An Automated Method for Subject Specific Global SAR Prediction in Parallel Transmission

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Introduction: SAR management is a critical issue in multiple coil excitations at ultra-high field strength. However, current parallel transmit SAR monitoring schemes are missing the key capability to track and manage SAR under in-vivo conditions. Existing hardware schemes monitor forward and reflective power in real time, but offer no capacity for prediction of subject specific RF power deposition. Conservative SAR measurement schemes considerably overestimate SAR in multiple coil excitations by assuming electric fields add constructively, without accounting for phase information that may reveal E-field cancellations. Such an approach poses unnecessarily restrictive limits on the applied RF power, which may compromise the performance of parallel transmission. In this study we implemented a method for in-vivo, real time, subject specific prediction of global RF power deposition and validated it in human subjects on an 8-channel 7T parallel transmit MR system. Preliminary phantom results were presented at a recent workshop (1).

Theory: Zhu (2,3) and Lattanzi. et al. (4) derived an expression to calculate global RF power deposition resulting from parallel excitation, once the E-field covariance matrix is known. These authors expressed global RF power deposition in quadratic form:

[1].

$$\varepsilon = [I_1 \quad . \quad I_m]^H \frac{1}{2}\left(\int_v \sigma(r) \begin{bmatrix} e_1(r) \\ . \\ . \\ e_m(r) \end{bmatrix}^* [e_1(r) \quad \dots \quad e_m(r)]\right) dv \begin{bmatrix} I_1 \\ . \\ . \\ I_m \end{bmatrix} = I^H \Phi I$$

where σ is the sample conductivity, e_i is the e-field generated when the i-th coil is driven with unit current, I_i is the complex valued current in the i-th coil, Φ is the E-field covariance matrix, m is the number of channels, and ^{H} represents the Hermitian-Conugate operator.

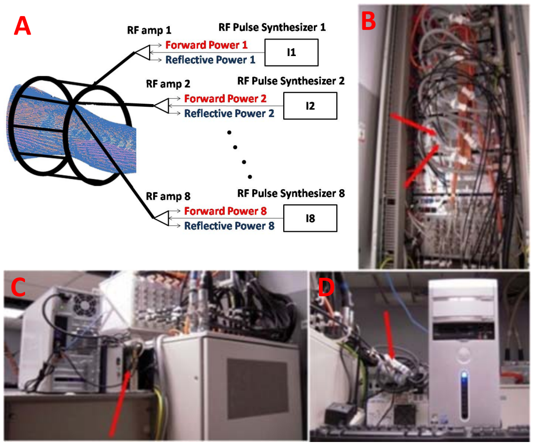

Figure 1. A. Illustration of the setup that was used for the subject specific power calibration and prediction model. B. Directional couplers for forward and reflected power measurement at the RF amplifier outputs. C. RF switchbox used to alternate between the channels. D. Power meter.

Material and Methods: Since the coils' E-fields are generally unknown; in order to predict global RF power deposition in practice using Eq. [1], the entries of Φ were estimated by varying the current weights and measuring the corresponding net power following a method outlined by Zhu (2). To calibrate and test our subject specific global power deposition model, we used a 7T Siemens scanner (Siemens Medical Solutions, Erlangen, Germany) equipped with an 8-channel parallel transmit system. To measure the forward and reflected power, a power sensor (Rhodes & Schwarz NRP-Z11) and RF switch (National Instrument Dual 16x1 MUX) were connected to independent directional couplers at the output of each RF power amplifier. (Figure1A).

To calculate Φ, eight pre-designed 40msec-long staircase-shape (100 steps total) RF pulses (figure 2) were applied to an eight-channel stripline coil loaded with a phantom. At each step of the RF staircase pulse the net power on each channel was calculated by subtracting net reflected power from net forward power. A Matlab algorithm was used to communicate with the power sensor and RF switch to automate the 16 port power measurement. Since the E-field covariance matrix is complex and Hermitian, estimating the entries of Φ involves solving for m^2 real variables, where m is the number of channels. For this reason, the first 64 staircase steps in the pulses were designed to extract the values needed for Φ measurement. The following 36 steps generated random current weights in each coil. This served as a global RF power prediction model validation in which the power predicted by Eq. 1 was compared to the net power measured on the RF couplers. This procedure was repeated in vivo on the left knee of two subjects. To verify that the model was accurate over a range of transmit voltages, a reference voltage of 60 volts was used for subject A and 120 volts for subject B.

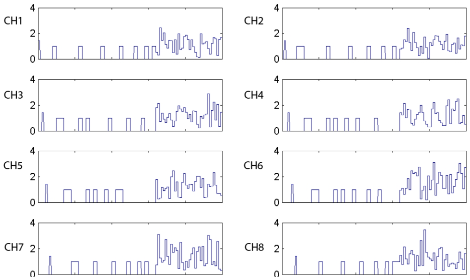

Figure 2. Absolute values of the staircase waveform applied to each Tx channel. The pulse duration was 40ms and the number of steps was 100.

Results and Discussion: Figure 3 shows the predictive capability of our calibration approach for the two in-vivo experiments. The maximum error of prediction was less than 10.6 percent for all 36 measurements on both subjects. Similar power prediction accuracy was observed in both subjects, indicating that the calibration was accurate over a range of transmit voltages; the mean ± standard deviation error between the predicted and measured power was 3.68 ± 4.39% and 2.51 ± 3.83% for the two subjects, respectively. These errors may be due to reported software and hardware variability of ~10%. The entire process (estimation of Φ and RF power prediction) was performed in ~17.5s and could thus be added as a routine power prediction prescan. The process could potentially be shortened by a factor of eight or more by introducing dedicated power meters for each channel reducing (or accessing built-in system power meters), the RF switching time that is the most time-consuming part of the power calibration.

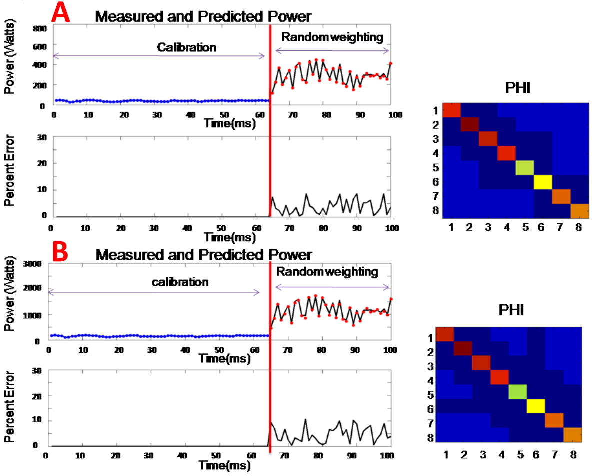

Figure 3. SAR calibration and prediction results for subject A and B. Calibrated (blue), measured (black) and predicted (red) power measurement. On the right we observe the two electric field covariance matrices PHI associated with subjects A and B, showing slightly different off-diagonal weightings. The same staircase pulses were applied to each of the subjects with different voltage. The reference voltages were 60 and 120 for subjects A and subject B, respectively.

Conclusions: In this study, global power deposition was accurately predicted in real time, under in-vivo conditions for an arbitrary set of RF excitation pulses. This was accomplished by playing out a short set of RF pulses and directly measuring the net RF power, then solving the resulting system of equations to derive the values of E-field covariance matrix elements. This automatic method of predicting global RF deposition accounts for constructive and destructive E-field interference and is therefore an improvement over existing schemes which assume a worst-case scenario where E-fields combine constructively, potentially overestimating SAR by a factor equal to the square of the number of transmitter channels. In addition, the proposed method is scalable to any number of transmitter channels and is inexpensive to implement since most manufacturers provide directional couplers with RF amplifiers.

References: 1. Alon L. et al. Automated In Vivo Global SAR prediction and monitoring for Parallel Transmission. ISMRM Parallel Workshop. Oct 09. .2. Zhu Y. In Vivo RF Power and SAR Calibration for Multi-Port RF Transmission. ISMRM 09. 3. Zhu Y. Parallel Excitation with an Array of Transmit Coils. Magn Reson Med 2004; 51:775-784. 4. Lattanzi R. et al. Electrodynamic Constraints on Homogeneity and Radiofrequency Power Deposition in Multiple Coil Excitations. Magn Reson Med 2009; 61:315- 334.