On the correction of cable losses for in-situ subject-specific global Q matrix calibration

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Target audience: MR physicists and engineers interested in RF safety, particularly in the context of parallel transmission.

Purpose: Radiofrequency (RF) coils with multiple transmit elements have been widely adopted by the high field MR community as a means of controlling RF inhomogeneity and accelerating RF pulses. Despite the reported benefits, it is not clear how to guarantee local and global SAR limits are always met – primarily due to difficulties in determining the electric fields produced by each transmit element in-vivo and how they interfere when applying RF pulses. Zhu *et al*[1] recently described a partial solution which enables the measurement of the global Q matrix[2] on a subject-specific basis. The Q matrix can then be used to predict the total power deposited in the subject for an arbitrary RF pulse[1] and be used to constrain RF shimming[3] and parallel transmission pulse design[4] optimisation problems.

It has been noted[1,4] that the measured Q matrices include losses due to imperfect hardware, and that these losses can be modelled as additive[1] (i.e. $Q_{measured} = Q_{bore} + Q_{hardware}$). Although this is true for coil losses and radiative losses, here we demonstrate that this model is invalid for the situation where serial losses occur between the power measurement locations and the individual coils inputs. We adopt a more sophisticated model[5], which enables accurate prediction of power deposition in a load if the serial losses are known.

Methods: Consider an MRI system with T transmit channels, with each RF amplifier-to-coil path equipped with a directional coupler for monitoring forward (F_t) and reflected (R_t) powers (subscript t=1,...,T). The RF path forward from the directional couplers leading to the coil ports can be parameterised by a single complex parameter, a_t, which describes the reduction in voltage and phase accrued from the output of the directional coupler to the coil input. Zhu *et al* proposed the use of equation 1 for modelling the total energy loss of the RF system when RF shims set **w** is applied, where Q_{NC} is the Q matrix calculated without accounting for path losses (NC = no correction). It was also suggested[1] that Q_{NC} can be modelled as the sum of a matrix representing path losses Q_{path}, which is diagonal for non-interacting paths (cables) and the Q matrix at the coil ports Q_{DC} (DC = diagonal correction).

$$[1] \qquad \sum_{t=1}^{T} F_t - \sum_{t=1}^{T} R_t = \boldsymbol{w}^H \boldsymbol{Q_{NC}} \boldsymbol{w} \quad = \boldsymbol{w}^H (\boldsymbol{Q_{path}} + \boldsymbol{Q_{DC}}) \boldsymbol{w}$$

Instead, to account for pathway losses, we shift the measurement reference plane[4] to the coil ports by explicitly attenuating the measured forward powers and amplifying the measured reflected powers, and account for the reduction in voltages at the ports by multiplying by matrix **A**=diag{a_1,a_2,...,a_T}. The obtained Q matrix is referred to as Q_{FC} (FC = full correction).

$$[2] \qquad \sum_{t=1}^{T} |a_t|^2 F_t - \sum_{t=1}^{T} R_t / |a_t|^2 = \boldsymbol{w}^H \boldsymbol{A}^H \boldsymbol{Q_{FC}} \boldsymbol{A} \boldsymbol{w}$$

These two formulations were tested experimentally using a 128MHz (3T), 4 channel coil consisting of rectangular loops mounted on a cylindrical former with geometrical decoupling between nearest neighbours and no additional decoupling measures taken for opposite elements (PulseTeq Ltd, Surrey, UK). RF pulses were generated using a multi-transmit Philips Achieva console driving Analogic AN8134 power amplifiers. Power monitoring was achieved using four Werlatone 50dB directional couplers (C8904) placed in line with RG223/U low loss coaxial cable feeding the coil elements at a distance of 1.3m (estimated cable losses < 0.19dB). The monitoring ports of the directional couplers were connected to a Pickering multiplexer (40-874-002) feeding two Rohde & Schwarz NRP-Z11 power meters. The multiplexer and power meters were controlled using Matlab and synchronised to the pulses by monitoring the RF amplifier gating TTL input. The coil array was tested empty and also loaded asymmetrically with a 2L phantom containing saline (conductivity = 18 Sm^{-1}). An RF pulse was designed containing the 16 RF shims required for Q matrix determination[1] and 48 random RF shims in order to test the predictive ability of the calculated Q matrices. First, total forward and reflected power was measured to determine the true Q matrix of the coil, Q_C. Then 3dB attenuators were inserted in line on each channel between the directional couplers and the coil elements to simulate increased cable losses, and the measurements repeated. The second dataset was processed three times. Q_{NC} was calculated by following the methodology as proposed by Zhu; Q_{DC} was obtained by taking Q_{NC} and subtracting off the diagonal matrix which resulted in the Q matrix most similar to Q_C (i.e. the best possible correction with an additive diagonal Q_{path}); Q_{FC} was obtained by including the known attenuations before calculating the Q matrix.

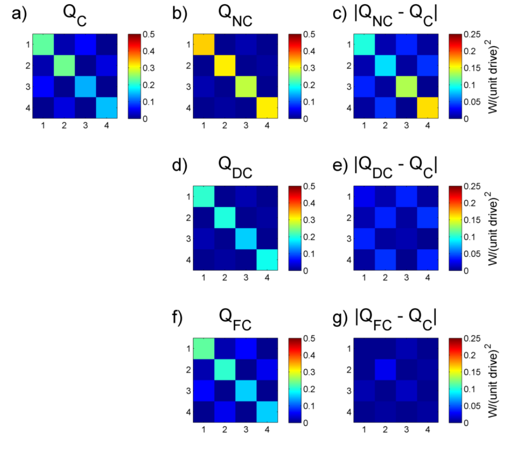

Figure 1 – Coil Q matrix (a), calculated Q matrices with attenuators inline (b, d, f) and their differences with respect to Q_C (c, e, g).

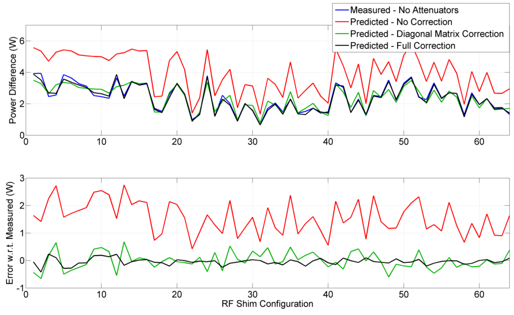

Figure 2 – Top: The measured power differences with no attenuators, and the predicted power differences using data with attenuators. Bottom: Differences of predicted power deposition with respect to measured.

Results and Discussion: Figure 1 shows the reconstructed Q matrices for the loaded coil case. Q_C is non-diagonal (Fig. 1a), indicating coupling between coil elements, although the geometrical coil decoupling results in very low Q matrix values for adjacent elements. The asymmetric positioning of the load results in variation in the amplitude of the diagonal entries. Not accounting for cable losses results in a primarily diagonal Q matrix (Fig 1b). Assuming a diagonal correction term can be applied (Q_{DC}) brings the diagonal elements closer to Q_C, but the off-diagonal terms are still incorrect (Fig 1d). The full correction brings the recovered Q matrix much closer to Q_C (Fig 1f). Figure 2 shows the measured power differences for the no attenuator case, and the predicted power differences using Q matrices reconstructed from attenuated data. Q_{NC} always overestimates the power deposited, Q_{DC} provides a limited degree of correction, and Q_{FC} is the most accurate of the three methods. The RMSE of the methods are 2.76, 0.10 and 0.02, respectively. We attribute the residual errors in Q_{FC} to imperfections in measurement. We have shown that accounting for cable losses is important for power deposition prediction, and that the proposed model can do this accurately. Using an incorrect model results in Q matrices which underestimate the off-diagonal components[4]. Both the diagonal and full corrections require knowledge of the coaxial cables transmission coefficients.

References: [1] Zhu Y. et. al. MRM (2012) 67:1367, [2] Bardati F. et. al. IEEE Bio. Eng. (1995) 42:1201 [3] Deniz CM. et. al. MRM (2013) 69:1379, [4] Deniz CM. et. al. MRM (2012) 67:164, [5] Pozer DM. (2011) Microwave Engineering 4th ed. Chapter 4, p. 184.