Hybrids of Static and Dynamic RF Shimming for Body Imaging at 7T

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Target audience: RF engineers and MR physicists.

Purpose: Body imaging at high field strength is hampered by B_1^+ inhomogeneities. To overcome this problem, static or dynamic RF shimming can be used. While dynamic RF shimming offers higher degrees of freedom, it also places much higher demands on the hardware, since full amplitude and phase modulation of the waveforms has to be realized for each individual transmit channel. Thus, current dynamic shimming systems are often limited to a rather low number of channels, e.g. only 8. However, the current trend is toward massively parallel transmit arrays with 32 channels or higher. To allow utilization of such transmit arrays without the need for expensive RF system upgrades, we propose to combine n subsets of m transmit elements to form adaptive elements that are excited by n fully modulated Tx channels. The mapping of the (n x m) individual Tx elements to the n adaptive elements and the amplitude and phase weightings (static RF shimming) of the elements within an adaptive element are variable and are determined based on the current imaging parameters, e.g. FOV. In this work, a method to optimize the amplitude and phase relationships of the elements linked together is proposed and the performance of this hybrid shimming strategy is investigated based on simulated B_1^+ maps.

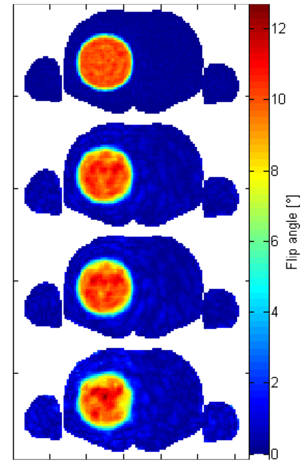

Fig 1: Excitation pattern for a circular target and an 8-channel coil. From top to bottom: all 8 channels, 8 channels combined in pairs with optimized amplitudes/ phases, only the 4 out of 8 elements that give the smallest flip angle error, and excitation with the mode

Methods: The calculation of dynamic shimming pulses is a linear least square problem $\min\|Ax - d\|$ with system matrix A, shim vector x, and target vector d. Combining several elements to one channel turns the system matrix into a function $A(\alpha)$, where α describes the amplitude and phase relationships of the elements. To solve the resulting optimization problem[1], first the parameters α are optimized by minimizing the projection of the target d into the null space of $A(\alpha)$. In [1] the calculation of the projection operator and its gradient is described. For the optimization, the Hessian of the projection operator was additionally derived and the MATLAB function "fminunc" with user-provided gradient and Hessian was used. To evaluate the performance of the hybrid shimming strategy, three situations were investigated based on simulated B_1^+ maps (CST Studio Suite, CST, Darmstadt, Germany; loaded with the Duke model[2]; liver-kidney region): **1)** an 8-channel tight-fitting body array, where the elements were combined in pairs; **2)** a 16-channel body array where the elements were combined to 8 pairs; and **3)** to 4 groups of 4 elements each. For the first scenario, all possible combinations were considered. As the number of possible combinations increases rapidly, only 100 randomly generated combinations were studied for the 16-channel coil. As a test scenario, the excitation of a circle with smoothed edges in the right half of the body with a 3.3 ms variable density spiral k-space trajectory was studied for various static RF shims within the adaptive elements: **a)** shims optimized using the method described above; **b)** 100 random shims per combination; **c)** connecting n elements directly to the fully modulated Tx channels and neglecting the remaining n·(m-1) elements of the array. For comparison, we also computed **d)** the flip angle error of the mode approach[3], where the n lowest modes (Cp^+, Cp^{2+}, …) defined by a phase increment of n x (360°/# of elements) are connected to the Tx channels.

Results/Discussion: The results are summarized in Table 1. Figure 1 shows an example of the generated excitation patterns. The pTx excitation with the shim for the adaptive elements optimized using the proposed method clearly outperforms the other shim strategies as well as the mode approach. The performance of the mode approach is not better than that of a random shim. This can be explained by the fact that the modes are not clearly defined at 7T if the coil is loaded with a heterogeneous body model. The situation might change if the modes were defined as optimized linear combinations based on the effective excitation created. Calculating the optimized shim needs about 4 minutes/20 minutes for the 8-element/16-element coil on a computer with dual Intel Xeon X5650 CPU. Without the analytical Hessian, the calculation requires 20 minutes/5 hours. For the 8-channel coil, optimization without the analytical gradient takes 50 minutes and directly optimizing the flip angle error instead of the projection takes 1 hour.

pTx array			**flip angle error in %: mean (std) [min, max]**			
	m	**n**	**a)** optimized	**b)** random	**c)** n coils	**d)** modes
1)	2	4	19.7 (0.9) [18.0, 22.1]	27 (2) [22, 42]	26 (3) [20, 37]	27.0
2)	2	8	6.8 (0.2) [6.5, 7.2]	8.2(0.3) [7.3, 9,3]	8.1 (0.3) [7.5, 8.7]	8.1
3)	4	4	19.3 (0.5) [18.1, 20.6]	28 (1) [23, 43]	28 (2) [25, 32]	29

Tab. 1: Flip angle error for a circular target and various static RF shims.

Conclusion: Hybrid shimming increases the performance of parallel transmit systems without increasing the number of independent, fully modulated Tx channels. The proposed method is suitable to determine optimal RF shims for a subset of coil elements constituting the adaptive elements that are excited by the available Tx channels, and the method is more beneficial than the mode approach[3] at 7 Tesla.

References: [1] Golub, Pereyra (1973). SIAM J. Numer. Anal. 10:413. [2] Christ et al. (2010). Phys. Med. Biol. 55(2):N23-38. [3] Vester et al. (2006). Proc. ISMRM 14:2024.

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