3D RF Shimming using Multi-Frequency Excitation

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Introduction RF shimming is a well-known technique, in which amplitudes and phases transmitted via a multi-element RF coil array are optimized to obtain a homogeneous B1 profile, i.e., to compensate wave propagation effects at field strengths of 3T or above (see, e.g., [1,2]). Usually, RF shimming is applied to 2D slice imaging. For 3D volume imaging, 3D RF shimming might be required due to 3D variations of the wave propagation effects. This 3D RF shimming can be performed via a *z*-segmented transmit array or 3D spatially selected RF pulses. This study investigates a more practical approach of 3D RF shimming using frequency encoding during RF transmission. Here, the elements of a transmit array are driven with different frequencies to excite different slabs in the excitation volume with individually optimized amplitudes and phases. This technique, called "Multi-Frequency Excitation" (MULTIFEX), might also be used for saturation and refocusing pulses as well as for 3D RF encoding [3] and 3D local excitation [4]. The study demonstrates the feasibility of MULTIFEX in experiments using a whole-body, eight-channel Tx/Rx system at 3T [5,6].

Theory The 3D imaging volume is divided into M slabs. Each slab is excited by a group of N_m elements (m=1…M) of the N elements of the array ($N=\Sigma_{m\leq M} N_m$). The elements of group m are driven with the frequency f_m given by Eq. (1) assuming a "slab selection" gradient G_z and an off-center z_m of slab m. After the determination of the 3D Tx sensitivity distributions $\underline{T}_n$, not only the amplitudes A_{nm} and phases φ_{nm} of the array elements (i.e., the complex weighting factors $\underline{A}=A_{nm}\exp(i\varphi_n)$) within each group can be optimized; also the design of the groups can be optimized, i.e., which coils are grouped, to which slabs the groups belong, and the thickness of each slab. The optimization problem can be described as the minimization of the error function δ (Eq. (2)). Here, $\underline{C}(\mathbf{r}_k)$ denotes a spatially constant function to achieve a spatially constant B1 distribution, and k denotes the spatial index within the corresponding slab. To simplify the optimization problem, the grouping of the array elements can be carried out "by hand". Then, RF shimming can be performed within each group as described in literature [1,2].

$$f_m = \gamma G_z z_m \tag{1}$$

$$\delta = \sum_{m\leq M} \sum_{k\leq K} \left(\sum_{n\leq N_m} \underline{A}_{nm} \underline{T}_n(\mathbf{r}_k) - \underline{C}(\mathbf{r}_k) \right) \tag{2}$$

Methods A 3T MR system (Philips Achieva, Philips Medical System, Best, The Netherlands) equipped with an 8-element Tx/Rx body coil and the corresponding RF channels [5,6] was used. The 3D sensitivities $T_n(\mathbf{r})$ of a cylindrical water bottle were acquired using "Actual Flip angle Imaging" [7]. To demonstrate the feasibility of MULTIFEX, M=2 groups were formed from alternating elements, i.e., $N_1=N_2=4$ to excite two different slabs (thickness 5 cm) with different settings of $\underline{A}_{nm}$ (Fig. 1). A 3D FFE sequence was used for acquisition (TR/TE=32.2/2.1ms, α=30°, voxel size 3.1×3.1×10mm^3).

Results / Discussion Fig. 2 shows two slices (upper / lower row) from the two slabs for different settings of $\underline{A}_{nm}$ (different columns). Column (a) shows shimming results for individually optimized $\underline{A}_{nm}$. Column (b) shows the results using the $\underline{A}_{nm}$ optimized for slab 1 applied to slab 2, and vice versa. The homogeneity is much lower than in column (a), underlining the need for slab-dependent optimization of the $\underline{A}_{nm}$. Column (c) shows shimming results from examining the two slabs with all eight coils in two separate experiments. The use of eight instead four coils (column (c) vs. column (a)) improves the homogeneity only slightly. Additionally, the corresponding quadrature mode is shown in column (d). The numbers in the upper right corners of the images indicate the corresponding standard deviations.

Conclusion The presented multi-frequency excitation is able to achieve 3D RF shimming using frequency encoded slabs. However, one has to keep in mind that splitting the Tx array into groups, the shimming potential of each group is lower than the shimming potential using all array elements. In practice, a suitable compromise between number of slabs (i.e., spatial resolution) and RF shimming potential has to be determined. Another compromise will be needed between SAR and shimming potential, since each Tx element might encode for multiple slabs simultaneously, as presented for single transmit coils [8]. This concept increases the degrees of freedom per slab, and thus, improves the shimming results, though at the expense of an increased SAR.

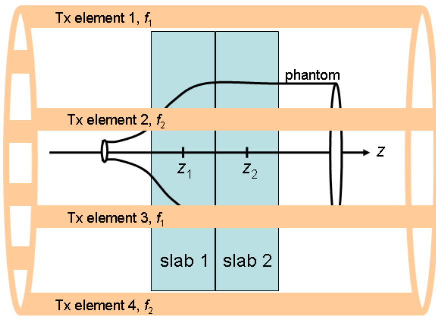

Fig. 1: Sketch of applied multi-frequency excitation for two slabs (blue). The odd numbered elements encode slab 1, the even numbered elements slab 2. The sketch refers to the used 8-element whole body Tx/Rx coil array with cylindrically arranged elements (orange).

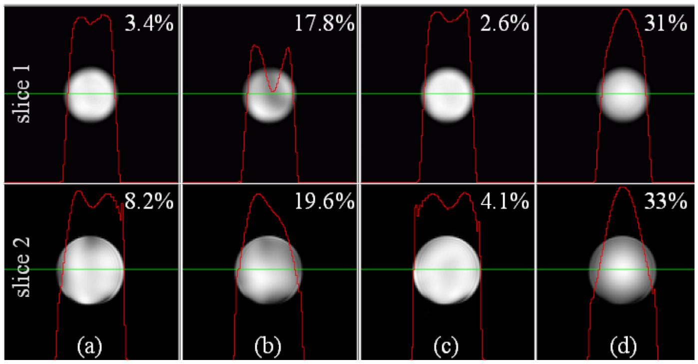

Fig. 2: Two slices (upper / lower row) from the two slabs for different settings of $\underline{A}_{nm}$ (different columns). (a) Shimming results for individually optimized $\underline{A}_{nm}$. (b) Results using the $\underline{A}_{nm}$ optimized for slab 1 applied to slab 2, and vice versa. (c) Shimming results for individually optimized $\underline{A}_{nm}$ using all eight coils. (d) Results from quadrature mode. The red lines show the profiles along the green lines.

References [1] Ibrahim TS et al., MRI 18 (2000) 733 [2] Seifert F et al., ISMRM 10 (2002) 162 [3] Hoult DI et al., JMRI 12 (2000) 46 [4] Ibrahim TS, IEEE Trans Med Imag 25 (2006) 1341 [5] Graesslin I et al., ISMRM 14 (2006) 129 [6] Vernickel P et al., MRM 58 (2007) 381 [7] Yarnykh VL, MRM 57 (2007) 192 [8] Müller S, MRM 6 (1988) 364