A matrix approach for mapping array transmit fields in under a minute

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Introduction: The use of coil arrays for RF transmission has opened new ways of tailoring RF excitation fields (RF-shimming [1]) and accelerating tailored spatial excitation (Transmit SENSE [2]) in order to mitigate RF inhomogeneity in ultra-high-field MRI. These increasingly powerful methods rely on crucial calibration information that is not easy to obtain, usually in the form of quantitative maps of the complex transmit B1 amplitudes. Quantitative B_1 mapping techniques mostly require the use of RF pulses that produce a set of high flip-angle pulses (>60°) throughout the sample in order to work accurately. This is often hard to achieve at very high field due to power and in-vivo SAR limits, resulting in long scan times and limited B_1 sensitivity. To address this problem we propose a novel array mapping technique that uses not individual coil profiles but a tailored set of basis array modes for multiple flip-angle measurements. Leading to enhanced sensitivity this approach enables B_1 mapping in substantially reduced scan times down to some tens of seconds for an entire array, observing in-vivo SAR limits at 7T.

Method: Applying individual currents (stacked in a vector $\mathbf{I}_c$) to each element c of a transmit array produces an excitation mode, which is a commonly used fact e.g. in RF shimming. Concatenation of several current vectors of such modes M leads to a matrix $\mathbf{I}_{M,c}$. Since the B_1 produced is linearly dependent on the currents applied, $\mathbf{I}_{M,c}$ describes the linear superposition of B_1 fields of modes. In order to characterize the excitations the array is able to produce, one can choose a significantly better set of linearly independent modes, than single coil excitation. The choice of the modes M is driven by two objectives: First, the resulting excitation must be as strong as possible throughout the sample in order to achieve the needed large flip angles for the mapping sequence within SAR constraints given. Second, the inversion of the matrix $\mathbf{I}_{M,c}$ must be numerically well conditioned in order not to enhance mapping errors and noise.

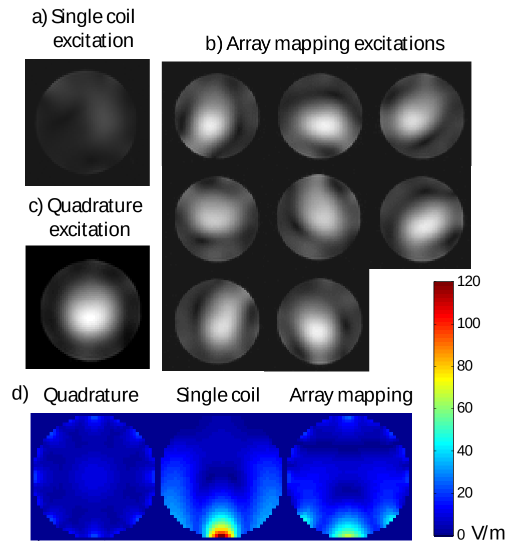


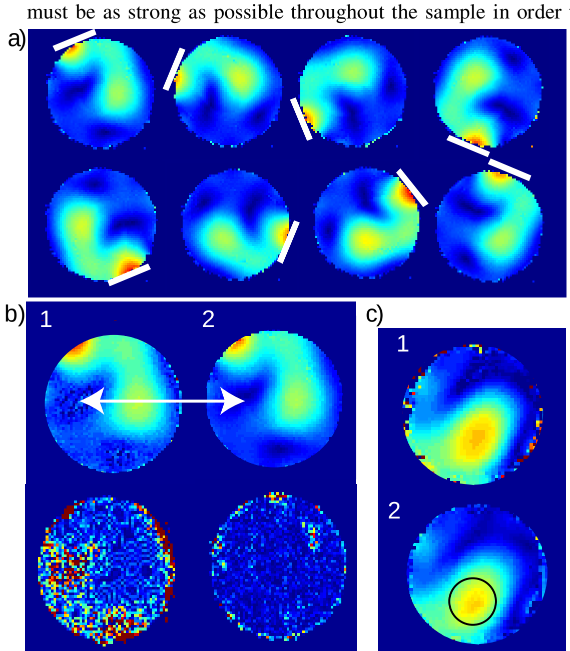
Figure 1: a) –c) FFE images with equal color scaling acquired using single coil excitation, modes M for novel array mapping technique and quadrature drive modes. d) simulated E-fields for the same total power

For circular arrays the common quadrature configuration with a linear angular phase increment is a good starting point for achieving large flip angles throughout the object. To ensure good conditioning of the inverse problem the basis set is then generated by selectively shifting the phase of each single element by 180°. For this approach the current distribution used for excitation can be described as

$$\mathbf{I}_{M,c} = \begin{cases} -1 & \text{if } M = c \\ 1 & \text{if } M \neq c \end{cases} \rightarrow \mathbf{B}_{1,c}(\bar{r}) = \sum_{M} \mathbf{I}^{+}_{M,c}\mathbf{B}_{1,M}(\bar{r}); \quad \text{where + denotes the pseudo-inverse} \quad (1)$$

This excitation and inversion scheme can be readily used in conjunction with existing B_1 mapping techniques. In the present work it was combined with the slice-selective technique described in Ref. [4], which relies on multiple-flip-angle measurements and nonlinear fitting of excitation, relaxation and off-resonance effects. The combined approach was tested using an 8-channel microstrip array coil [3] in conjunction with an RF-shim-capable feed system. For comparison, the same mapping technique was used with conventional single-element excitation. The mapping scans were performed with a spin-warp gradient echo technique (following Ref. [4]) as well as with a much faster EPI readout, exploiting the greater sensitivity of the new excitation scheme. All measurements were performed in a spherical saline phantom 15 cm in diameter, using a 7T Philips Achieva system..

Results: Figures 1 a) to c) show the received signal using the different drive modes with the same power applied to each channel in a low flip-angle gradient echo sequence plotted with the same color scaling. It can be seen that the signal yield from single coil excitation is significantly lower while quadrature and all array mapping excitation modes used show much higher and more homogenous excitation. Fig. 1 d) shows FDTD simulated E-field [5] distributions of the different drive modes with the same total power applied to the entire array. It can be seen that driving a single coil has a 6 times higher maximum E-field than quadrature drive. The proposed array modes for mapping produce only 3 times higher maximum E-field have a significant SAR advantage compared to single coil excitation. Figure 2 a) shows the B_1 maps measured using the novel method. The position of the strip-line element virtually used for excitation is marked as a white rectangle. Fig. 2 b) shows the comparison of using single coil excitation (left) and the proposed method (right) applying the same method and maximum power per element. The corresponding noise maps below show that the quality is dramatically increased in regions of low B_1 field and also obvious systematic errors are reduced as marked by the arrow. The measurement takes 4 min per mode using spin warp readout resulting in a total measurement time of 32 minutes. However, using a fast EPI readout, the measurement time was reduced to a total of 40 s and due to the high signal yield of the method the results are not compromised as Fig. 2 d) shows. The accuracy of the fast readout we have validated by planning a RF-shim and comparing to the measured excitation (Fig. 1c).



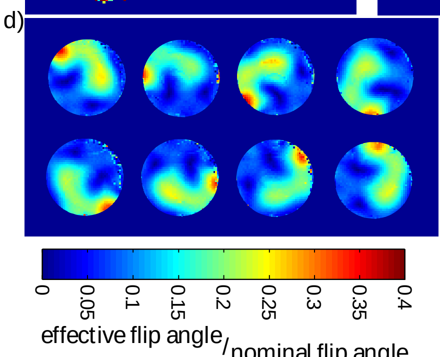


Figure 2: a) Resulting B_1 maps for all 8 elements of the coil using the novel approach with spin-warp readout. b) comparison of B_1 maps acquired by single coil excitation (1) and by the novel approach (2), the noise appearing in both methods is plotted below. c) comparison of RF shim achieved (1) and planned from acquired B_1 maps using fast readout (2). d) B_1 maps acquired in 40 s using fast readout.

Conclusion: We have demonstrated that B_1 maps of an 8-channel array can be acquired within 40 s without significant increase of SAR nor loss in accuracy. The method allowed to plan an RF-shim experiment with high reliability and within an amount of time which is practical for in-vivo experiments.

References: [1] D. I. Hoult, JMRI 12, 2000, [2] U. Katscher et al. MRM 49, 2003 [3] D. Brunner et al. Proc. ISMRM 15 (2007) p.448, [4] D. Brunner et al. Proc.ISMRM 15 (2007) p.353, [5] J. Fröhlich et al. International Microwave Symposium Digest, Honolulu, Hawaii, USA, p. 2217-2220