In Vivo RF Power and SAR Calibration for Multi-Port RF Transmission

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Introduction: While a substantially increased degree of freedom inherent of parallel RF transmit facilitates excitation profile control, it meanwhile raises concerns that poorly guided multi-port RF pulse or shimming calculations, or multi-channel hardware failure may inadvertently elevate SAR. One can address the concerns to some extent by monitoring RF power at the ports, where power sensors are implemented to measure individual port forward and reflected power, calculate in real-time net forward power into the subject and stop scan when estimated overall SAR reaches a threshold. To better manage SAR however one must complement the real-time monitoring with a more proactive scheme. In principle, for multi-port RF pulse design one can explicitly minimize SAR by guiding the design with a predictive model that tracks SAR (1). In this work we developed a practical method that is capable of establishing such a model under *in vivo* imaging conditions. The model predicts, for any set of RF pulse sequences or shimming coefficients, the overall SAR of the multi-port operation. Since RF field and power deposition are substantially subject dependent and both crucial to imaging performance, especially in high field MR, power model calibration is going to play an equally important role as B1 calibration is. The two are expected to guide pulse or shimming calculations on a subject-specific basis, and enable effective control of SAR as well as excitation profile. The two also serve as key inputs to analysis that gauge RF pulse / coil performance with g_t factor and ultimate intrinsic SAR (2,3).

Methods and Results: When RF signal gets transmitted (Tx) / detected (Rx), the $B1^+$ / $B1^-$ fields interact with the spin system, forming the basis of MR signal induction / detection. The concomitant E field meanwhile gives rise to RF loss in the object and dictates SAR / noise. Optimizing source configuration and thereby the RF coil currents' magnitude / phase, temporal modulation and spatial distribution is critical to MR imaging performance. To exert control during Tx, an MR scanner in practice uses a designed RF pulse sequence to update the magnitude and phase of a Larmor-frequency sinusoidal pulse every Δt (e.g., Δt=2usec). The control is multiplied in multi-port Tx, or, parallel Tx, which includes B1 shimming as a special case. For any Δt interval, the magnitude-phase pairs specified by multiple RF pulse sequences, expressed with complex scalars $w_p^{(n)}$ (n = port index and p = interval index), define the source configuration.

One important prerequisite to the optimization is the knowledge of $B1^+$ distribution and E field-induced RF loss given a source configuration. For establishing a predictive SAR model that can guide RF pulse sequence or B1 shimming calculations, a quadratic model employing $\mathbf{\Psi}$, an experimentally measured Rx noise covariance matrix, was proposed (4). In practice however the preamplifiers of the Rx chains present to the multiple ports a different set of impedance during Rx than the power amplifiers do during Tx, necessitating non-trivial pre- or post-transform measures. We propose a direct method that, based on a multi-port concept (Fig.1), establishes a predictive SAR model using an appropriate system model together with data from a calibration process.

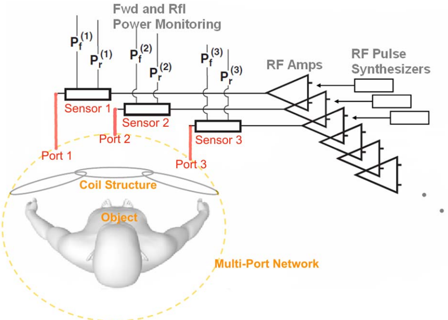

Fig. 1 The imaged object and the RF coil structure can be viewed as a multi-port network that interacts with a plurality of sources through the ports.

An MR system with linearity adequately maintained facilitates RF loss calibration and minimization – it can be shown that over a Δt time interval local as well as overall RF power dissipation in the N-port network can be expressed as quadratic functions in $w^{(1)}, \ldots$ and $w^{(N)}$. In matrix form: local RF power dissipation = $\mathbf{w}^H \mathbf{\Lambda} \mathbf{w}$ and overall RF power dissipation $\xi = \mathbf{w}^H \mathbf{\Phi} \mathbf{w} = \Sigma p_{fwd} - \Sigma p_{rfl}$, where $\mathbf{\Lambda}$ and $\mathbf{\Phi}$ are N-by-N positive definite Hermitian matrices, $\mathbf{w} = [w^{(1)} \ldots w^{(N)}]^T$ is a vector collecting the magnitude-phase pairs the N RF pulse sequences define for the time interval, ^{H} denotes conjugate transpose, Σp_{fwd} = sum of forward power into the ports, and Σp_{rfl} = sum of reflected power from the ports. With power sensors at the ports capable of measuring forward and reflected power, $\mathbf{\Phi}$ can be estimated through experiments. Given a source configuration $\mathbf{w}_q$, $\Sigma p_{fwd} - \Sigma p_{rfl}$, the net power dissipation computed from the sensor readings, is related to $\mathbf{w}_q$ by

$$\Sigma p_{fwd,q} - \Sigma p_{rfl,q} = \mathbf{w}_q^H \mathbf{\Phi} \mathbf{w}_q = \Sigma \, \mathrm{conj}(w_q^{(i)}) w_q^{(j)} \Phi_{ij}, \qquad [1]$$

Eqn.1 is a linear equation with Φ_{ij}, the entries of $\mathbf{\Phi}$, as the unknowns, and product terms, $\mathrm{conj}(w_q^{(i)}) w_q^{(j)}$, as the coefficients. Carrying out calibration experiments with N^2 or more judiciously selected source configurations played out one at a time can probe the RF loss characteristic of the multi-port network, allowing Eqn.1-type linear equations be assembled and all the entries of $\mathbf{\Phi}$ be determined. This process does not involve MR imaging and may be completed in a fraction of a second with an automated measuring system. One simple scheme for resolving $\mathbf{\Phi}$ is to determine each Φ_{ii} using a $\mathbf{w}$ with 1 at its i^{th} entry but 0's elsewhere. $\Phi_{ij} = \mathrm{conj}(\Phi_{ji})$ can be subsequently determined one pair at a time by using first a $\mathbf{w}$ with 1 and 1 at its i^{th} and j^{th} entries respectively and 0's elsewhere, and then a $\mathbf{w}$ with 1 and $e^{j\pi/2}$ at its i^{th} and j^{th} entries respectively and 0's elsewhere. There is a link between the predictive SAR model and an established multi-port system theory (5). The latter gives a quadratic model too but uses **S,** the system's scattering matrix, as a foundation. In a hypothetical case where the ports all see 50Ω during Tx, Rx and **S** measurement, the theory gives $\mathbf{\Psi} = kT(\mathbf{I} - \mathbf{S}\mathbf{S}^H)$. By invoking the principle of reciprocity, we then have $\mathbf{\Phi} = c(\mathbf{I} - \mathbf{S}\mathbf{S}^H)$. In this case $\mathbf{\Phi}$ provides much information about **S**, and vise versa. For example, knowledge of $\mathbf{\Phi}$ allows determination of all of **S**'s eigenvalues.

While waiting for a properly equipped parallel Tx scanner (6) to be restored, we assessed the present method's feasibility by analyzing data collected previously on this system, where a power sensor (Rohde & Schwarz NRP-Z21) and an RF switch (National Instrument Dual 16x1 MUX) were implemented to measure forward and reflected power at all eight ports. One set of power data were collected when the scanner was configured for parallel Tx MRI of a cylinder phantom inside an 8-loop head Tx-Rx array (7), and another set, the same phantom inside an 8-rung head TEM array. However neither set was collected purposefully for the present study. For each set, 63 source configurations assuming various combinations of amplitudes but uniform zero phase were involved, which turned out to be sufficient for constructing real($\mathbf{\Phi}$) using some and for subsequent model-testing using the rest. Results for each of the two parallel Tx configurations (shown in Fig.2 a and b respectively) indicated excellent agreement between actual measurements and the model-based SAR predictions.

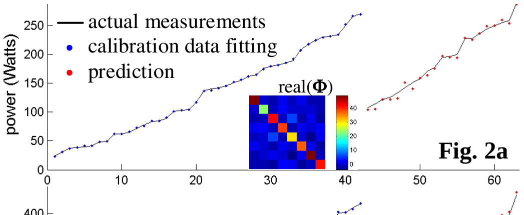

Fig. 2a

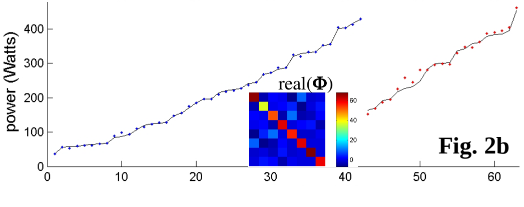

Fig. 2b

Discussions The SAR management method uses a model to directly tie parallel RF pulse sequence or multi-port RF shimming calculations with *in vivo* SAR. Calibration of the model is readily carried out *in vivo*. A connection with an established multi-port system theory as well as preliminary experimental data offered a validation. The model may additionally provide insights into multi-port hardware/coil characteristics under patient imaging conditions. The method seems to be implicitly helpful to local SAR management – pulse/shimming optimization (1,2) aiming at minimizing the quadratic model-based metric, essentially an L2 norm, tends to curb excessive elevation of local power deposition (whose volume integral gives the overall SAR).

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