Real-time SAR Monitoring to ensure Patient Safety for Parallel Transmission Systems

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Introduction

Parallel transmission [1,2] is important for B_1-shimming [3] or shortened multi-dimensional RF pulses [4] (e.g. for local excitation). For in-vivo experiments, SAR limits have to be observed, which is more complex for parallel RF transmission systems. Therefore, patient safety considerations follow two directions, which are essential for parallel transmission systems [5-8]. First, the calculated demand RF pulses for parallel transmission must conform with existing SAR limits [9], and second, their realization in the parallel transmit system must be assured to prevent unsafe conditions.

The effects of a deviation between the demand and actual RF signals are investigated in a view of potential violation of existing SAR limits. This includes the case of a incorrectly calibrated RF chain or of RF channel failures [10,11]. To ensure patient safety, an amplifier shutdown unit and SAR monitoring were implemented on a whole body 3T MRI system with eight parallel RF transmit channels [8].

Methods

Simulations using the finite-difference time-domain (FDTD) method ("XFDTD", Remcom, Inc., USA) were carried out for a multi-channel body coil (MBC) operating at 3T with eight ideally decoupled TEM transmit elements (Fig. 1). A bio-mesh model of the "Visible Human Male" [12] with a resolution of 5mm was used for the determination of the coil sensitivities. The individual simulated electric fields of the coil elements were superimposed in the calculation of $SAR = \sigma\,|E|^2/\rho$, where σ is the electrical conductivity, and ρ is the mass density of tissue. For the Transmit SENSE pulses investigated, the 10g SAR values were calculated for the complete bio-mesh using a 12-field component method and an improved average algorithm [13]. The parallel RF excitation pulses were calculated iteratively using a conjugate-gradient method [14]. 2D Transmit SENSE pulses were calculated using spiral k-space trajectories with a numerical field-of-excitation of 64×64 pixels for reduction factors R up to 8. As an example for an application, the kidney (segmented region) was locally excited in a transversal slice. A safety concept on real-time SAR monitoring was implemented, using pick-up coils located at each individual RF coil element. The transmitted RF is sampled during each RF pulse for all eight RF Tx channels and processed in real-time.

Results and Discussion

Previous simulations of the effects of RF channel failures [10,11] showed that SAR limits might be exceeded, if, when operating at the SAR limit, even a single, not correctly calibrated RF channel, may cause violations of the limit. As shown in Fig. 2a), the worst case of 20% above limit occurs for a phase shift of 250° for coil 6; phase deviations at two coils even lead to a 38% increase of the SAR (Fig. 2b)). The latter case is visualized in Fig. 3. These violations also occur for other pulses, e.g. sinc pulses, used in RF shimming techniques with amplitude/phase variations.

The use of a power-monitoring unit (PMU) per channel, that monitors the maximum peak and average power, is insufficient to guarantee patient safety and to prevent safety hazards for parallel transmission systems, since phase deviations at the transmit coil or channel failures are not detected. Instead, demand SAR monitoring (Fig. 4) is proposed to overcome this problem. Fig. 4a) shows a measured waveform (blue) deviating from the demand waveform (red). Note the green zoomed-in region in Fig. 4b). The detected deviation leads to a scan termination. SAR reduction techniques, as e.g. proposed in [2] or VERSE [15] adapted for parallel transmission, were not considered in this investigation. However, the use of these techniques can lead to a lower local SAR (increase).

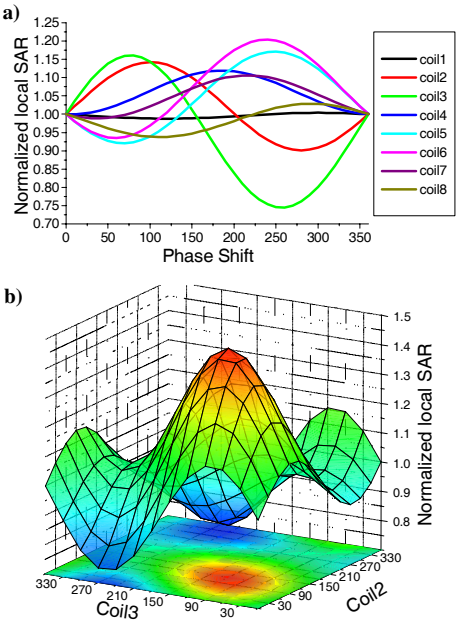

Fig. 2: Impact of a phase error on local SAR for Transmit SENSE excitations for an incorrect phase of a) one coil element and b) two coil elements.

Conclusion

Patient safety concepts for parallel RF transmission systems need special attention, since phase and amplitude errors in the RF chain or a failure of RF transmit channels may lead to an increased local SAR and violations of existing SAR limits. To ensure patient safety, SAR monitoring and an amplifier shutdown unit and are needed to detect the violation of the RF demand and to abort the running scan immediately. These mechanisms ensure patient safety for parallel RF transmission systems.

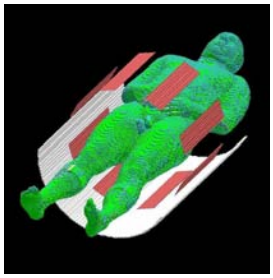

Fig. 1: An eight-channel MBC coil loaded with the NLM "Visible Human Male" bio-mesh

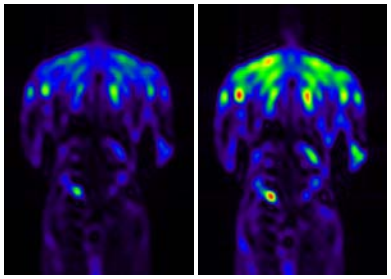

Fig. 3: Spatial local SAR distribution (coronal view) of the bio-mesh with correctly calibrated RF phases for $R = 8$ (left). Local SAR increase of 38% for incorrect phases on two channels (right).

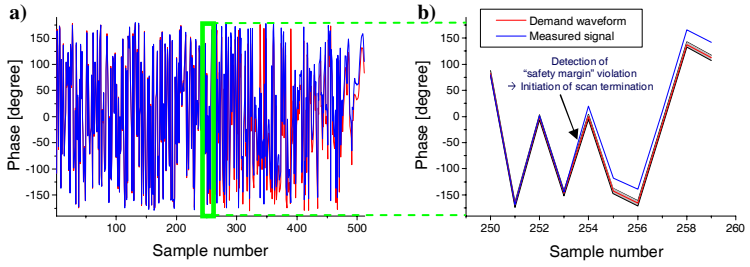

Fig. 4: For a selected pattern (2D RF FOX: 64×64, reduction factor R=8), the RF demand waveform (red) and measured signal (blue) are shown (a). A zoom-in (b) shows a violation of the safety margin (gray) due to a phase deviation of 25° from the RF demand waveform. This leads to the initiation of a scan termination.

References

[1] Katscher U, et al. [2003] MRM 49:144-150
[2] Zhu Y [2004] MRM 51:775-784
[3] Ibrahim TS, et al. [2000] MRI 18:733-742
[4] Pauly J, et al. [1989] MRM 81:43-56
[5] Zhu Y, et al. [2005] ISMRM 13:14
[6] Ullmann P, et al. [2005] MRM 54:994-1001
[7] Setsompop K, et al. [2006] MRM 56:1163-1171
[8] Graesslin I, et al. [2006] ISMRM 14:129
[9] FDA [2005] IEC 60601-2-33, 2nd Ed.
[10] Graesslin I, et al. [2006] ISMRM 14:2470
[11] Graesslin I, et al. [2006] MAGMA 19:S261
[12] NLM [1996] "Visible Human Project"
[13] Caputa K, et al. [1999] IEEE Ant. & Prog., 41:102-107
[14] Graesslin I, et al. [2005] MAGMA 18:S109
[15] Conolly S, et al. [1988] JRM 78:440–458