Static and Dynamic RF-shimming in the framework of Transmit SENSE

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Introduction: MRI at main fields of 3 T and above might be hampered by B1 field inhomogeneities caused by, e.g., dielectric resonances. One possible method to compensate for these inhomogeneities is given by adjusting amplitude and phase of the driving currents of the different elements of an RF transmit array, e.g., different rods of a TEM resonator [1]. An alternative to this "static" RF shimming might be "dynamic" RF shimming using spatially selective RF pulses [2], designed to compensate the observed signal modulations. Enabling different elements of the transmit array to excite different spatial patterns, spatially selective RF pulses could be shortened via parallel transmission, and thus, might become feasible even in the case of 3D applications [3,4]. This study first shows, that "static " RF shimming can be deduced as asymptotic limit of "dynamic" RF shimming. Then, it compares the performance of "static" and "dynamic" RF shimming using simulations based on an 8-channel cylindrical head coil and Transmit SENSE [3] for B_0 = 3 T.

Theory: The central equation of Transmit SENSE is [3]

$$p_{des}(\mathbf{k}_u) = \sum_{i \le N} \sum_{v \le M} s_i(\mathbf{k}_u - \mathbf{k}_v)\, p_i(\mathbf{k}_v) \; . \qquad (1)$$

Here, N is the number of rods, M is number of pixels of the **k**-space grid, p_{des} is the desired excitation pattern in **k**-space, and s_i is the sensitivity of rod i in **k**-space. The Fourier transformed spatial pattern to be excited by rod i is denoted with p_i, which is proportional to the B_1 waveform to be transmitted by this rod [2]. The trajectory $\mathbf{k}_v$ in the excitation **k**-space is reduced by a reduction factor R, and $\mathbf{k}_u$ corresponds to the full-length trajectory. Thus, the solution of Eq. (1) yields shortened spatially selective RF pulses to be used for "dynamic" RF shimming. Moreover, Eq. (1) can be used for "static" RF shimming to derive the optimum complex rod weighting factors A_i (i.e. the amplitudes and phases) for the otherwise identical RF pulses of the N rods. To this goal, Eq. (1) is rewritten for a reduction factor R, which equals the number of pixels M. Then, the $p_i(\mathbf{k}_v)$ contain only one data point $p_i(\mathbf{k}_v = 0)$, which corresponds to the weighting factors A_i of "static" RF shimming. The convolution in Eq. (1) reduces to a multiplication

$$p_{des}(\mathbf{k}_u) = \sum_{i \le N} s_i(\mathbf{k}_u)\, p_i(\mathbf{k}_v = 0) = \sum_{i \le N} s_i(\mathbf{k}_u) A_i \; . \qquad (2)$$

Thus, Eq. (2) can be taken as matrix/vector multiplication, and the wanted A_i can be calculated by a (pseudo)inversion in the Fourier or in the image domain, yielding

$$\underline{A} = \underline{\underline{S}}^{+} \underline{P}_{des} \qquad (3)$$

with $\underline{A}$ containing the factors A_i, $\underline{P}_{des}$ the discretized spatial excitation pattern in the image domain, and $\underline{\underline{S}}^{+}$ is the pseudoinverse of the matrix $\underline{\underline{S}}$, which in column i contains the M pixels of the spatial sensitivity distribution of rod i ($i \le N$). This method of deriving $\underline{A}$ can be applied independently of the number of available rods N. Since usually $N << M$, Eq. (2) is usually a strongly overdetermined set of equations, potentially requiring regularized inversion [5].

Methods: A transmit TEM resonator array of up to N = 32 equidistant, independent stripes is arranged in a cylindrical RF screen (diameter = 30 cm, length = 30 cm, see Fig. 1). The stripes are assumed to be fully decoupled. As a head model, a sphere is placed in the coil with diameter 0.16 m, permittivity ε_r = 81, and conductivity σ = 0.5 S/m. In the framework of the software package FEKO [6], the sensitivities of these stripes are calculated in the central plane perpendicular to B_0. Then, this framework is used to simulate experiments performing "static" and "dynamic" RF shimming. For the "dynamic" RF-shimming, independent B_1 waveforms are derived for the different stripes using Eq. (1), assuming a Cartesian trajectory in the excitation **k**-space. The desired excitation pattern is defined as constant within the field of excitation (FOX) on a 32×32 grid, i.e. the simultaneous transmission of the B_1 waveforms should yield a homogeneous transverse magnetization despite of dielectric resonances and the inhomogeneous sensitivities of the individual stripes. Simulations are performed for cases $2 < R < 32$ and $1 < N < 32$. On the other hand, the weighting factors $\underline{A}$ are determined via Eq. (3) for "static" RF shimming. Finally, the homogeneity of the spatial patterns excited in these simulated experiments are calculated as standard deviation within the ROI, i.e. the spherical head model.

Results and Discussion: The result for the "static" RF shimming and N = 8 stripes is shown on Fig. 2. The homogeneity of the resulting transverse magnetization is 5.2%. The result for "dynamic" RF shimming using N = 8 stripes and a reduction factor R = 2 is shown on Fig. 3. The homogeneity is 0.003%. Fig. 4 shows the homogeneity for "dynamic" RF shimming for different values of R and N. For all cases $R < N$, the resulting homogeneity is better than 1%. Increasing R beyond the usual limit $R = N$ (potentially up to $R = M$) decreases the resulting homogeneity. In a real system featuring full time-dependent control over different RF channels, a reduction factor might be chosen yielding a homogeneity of the order of the SNR expected in the final image.

Conclusion: "Dynamic" RF shimming compensating B1 field inhomogeneities at high main fields with spatially selective RF pulses seems to yield significantly better performance than "static" RF shimming, where amplitude and phase of the RF transmit array is adjusted. The spatially selective pulses can be shortened using parallel transmission. The classic "static" RF shimming can be taken as the asymptotic limit of "dynamic" RF shimming using a reduction factor equal the number of pixels in the excitation **k**-space.

References: [1] Ibrahim TS et al., MRI 18 (2000) 733-742 [2] Pauly J et al., JMR 81 (1989) 43-56 [3] Katscher U et al., MRM 49 (2003) 144-150 [4] Zhu Y, MRM 51 (2004) 775-784 [5] Tarantola A, *"Inverse Problem Theory"*, Elsevier Amsterdam, 1987 [6] Jakobus U, IEEE Antennas & Prop. Conf. 436 (1997) 182-5

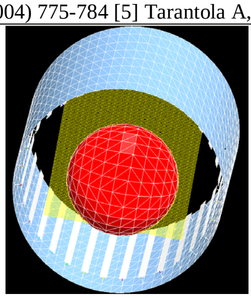

Fig. 1: Sketch of the simulation scenario. A transmit array of up to 32 independent stripes (white) is arranged in a cylindrical RF screen (blue), loaded with a spherical head model (red). Furthermore, the central plane (yellow) is indicated as field of excitation (FOX).

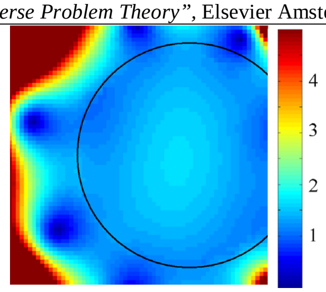

Fig. 2: Normalized transverse magnetization obtained with "static" RF shimming adjusting amplitude and phase of the otherwise identical B1 waveforms for N = 8 stripes. The achieved homogeneity, i.e. the standard deviation within the indicated ROI is 5.2%.

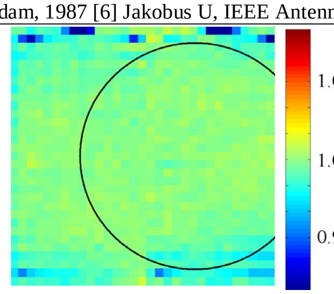

Fig. 3: Normalized transverse magnetization obtained with "dynamic" RF shimming, i.e. spatially selective pulses for N = 8 stripes applying a time reduction factor of R = 2 using Transmit SENSE. The achieved homogeneity, i.e. the standard deviation within the indicated ROI is 0.003%.

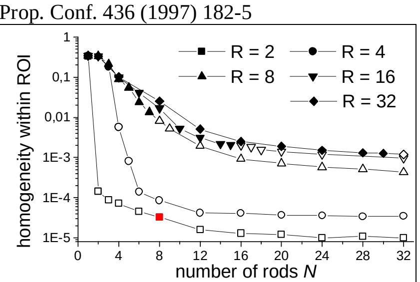

Fig. 4: Homogeneity for "dynamic" RF shimming using spatially selective pulses with a pulse duration reduced via Transmit SENSE. The homogeneity is better than 1% for all cases $R < N$. The red square $R = 2$ / $N = 8$ corresponds to the result shown in Fig. 3.