Real time RF monitoring in a 7T parallel transmit system

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Introduction: Parallel RF transmission (pTx) has great utility for B_1^+ mitigation at high field [1] and the generation of spatially tailored magnetization [2] with substantially reduced pulse duration compared to single-channel excitations. Current challenges to high-field applications of pTx *in vivo* include the monitoring and management of local SAR. In this work we developed and tested real-time RF monitoring system for a MAGNETOM 7T (Siemens Healthcare, Erlangen, Germany) with an 8-channel prototype pTx system that limits local SAR based on numerical simulation of E fields and power deposition in a segmented head model, and tracks and compares RF waveforms on each channel to the expected digital pulse waveform and shuts down the scan in the event of a mismatch due to e.g. a broken coil, RF amplifier failure, phase discrepancies, or other spurious sources of pTx RF errors.

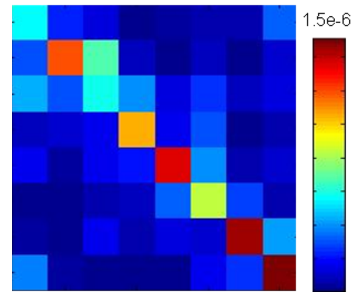

Figure 1. Magnitude of an 8x8 complex-valued coupling matrix, showing signal received by each pick-up loop (columns) due to RF on one pTx channel at a time (rows).

Methods: The monitoring system is based on small pick-up loops (~5mm in diameter) that were placed within each of the 8 elements of a transmit loop coil array used at our 7T Siemens pTx system. The received monitoring signals bypassed the preamp and second stage of amplification and were attenuated by 30 dB at the receiver, which was the level necessary to allow transmission at 190V simultaneously on all 8 channels without clipping artifacts.

Transmission of RF on channel *k* generates non-trivial monitoring signals on all 8 channels due to coil coupling. To account for these coupling effects and resolve independent pTx waveforms by observation of the monitoring signals, a separate calibration step precedes the pTx exam to estimate the full complex-valued 8x8 coupling matrix. Row *k* (*k*=1…8) of the coupling matrix is generated by playing an RF pulse on channel *k*, and receiving data on all 8 pick-up loops, followed by a least-squares estimate of 8 complex-valued weights that relate the transmission to pickup loops and populate row *k* of the correlation matrix, α. The estimated waveforms are $\mathbf{B_{est}} = \mathbf{TX_{vol}}*\mathbf{B}*\alpha$, expressed as an Nx8 matrix (N=number of RF samples), $\mathbf{TX_{vol}}$ is the maximum voltage and **B** are the ideal Nx8 pTx waveforms. A gradient-recalled-echo (GRE) sequence was modified by adding an acquisition event during the excitation period in order to receive the signal from the pick-up loops. The RF monitoring is implemented in the online scanner image calculation environment, and is able to stop the sequence at a time when predefined error thresholds are reached. The shutdown reaction time is guaranteed to be less than 10 ms.

Results and Discussion: An example of coupling-matrix magnitude is given in Figure 1, showing predominantly a diagonal pattern and revealing, e.g., that the pick-up loop on the 3rd transmit channel receives lower signal compared to the rest of the loops. Figure 2a compares $\mathbf{B_{est}}$ with **B** of one TR of a GRE acquisition where the maximum and mean error were 0.94% and 0.0017%, for the real part, and 1.5% and 0.012% for the imaginary part, respectively. The worst maximum and mean errors observed over many TR periods were 6.5% and 0.4% for the real part, and 10.6% and 0.6% for the imaginary part, respectively. To demonstrate the shut-down mechanism of the monitoring system during a pTx scan session, we introduced an artificial phase jump on one of the transmit channels by adding a 0.75m long coax cable at its output (phase lag ~120^0). This phase offset violated the comparison test, as shown in Figure 2b, and triggered a shutdown. The calculation of the coupling matrix was repeated for the case when the transmit system was driven using the eight orthogonal birdcage (BC) modes of a Butler matrix transformation of the 8-channel pTx loop array [3]. The quality of the measurements (not shown) was equivalent to the ones in Figure 2.

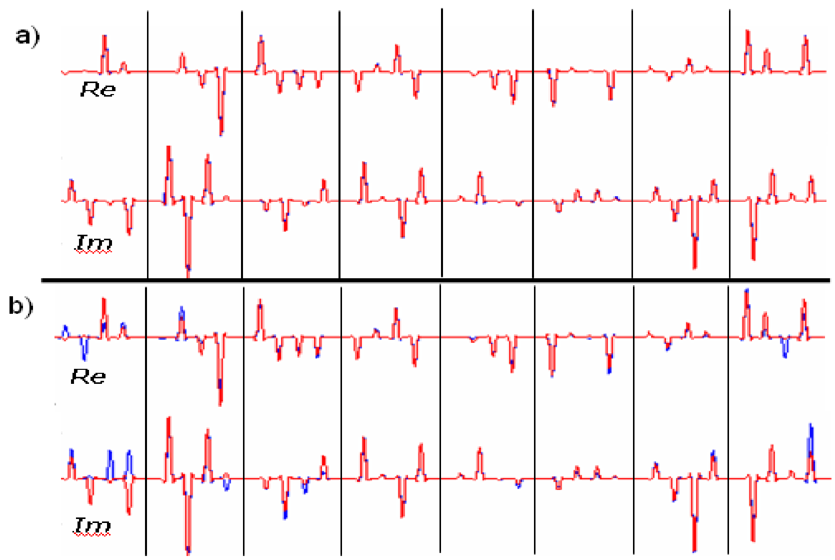

Figure 2: Overlay of quantitative comparison of the real and imaginary parts the **B** (red) and measured signals from the 8 pick-up loops ($\mathbf{B_{est}}$, blue); **a)** Experimental measurement of a 4-spoke pTx RF-pulse used for B_1^+ mitigation, showing excellent matching between the two waveforms. **b)** Same experiment as in a) but with purposefully added phase on one of the transmit channels, showing larger error values that triggered a shutdown of the scan.

Conclusion: We implemented a local SAR monitoring system based on real-time monitoring of RF waveforms that measures the RF phase and magnitude, detects discrepancies between the ideal and measured waveforms, and aborts the sequence if error thresholds are violated. The coupling matrix calibration scan, estimated once per exam, includes 8 acquisitions for a total of less than 20 seconds of scan time. This monitoring setup, together with accurate models of local SAR for the given transmit coil and pTx pulse, is critical for reliable and safe *in vivo* acquisitions using pTx.

Acknowledgements: NIH R01EB006847, R01EB007942, R01EB000790, NCRR grant P41RR14075, Siemens Healthcare.

Disclaimer: The concepts and information presented in this paper are based on research and are not commercially available.

References: [1] Grissom W. et al., MRM, 56, p. 620-629, 2006; [2] Setsompop K. et al., MRM, 60, p. 1422-1432, 2008; [3] Alagappan V. et al., MRM, 57, p. 1148-1158, 2007;