Time Interleaved Acquisition of Modes (TIAMO): an Analysis of SAR and Image Contrast Implications

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Introduction: High static field strengths of 7 Tesla and above are challenging due to the severe B_1 inhomogeneities caused by the short wavelength. Several methods have been proposed to tackle this problem including RF Shimming (1) and Transmit SENSE (2). Recently, an acquisition scheme called Time-Interleaved Acquisition of Modes (TIAMO) (3) has been proposed to reduce the impact of B_1 inhomogeneity. The basic premise is to excite two (or more) different B_1^+ modes using static RF shimming in an interleaved acquisition, where the complementary RF patterns of the two modes can be exploited to improve overall signal homogeneity. The cost in time for acquiring a multitude of images can at least partly be compensated by forming virtual elements in a GRAPPA reconstruction. Since the B_1^+ distributions of the individual utilized modes are inhomogeneous, the contrast in the final image is expected to deviate from an image acquired with a uniform B_1^+. With respect to power deposition in the exposed body region, it is also expected that TIAMO will likely produce a lower time-averaged specific absorption rate (SAR) than either of the utilized modes, because the different power loss densities of the alternately applied excitation modes result in a smoothed overall SAR distribution.
In this work the impact of TIAMO on the image contrast as well as on the time-averaged SAR at 7 Tesla is addressed in detail.

Materials and Methods: For the SAR and homogeneity calculations, three different human models (2 male, 1 female) were used. Field distributions in all models were calculated in CST Microwave Studio (CST AG, Darmstadt, Germany) for an 8-channel head coil and a flexible 8-channel body coil positioned over the liver. The calculated E- and B-fields as well as the material parameters of the models were interpolated to a 4 mm isotropic mesh and used in subsequent homogeneity and SAR calculations in Matlab (The Mathworks, Natick, MA, USA).
As a measure of homogeneity, the standard deviation of the B_1^+ of the individual RF shims and of the sum of squares of the two shims in TIAMO was calculated in an axial slice in the center of each coil within the human body model. 50,000 random shims, all 8 CP-modes, 2 optimized shims and 2 TIAMO settings were evaluated.
A comparison of RF shimming versus TIAMO efficiency in terms of mean B_1 amplitude in a slice over SAR was performed based on signal intensity in the final image. For a valid comparison, it was assumed that the acquisition of any conventional RF shim was performed twice and the final image was given by the sum of squares (SoS), just as the final image in TIAMO is given by the SoS of the two modes. Accordingly, the SAR efficiency was calculated as

$$efficiency_{shimming} = \frac{\sqrt{2}\,\overline{|\mathbf{B}_1^+|}}{\sqrt{\overline{SAR_{10g}}}} \quad \text{and}$$

$$efficiency_{TIAMO} = \frac{\overline{\sqrt{|\mathbf{B}_{1,1}^+|^2 + |\mathbf{B}_{1,2}^+|^2}}}{\sqrt{\overline{SAR_{10g}}}}.$$

Here $\mathbf{B}_{1,1}^+$ and $\mathbf{B}_{1,2}^+$ are the transmit fields of the first and second TIAMO modes, respectively. Note that the square and the square root denote element-wise operations and the bar denotes the mean throughout all elements of the matrix.
For contrast measurements, a phantom consisting of a matrix of 10 by 10 cylinders was used. These were filled in a checkerboard pattern with either water or rapeseed oil. To provoke strong B_1 inhomogeneities, the checkerboard phantom was inserted into a water-filled canister. For comparison with a nearly homogeneous transmit field, the experiment was repeated without the water-filled canister. Five 2D sequences were evaluated: a T1- and a T2*-weighted FLASH sequence, a PD- and a T2-weighted Turbo Spin Echo sequence (TSE), and a T1-weighted Spin Echo (SE) sequence. All sequences had a field of view (FOV) of 200 x 200 mm² and a matrix of 256 x 256 with a slice thickness of 5 mm. The contrast was evaluated by placing a circular region of interest (ROI) in every compartment of the phantom in an axial slice acquired with each of the above-mentioned sequences. Every ROI contained about 80 pixels. The mean signal in each ROI was determined and the ratio of this signal to the mean signal from the 4 surrounding compartments filled with the other liquid was calculated to get an approximation of the contrast distribution. The standard deviation of this contrast distribution was used as a quality measure.

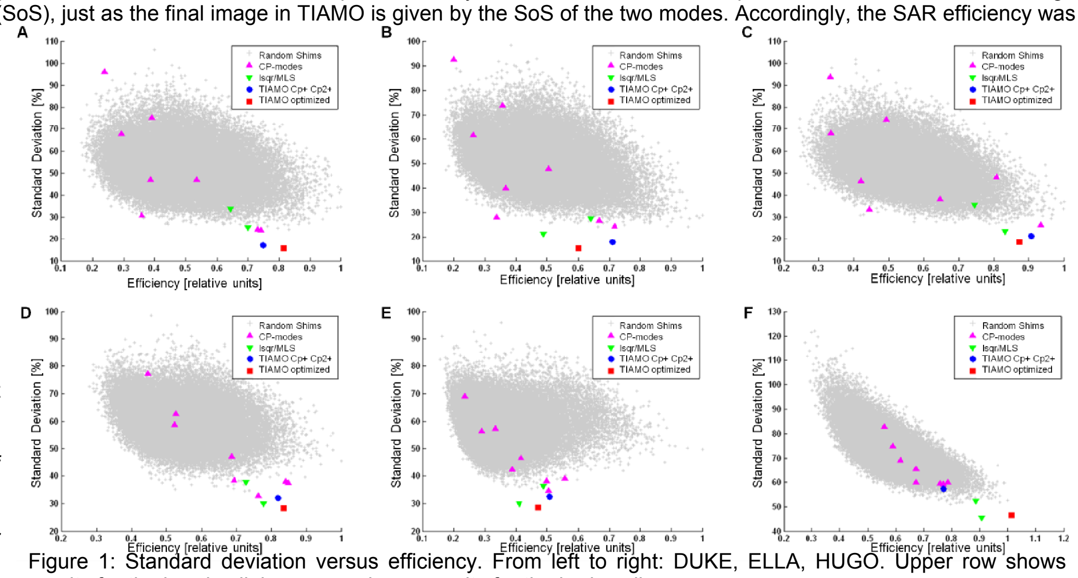

Figure 1: Standard deviation versus efficiency. From left to right: DUKE, ELLA, HUGO. Upper row shows results for the head coil, lower row shows results for the body coil.

Results and Discussion: Figure 1 depicts the results for the simulations as a scatter plot. The efficiency is normalized to the maximum of the random RF shims in each plot. The ideal case would be found in the lower right corner of each plot, representing a high efficiency and a low standard deviation of B_1^+ (high homogeneity). TIAMO clearly provides the lowest standard deviation while achieving a good efficiency at the same time.
Figure 2 shows the images of the checkerboard phantom for all used sequences.
The table shows the calculated standard deviations of the contrast.

	T1 FLASH	T2* FLASH	PD TSE	T2 TSE	T1 SE
CP^+, Air	3.1	11.7	3.5	7.0	2.8
CP^+, Water	38.5	36.4	88.8	77.0	120.3
CP^{2+}, Water	16.7	32.5	75.2	48.5	86.4
TIAMO	9.3	9.2	6.8	6.7	32.4

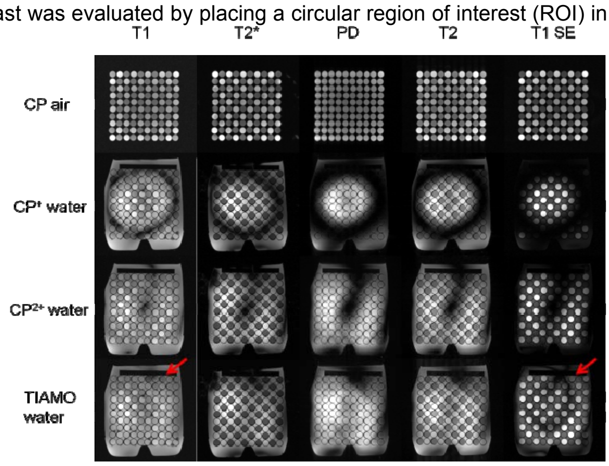

Figure 2: MR images of the checkerboard phantom acquired with the 8-channel head coil. Arrows point out contrast errors in the TIAMO images

From the results it can be seen that the T1-weighted sequences suffer from the inhomogeneities of the TIAMO modes.

Conclusion: As long as sequences are considered which do not necessarily demand a temporally homogeneous excitation to achieve the desired contrast throughout the image (e.g. T1 saturation), TIAMO is superior in B_1^+ homogeneity compared to conventional RF shimming while being highly SAR efficient. Therefore, TIAMO can enable almost homogeneous high-field imaging throughout the entire field of view.

(1) Collins et al., MRM 54, 2005; (2) Katscher et al., MRM 49, 2003, (3) Orzada et al., MRM 64, 2010