Comprehensive RF Safety Concept for Parallel Transmission Systems

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Introduction

RF safety is a prerequisite for in vivo parallel transmission MRI experiments. In this abstract, a comprehensive RF patient safety concept is proposed to ensure scanning within the SAR limits with multi-channel RF transmit coils. Two paths are pursued. Before the scan, SAR calculations are carried out in (almost) real-time for demand waveforms to verify the conformity with existing SAR limits [1]. During the scan, the deviation from the desired waveform is monitored to detect violations of the SAR limits or any unsafe conditions.

Methods

SAR calculation prior to the scan: SAR limits have to be verified before a scan. Here, four different methods of determining the SAR are compared. The first method is a worst-case analysis similar to [2], which sets the RF amplitudes to the maximum possible output power for all channels neglecting any phase information. In the second method, all samples of the RF pulse are set to the maximum amplitude in the corresponding channel. The third method considers the correct amplitudes of the individual samples, but no phase information. And the forth method considers also the phases leading to the exact solution. The E-fields were pre-calculated using finite-difference time-domain simulations ("XFDTD", Remcom Inc., USA) for an ideally decoupled 3T multi-channel body coil (MBC) [3]. Bio-mesh models (resolution: 5mm) were used for the field calculations, including rescaled versions of the "Visible Human Male" [4]. The pre-calculated E-fields of the coil elements were averaged according to [5] and stored in a database. For the SAR calculation, the fields were superimposed in a weighted manner (according to the RF pulse). As the visible human model comprises roughly 750k cells, this is a time-consuming process. Therefore, a high performance graphics card (Quadro FX 5600, NVIDIA® Corporation, USA) is used with 128 processors (3.8ms/RF sample) resulting in a speedup of about 100 compared with a PC (Intel Xeon processor at 3GHz). The card has been integrated into the acquisition and processing unit of the eight-channel transmit 3T MRI system ([6], Achieva, Philips Medical System, Netherlands). The scan-specific information like patient weight, sex, and position in the MR scanner are used to find the appropriate pre-processed bio-mesh model required for the SAR calculation.

Waveform monitoring during the scan: Existing solutions of RF monitoring during the scan use a power-monitoring unit (PMU) per channel, measuring the maximum peak and average power. Such a setup does not guarantee patient safety for multi-channel transmit coils, since potential phase deviations at the transmit coils or potential channel failures are not detected. Furthermore, for multi-channel transmit experiments, the local SAR is the limiting factor, and not the global SAR. In general, the ratio between local and global SAR is not constant and can vary significantly [7].

The pick-up coil (PUC) monitoring [8] is used to sample the transmit currents in the RF coil elements during RF transmission in real-time. A watchdog timer secures the safety critical monitoring software. Calibration of the PUCs was performed. Furthermore, the RF pulses were pre-compensated to account for coil coupling (active decoupling approach [9]), which virtually decouples the elements of the MBC. Active decoupling is a prerequisite to fit the RF simulation model to the real coil configuration for correct SAR calculations. Furthermore, it is required to enable correct RF demand monitoring to keep the safety margin small. The selection of the safety margin is of central importance for the proper function of the concept. For margin definition, the amplitude and phase changes for different volunteers, their positions in the coil as well as their motion (e.g. breathing) were investigated. Furthermore, the impact of a permanently tuned single channel receive coil (∅=10cm) on amplitude and phase change was investigated as an example of a possible hazardous situation.

The 2D Transmit SENSE RF pulses [10] used for the worst-case analysis were calculated for the local excitation of the kidneys [7] for reduction factors *R* of up to 7.1.

Results and Discussion

The results of the analysis using the first three methods, normalized by the forth, "exact" method, are shown in Fig. 1. The example of Transmit SENSE pulses with different reduction factors (the ratio between accurate calculation and worst case estimation is up to 570) underlines the need for a more realistic SAR estimation than just a worst-case approximation. Fig. 2 shows that the SAR has a strong dependence on the position of the bio-mesh [4]. This leads to an overestimation of the SAR by up to a factor of 5.6 (with respect to the worst case position) in case of a circular polarized field (emulation of standard body coil). As most scans at 3T are SAR-limited, a correct SAR calculation is very important taking the actual patient position into account.

In Fig. 3, two examples are shown for a possible safety margin violation. A malfunctioning of the surface receive coil was emulated by tuning the coil to resonance after 1 second of normal scanning, causing a decrease of the amplitude of 55% in combination with a phase deviation of 10° (Fig. 3a)). The decrease of the amplitude can be explained by the detuning of the RF transmit coils, which leads to an unpredictable behavior. Modest patient movement like breathing (Fig. 3 b)) causes an amplitude change in the order of 3%, which should not lead to a scan termination. The calculated SAR increase induced by breathing was less than 0.01% for four subjects investigated. Even, a breath-hold in worst-case situation (with respect to SAR) leads to an increase of only up to 3%. Based on these results, the safety margin was set to a value above the changes caused by typical motion in the scanner. Fig. 3a) also shows the proper function of the safety mechanism. The provoked malfunctioning of the receive coil is detected in real-time, and the scan is terminated within a few hundred milliseconds. This monitoring concept is also applicable for MRI systems with a high number of Rx coil elements, or for safe catheters [11] in interventional procedures.

The safety margin can be reduced significantly, if a real-time feedback loop is used to change the input signal of the RF amplifier accordingly with the desired RF demand. Alternatively, current sources [12] could be used.

Conclusion

The extra degree of freedom of parallel RF transmission systems can lead to significant violations of existing SAR limits in case of system failure or miscalibration. Accurate SAR determination in (almost) real-time in combination with the concept of RF waveform monitoring can ensure patient safety for RF parallel transmission systems.

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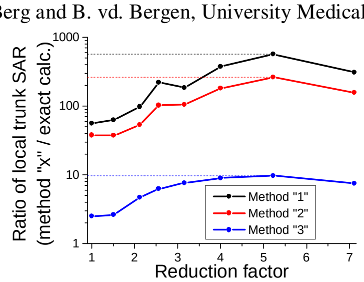

Fig. 1: Different SAR estimation methods are compared with the exact calculated SAR for TxSENSE pulses with various *R*.

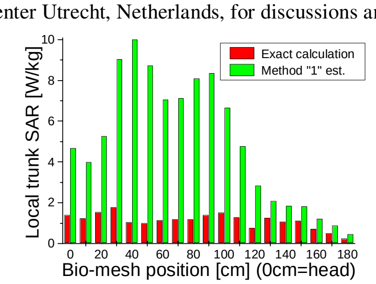

Fig. 2: Position-dependence of the local trunk SAR using the MBC emulating a standard body coil.

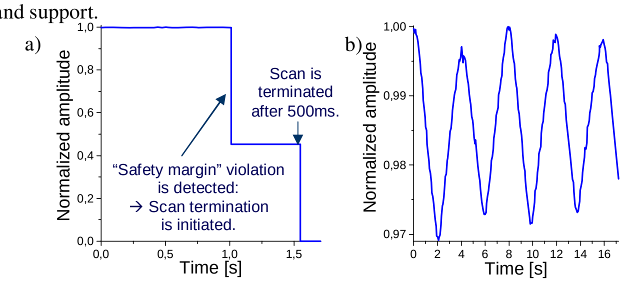

Fig. 3: Deviation from RF demand induced by a) resonant object in the MR scanner, which leads to a scan termination and b) respiration.

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