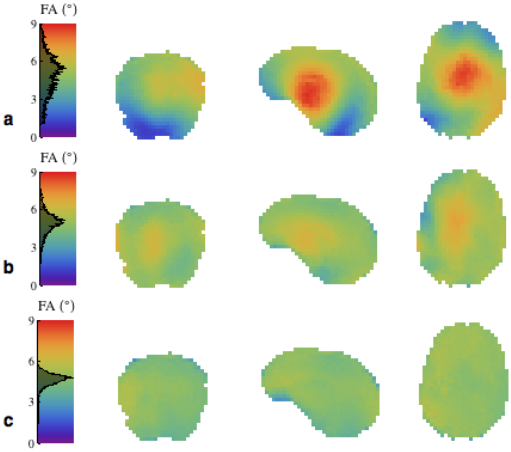

Fig 1: Measured FA distributions in the human brain subject #1. FA distributions obtained with the CP-mode and static-shim where scaled to produce and average of 5°. For each measurement the corresponding histogram is superimposed on the color bar. **a**: CP-mode. **b**: Static shim. **c**: 5 k_T-points.

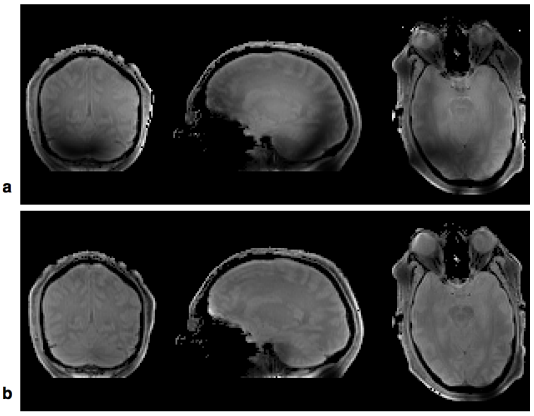

Fig 2: Proton-density weighted FLASH images obtained using the pseudo CP-mode and 5 k_T-points (Subject #2). The receive profile was removed in post processing. **a**: Image obtained using CP-mode (100-µs). **b**: Image obtained using 5 k_T-points (490-µs).

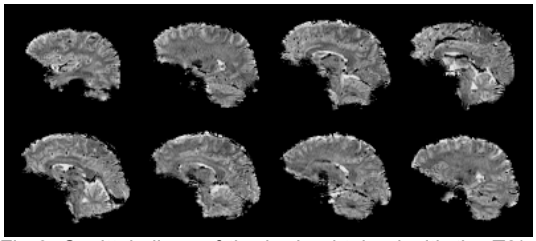

Fig 3: Sagittal slices of the brain obtained with the T2*-weighted FLASH using 7 k_T-points (subject #3). The receive profile and non-brain tissues were removed in post processing.

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