Maximum Efficiency RF Shimming

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Introduction: Radiofrequency (RF) shimming (1,2) using multiple transmit channels can reduce B_1^+ field inhomogeneities at high magnetic field strengths. Depending on the particular application, different RF shimming methods have been proposed, for example targeting homogeneity in B_1^+ magnitude only (3), or facilitating the adiabatic condition of the RF pulse (4,5). In the present study, we describe a maximum efficiency RF shimming approach, in which RF shimming weights are calculated to maximize B_1^+ strength while minimizing RF power deposition into the subject (global SAR). The advantage of the proposed RF shimming method in terms of reduced power deposition is demonstrated using adiabatic and sinc RF pulses.

$$[1]\ \mathbf{B}_1^+ = \mathbf{Cw} \text{ where } \mathbf{C}_{mn} = \mathbf{b}^{(n)}(\mathbf{r}_m)$$

$$[2]\ \left\|\mathbf{B}_1^+\right\|^2 = \mathbf{w}^H \mathbf{\Gamma w} \text{ where } \mathbf{\Gamma} = M^{-1}\mathbf{C}^H\mathbf{C}$$

$$[3]\ P \cong \int_v \frac{\sigma(\mathbf{r})}{2}\left\|\mathbf{E}(\mathbf{r})\right\|_2^2 dv = \mathbf{w}^H \mathbf{\Phi w}$$

$$\text{where } \Phi_{i,j} = \frac{1}{2}\int_v \sigma(\mathbf{r})\mathbf{e}^{(i)}(\mathbf{r})^* \cdot \mathbf{e}^{(j)}(\mathbf{r})dv$$

$$[4]\ \eta = \frac{\mathbf{w}^H \mathbf{\Gamma w}}{\mathbf{w}^H \mathbf{\Phi w}}$$

Methods: The calculation of the complex-valued RF shimming weights for maximum transmit efficiency was based on a transmit efficiency metric defined as B_1^+ magnitude squared per unit dissipated power, following earlier work by Zhu et al. (6). After selecting the region of interest (ROI) over the area where maximum efficiency is desired, the values of B_1^+ at all M spatial locations included in the ROI are combined in matrix form as in Eq. [1], where **w** is an N x 1 vector containing the RF shimming weights for each transmit coil and **C** is an M x N matrix that contains the coils' B_1^+. The average B_1^+ squared in the ROI can be expressed as in Eq. [2], where $\mathbf{\Gamma}$ is the N x N positive-definite Hermitian B_1^+ correlation matrix, and ^{H} denotes the conjugate transpose. The elements of the matrix **C** can be measured with any B_1^+ mapping technique, allowing the evaluation of $\mathbf{\Gamma}$. The total RF power deposited into the object by the transmit array at time t can be calculated by integrating the electric fields over the volume of the object, as shown in Eq. [3], where σ is the electrical conductivity, and $\mathbf{\Phi}$ defines the N x N positive-definite Hermitian RF power correlation matrix. A recent study proposed a rapid *in vivo* calibration scheme to measure the subject specific power correlation matrix (7). Once $\mathbf{\Phi}$ is known, RF power dissipation can be determined for any possible set of RF shimming weights **w,** allowing accurate prediction of global SAR for any RF pulse.

Using the derived expressions for the average B_1^+ squared and the total RF power deposition, the transmit efficiency metric (η) can be defined as in Eq. [4] (6), independent of the overall scaling of RF shimming weights **w**. The weights that maximize η can be found using various numerical optimization algorithms. However, the optimization can be treated as a generalized eigenvalue problem, which does not require a nonlinear search and guarantees finding the global optimum. From the solution, which, for example, can be obtained with the Matlab (MathWorks, Inc.) function eig($\mathbf{\Gamma}$,$\mathbf{\Phi}$), the largest eigenvalue and its corresponding eigenvector represent the maximum transmit efficiency and the maximum efficiency RF shimming weights, **w**, respectively.

We evaluated the benefits of maximum efficiency RF shimming in 7T hip articular cartilage imaging, a deep tissue application requiring high resolution. Experiments were performed on healthy volunteers using a whole body 7 T scanner (Magnetom, Siemens Medical Solutions, Erlangen, Germany) equipped with an eight-channel parallel transmit system (1kW peak power per transmit channel). A 10-channel transmit/receive modular array (8) consisting of five loop/stripline modules was used for RF excitation and reception. The four loops closest to the targeted ROI were used for RF transmission and reception, while the remaining 6 elements (1 loop and 5 striplines) were used for RF reception only. Conservative in vivo RF power limits that restricted power to 16 times less than that required for a single loop to locally heat a meat phantom at a rate of 1°C per 10 minutes were applied in all acquisitions.

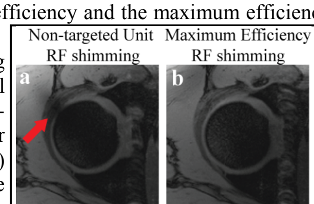

Figure 1: Axial GRE images of volunteer 1 at 7 T, acquired with non-targeted unit RF shimming (a) and with maximum efficiency RF shimming (b)

Individual transmit channel B_1^+ calibration was performed following the method described in Ref. (4). Calculated maximum efficiency RF shimming and non-targeted unit RF shimming weights (unit amplitude and zero phase in all transmit channels) were used to acquire axial GRE images in the hip joint with the following parameters: acquisition matrix = 512 x 512, spatial resolution 0.7 x 0.7 x 2 mm^3, TE/TR = 4.73/400 ms, FOV = 360 x 360 mm^2, bandwidth (BW) = 300 Hz / pixel, and acquisition time 210 seconds. In order to compare the power efficiency, forward and reflected power readings were obtained using power sensors during GRE image acquisition.

Although the proposed RF shimming method does not aim inherently at increasing B_1^+ homogeneity, it could be used together with special RF pulses, such as adiabatic pulses, which are known to improve flip angle uniformity. A drawback of adiabatic pulses is the high RF power deposition resulting to satisfy the adiabatic condition at every voxel within the ROI. Since maximum efficiency RF shimming aims to maximize the B_1^+ field while minimizing power deposition, adiabatic pulses could benefit from our proposed method. We tested this hypothesis both in simulation and in experiments with an adiabatic half passage (AHP) RF pulse (9) of length 10.24 ms. For both the maximum efficiency and the non-targeted unit shimming, the adiabatic condition was determined at the location within the ROI with the weakest B_1^+, by calculating the frequency response of the AHP RF pulse over a range of transmit voltages using Bloch simulations. The adiabatic condition at this position was satisfied when the z-component of magnetization at zero frequency was approximately zero and not affected by further transmit voltage increase.

Results: Axial GRE images acquired using non-targeted unit and maximum efficiency RF shimming (volunteer 1) are shown in Figure 1. Non-targeted unit RF shimming resulted in high B_1^+ inhomogeneity in the hip region and a local signal drop (red arrow in Fig 1a). Targeting maximum efficiency in an ROI covering the left hip articular cartilage resulted in improved homogeneity over the hip region (Fig. 1b) and in ~2.4 times increase in transmit efficiency. Measured net average RF power deposition in the volunteer was 155 W with non-targeted unit RF shimming and 58.8 W with maximum efficiency RF shimming. Similar average flip angles in the ROI (26.6° ± 10.1° / 23.3° ± 9.77° non-targeted unit / maximum efficiency RF shimming) were obtained with ~2.6 times lower net average power deposition using the proposed RF shimming method.

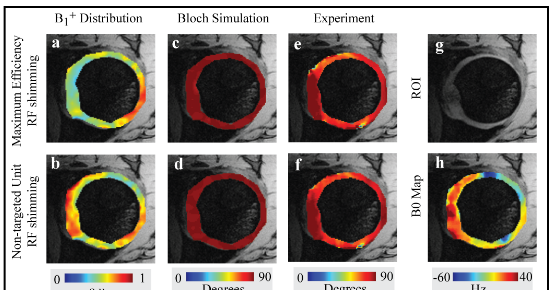

Figure 2: Adiabatic half passage (AHP) RF pulse results

Using maximum efficiency RF shimming and non-targeted unit RF shimming weights, we assessed the power deposition of an AHP RF pulse for volunteer 2. Figures 2a and 2b show the B_1^+ distribution in the ROI using both sets of RF shim weights. The voltage required to meet the adiabatic condition at points inside the ROI with the weakest B_1^+ distribution was 140 V for maximum efficiency shimming and 144 V for non-targeted unit shimming. Both methods resulted in 2.31 µT peak B_1^+ field in the weakest B_1^+ location. Bloch simulations of AHP RF pulses with the specified voltages resulted in a mean of 1% ± 3% z-magnetization, which corresponds to an average flip angle of 89.42° ± 1.72°. Experimentally measured flip angle maps show maximum efficiency RF shimming resulted in a ~50% decrease in the measured maximum net power deposition compared to non-targeted unit shimming, 411 W compared to 789 W (Fig. 2e and 2f). Compared to Bloch simulation results (Fig. 2c and 2d), experimental flip angle maps show some deviation from uniform 90 degree flip angle. This deviation resulted from the main magnetic field inhomogeneities (Fig. 2h), which affected the AHP RF pulse's performance due to its off-resonance response. This was confirmed in additional Bloch simulations that incorporated the off-resonance maps.

Discussion: In this work, we have demonstrated a maximum efficiency RF shimming method that aims at maximizing the flip angle over a defined ROI while minimizing the global RF power deposition. Simulation and *in-vivo* experimental results showed that the proposed RF shimming method allows increases in transmit efficiency. Power measurements for sinc and AHP RF pulses confirmed up to 50% reduction in RF power deposition while maintaining average flip angle distributions in the hip articular cartilage.

References: (1) Hoult D.I. et al. (2000): JMRI 12: 46-67. (2) Ibrahim T.S. et al. (2001): MRI 19: 1339-47. (3) Mao W. et al. (2006): MRM 56: 918-922 (4) Balchandani P. et al. (2011): ISMRM 2907 (5) Setsompop K. et al. (2007): ISMRM 1687. (6) Zhu Y. et al. (2010): ISMRM 1518.(7) Zhu Y. et al. (2011): MRM *in press*. (8) Brown R. et al. (2010): ISMRM: 3807.(9) Garwood M. et al. (2011): JMR 153: 155-177