Local SAR Estimation for Parallel RF Transmit at 7T Using Directional Couplers

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Introduction: Parallel RF Transmit (pTx) in high field MRI not only affects the superposition of the B1+ fields of all the transmit channels but also the concomitant electric fields. Therefore, pTx requires careful local SAR management and monitoring. There are two major challenges in predicting local SAR in pTx that must be considered: 1) Modeling coil coupling is difficult. It is easier to enforce ideal decoupling by simulating each element individually with the other elements detuned. Coupling can be accounted for by measuring the S-matrix directly and subsequently applying them to the ideally decoupled simulations.[1] 2) Current flowing on the element is responsible for the field produced. In order to scale a simulation by power, it is necessary that tuning and matching of the simulation exactly matches that of the actual element.[2]

Previous work has been done on this subject using pickup coils as a proxy for measuring current in the transmit (Tx) element[3]. The major drawback of this method is that pickup loops might not be present on all transmit arrays. Also, in a highly coupled system, it can be difficult to make a pickup coil sensitive to only a single element.

A different approach is to use directional couplers to measure forward and reflected power waves on the Tx line.[4] The advantages of using directional couplers over pickup coils are 1) that they are only sensitive to a single element; 2) they measure accurately the complex coupling values; and 3) can be used with any generic pTx array. However, as previously mentioned, scaling by power requires a very accurate simulation that exactly mimics the real Tx element up to the point at which you measure the power. An easier approach is to scale by current, as is done in pickup coil SAR monitoring.

We propose a method for converting directional coupler values to Tx element current values, thus allowing for the correct scaling and linear combination of simulated fields. This is necessary in order to accurately predict local SAR without overly complex simulations.

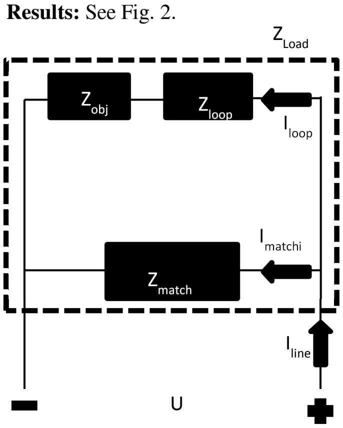
Theory: In order to convert power on the transmission line to current on the transmission element, we start by considering a circuit model for a standard loop coil with a parallel matching circuit (Fig 1). When a parallel matching circuit is present, the current at the coil connection is not equal to the current in the loop. The matching network acts as a transformer between the current on the line and the current in the loop, changing both the amplitude and phase of the current. Additionally, the impedance of the loop itself is changing with loading and coupling (which is reflected by Z_{obj} in Fig. 1), thus the complex ratio between the line current and the loop current will not be the same if the loading or coupling changes. However, we can assume that the impedance of the parallel matching circuit is not affected by the object given its small size in relation to the loop. Fig. 1 shows the circuit analysis equations used to derive current on the loop coil using only measured values (a and b) and the complex impedance of the parallel matching circuit. Here it was assumed that the coils are matched to a 50 Ohm transmission line.

Methods: Directional couplers were installed and calibrated to give the forward (a) and reflected (b) waves at the coil connection plane. Measurements were done on a Phillips 7T scanner (Achieva, Cleveland, USA) using two rectangular loop elements to form a small transmit array and a standard spherical phantom (10 cm diameter, σ = 1 S/m, ε_r = 80). Simulations were performed using Semcad X (Speag AG, CH) with the intent of replicating, as close as possible, the same setup used in the MR experiment; however tuning and matching was realized by a different network compared to the physical Tx element.

For this experiment, two elements were calibrated individually and then combined to form a pTx coil. The calibration step requires measuring the complex ratio of I_{line} to I_{loop} for a given load which is then used to determine the parallel matching impedance (solving for $Z_{matching}$ in Eq. [2]). I_{line} is deduced from the directional coupler readings. I_{coil} is determined by comparing B1+ maps with simulations. Element current amplitude is determined by comparing B1 maps to simulated B1 maps. Element coil phase is determined from comparing transceive phase images to transcieve phase in simulation. Note that the reference phase in the simulations is different from the reference phase used to calibrate the directional couplers. Thus the value for $Z_{matching}$ is known up to an arbitrary phase shift. However, this phase offset cancels out when the reverse operation is done, using Eq. [5] to calculate loop current.

Validation experiments were done by combining the two elements in a pTx array. B1 maps (AFI) were collected using various drive settings. Directional coupler values and the calibrated $Z_{matching}$ were used to predict element current amplitude and phase (using Eq. [3], [4], and [5]). Predicted element current was subsequently used to predict the coupled B1+ distribution by scaling simulated individual element B1+ maps (normalized to unit current) and summing them together.

Results: See Fig. 2.



[1] $$I_{line} = I_{loop} + I_{Matching}$$

[2] $$\frac{I_{loop}}{I_{line}} = 1 - \frac{I_{matching}}{I_{line}} = 1 - \frac{U/Z_{matching}}{U/Z_{load}} = 1 - \frac{Z_{load}}{Z_{matching}}$$

[3] $$I_{line} = \frac{a-b}{\sqrt{50}}$$

[4] $$Z_{load} = 50\frac{a+b}{a-b}$$

[5] $$\therefore\ I_{loop} = I_{line}\left(1 - \frac{Z_{load}}{Z_{matching}}\right)$$

Figure 1: Circuit model of a standard loop coil with a parallel matching component. The impedances can be separated into different components highlighting how $Z_{matching}$ is crucial in transforming the amplitude and phase of the current as it enters the loop. Equations explain how we derive an expression for loop coil current [5] using basic circuit analysis [1] & [2], and measured forward and reflected waves from directional couplers [4]&[5]. Note: 50 ohm = characteristic impedance of the transmission line.

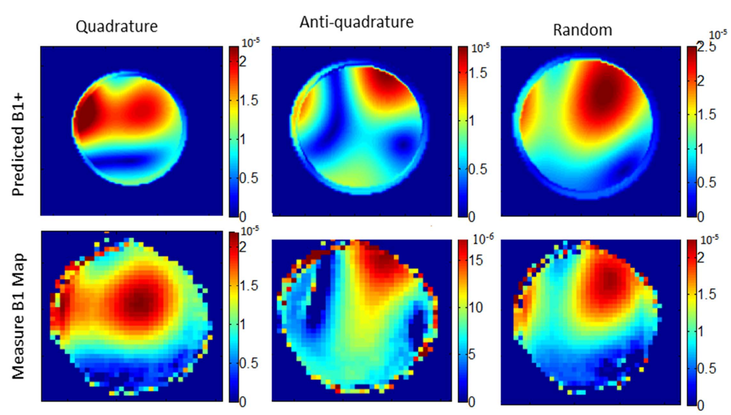


Figure 2: Coupled B1+ distributions were predicted based on loop current values determined from directional coupler values and Eqs. [3], [4], and [5]. Predicted and measured B1 maps are shown for 3 different drive settings of a two element pTx array.

Discussion and Conclusion: Through a straight forward calibration step it is possible to use current scaling with directional coupler measurements, rather than power scaling, for combining simulated field distributions. The calibration step involves estimating the complex impedance of the parallel component of the matching circuit. Most loop coils have a matching network for better efficiency. For Tx elements that do not have matching circuits, the element current will be equal to the line current. We used B1 maps to illustrate coupling. Although, electric field is responsible for local SAR, it can be assumed that electric field distributions will scale and sum in a similar manner as B1+. However, these are preliminary results and further investigation is necessary. The benefit of this work is that directional couplers can be used for pTx local SAR monitoring without the difficulty of creating perfectly matched simulations of the circuitry (matching, tuning circuitry and transmission line) between the coil element and the plane where the bi-directional couplers are placed.

References: [1] Homann H. Karlsruhe Transactions on Biomedical Engineering, Vol.16. (2012). [2] Kozlov et al, JMR. 2009;200(1):147-152. [3] Graesslin et al, ISMRM 2007:1086. [4] Zhu et al, MRM, 2012;67:1367-1378. *This work was supported by the Initial Training Network, HiMR, funded by the FP7 Marie Curie Actions of the European Commission (FP7-PEOPLE-2012-ITN-316716)*