SAR & RF Power Monitoring

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Target Audience

Engineers and physicists interested in radio frequency (RF) safety for single and parallel transmission magnetic resonance (MR) systems

Highlights

- Achieving RF patient safety during MR examinations is more challenging for parallel transmission systems and local transmit arrays.
- Various monitoring approaches from RF power monitoring to real-time specific absorption rate (SAR) monitoring exist.
- RF shimming is a means to improve image quality and to reduce the SAR.

Objectives

- Understand the RF safety mechanisms of single and parallel transmission systems
- Understand the preparatory steps required prior to the scan as well as the need to monitor during the scan
- Differentiate between RF power monitoring, RF waveform monitoring, and SAR monitoring and understand their role in realizing patient safety

Introduction

MR imaging at high field strengths (3T and above) leads to undesirable signal and contrast variations resulting from inhomogeneities of the RF field [1], which may impact the diagnostic image quality. These RF field inhomogeneities can be reduced by employing multiple RF transmission channels or parallel RF transmission. Image quality can be improved by tailoring the B_1^+ transmit field per patient, thus providing a more homogeneous excitation. Ensuring RF safety for the patient requires the implementation of a safety mechanism, usually a combination of hardware and software. Using local RF transmit coils, as opposed to volume coils, further complicates the RF modeling and the safety hardware provisions.

Methods

Specific absorption rate prediction

Ensuring patient safety during *in vivo* MR examinations requires to limit the increase of the tissue temperature resulting from RF pulse energy transferred into the human body. The SAR is commonly used to measure RF heating, because it is easier to manage and to control than determining the temperature increase in the human body. The International Electrotechnical Commission [2] and the U.S. Food and Drug Administration provide guidelines for the safe operation of MRI equipment.

With the availability of parallel transmission systems, ensuring RF patient safety has become more complex due to the additional degrees of freedom in parallel transmission that allow tailoring the RF transmit fields. The increased field strength creates larger deviations between the spatial distribution of SAR patterns and the resulting spatial temperature distribution including hotspots obtained from thermal modeling. Recently, the "Cumulative Equivalent Minutes at 43°C" (CEM43) concept [3-6] used in hyperthermia, as well as thermal modeling, has been investigated in the context MRI. For validation purposes, a commonly used non-invasive temperature mapping method is the proton resonance frequency method [7].

For predicting the SAR, the electric field strength E, the mass density ρ, and the electrical conductivity σ of the tissue need to be known. As these variables cannot be determined easily in the

patient, simulations using standardized patient models [8-14] provide suitable expected global and local SAR values before a scan. With the use of models (RF coil and patient), suitable SAR error margins must be considered. Recently, an increased number of models has become available [13, 15-17].
If the predicted global or local SAR exceeds the SAR guidelines [2], the scan parameters must be adapted accordingly [15-19]. While RF shimming typically improves image quality, commonly it also reduces the SAR, which can shorten the scan time. Alternatively, sequence design methods using SAR constraints—known as SAR management—can be used to meet the SAR guidelines [20, 21]. Matching RF simulations and the experimental situation [22] requires calibrating and adjusting the MR system (at installation time and during preparation phases preceding the scan).

Monitoring and Supervision

To detect potentially unsafe situations for the patient, a supervision system analyzes the RF signals and terminates the scan if the SAR prediction exceeds the allowed limits. While monitoring peak and average RF power is sufficient in single-channel transmit systems (most commonly integrated in the RF amplifier), SAR management becomes more challenging in parallel transmission systems. Various monitoring and supervision concepts have been described for this purpose [23-27]. For monitoring and supervision, appropriate sensors are required, for example, directional couplers [28] or pick-up coils (PUCs) [23, 29, 30].
It is desirable to consider not only the amplitude, but the complex RF signals, because the transmit phase significantly influences the actual SAR in parallel transmission. Supervising the complex RF waveform rather than its amplitude and phase separately helps to minimize the error margins used during supervision. When the supervision system has calculated the global and local SAR during the scan, it becomes possible to significantly reduce the problem of SAR overestimation. This supervision is done by sampling the RF signals via PUCs (or directional couplers) and predicting the SAR based on the transmitted RF, using the same model as for predicting the SAR before the scan [29, 31].
Unfortunately, unsafe patient situations may remain undetected, because different RF inputs can lead to the same SAR. Such situations can be identified when supervising the RF as well as by determining if (a) the RF signal deviation results from the RF chain or (b) from a mismatch between the assumed model and the real scan situation (e.g., from significant patient movement or resonant objects). In case of (a), the supervision SAR would be correct, while in case of (b), the supervision SAR would be incorrect, and the scan would need to be aborted [32, 33].
Figure 1 illustrates the essential parts of the MR system related to the RF transmit chain.

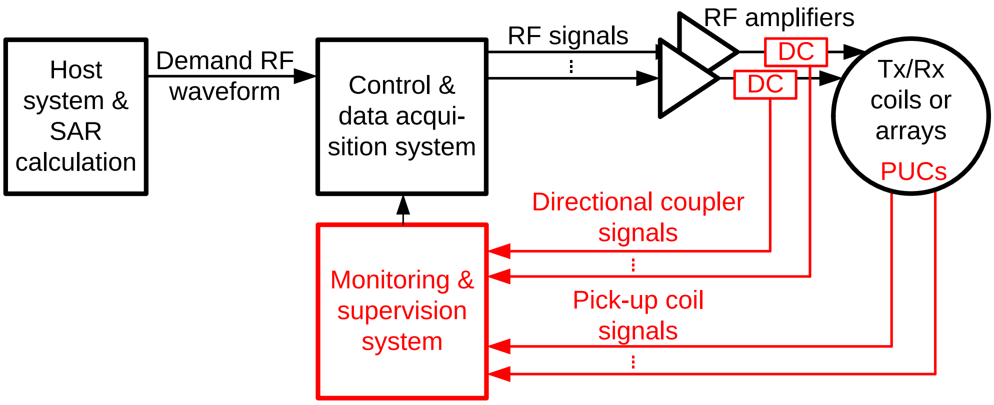

Fig. 1: The SAR is predicted prior to the scan based on the target RF waveform, which is converted to RF signals by the data acquisition system (DAS), as shown here for a parallel transmit system. The amplified signals are routed to a multi-channel transmit/receive coil. The RF signals of the directional couplers (DCs) or pick-up coils (PUCs) (in red) are monitored for safety reasons.

While the presence of implanted devices is contraindicated for MR examinations, the interest in performing such examinations is increasing, since the number of patients wearing such implants goes up. PUC supervision may be used to detect potentially unsafe situations, as has been shown in proof-of-principle experiments [34-36].

Experimental Verification of SAR Prediction and Supervision

Exemplarily, the experimental verification such a SAR Prediction and Supervision experiment is described in detail [33].

To test the SAR supervision based on transmitted RF pulses via PUC monitoring, phantom experiments were performed, and RF shimming and local excitation were used as examples. A spherical phantom (diameter=20cm, σ=0.37S/m, ε_r=80) was simulated and used for the SAR prediction and supervision. The phantom was placed in the isocenter of the MR system.

B_1^+ shimming was performed based on maps measured with DREAM [37] (nominal flip angle α=50°, imaging flip angle β=3°, repetition/echo times $TR/TE_{FID}/TE_{STE}$=3.4/2.1/12ms, scan resolution $3.5\times3.5\times10mm^3$).

For a fast gradient echo scan, TR and α were varied from 5.3 ms to 40 ms and from 20° to 150°, respectively, resulting in a predicted $SAR_{WB} < 4\ Wkg^{-1}$ and $SAR_L < 15\ Wkg^{-1}$ (SAR_{WB} is the global SAR and SAR_L is the local SAR).

In a second set of experiments, spatially selective RF pulses were used to compare the predicted and supervised SAR. A disc-shaped 2D region of 5 cm diameter was excited in the center of the phantom. A spiral k-space trajectory with a numerical field-of-excitation of 32×32 pixels was used. The Transmit SENSE pulses were calculated using a pulse calculation algorithm based on Lagrange multipliers [34] (TR ranging from 7 ms to 170 ms, and α ranging from 20° to 100°, resulting in a predicted $SAR_{WB} < 4\ Wkg^{-1}$ and $SAR_L < 8\ Wkg^{-1}$).

For all scans, the SAR was calculated per RF pulse and averaged for all RF pulses. The difference was determined between the predicted SAR and the supervision SAR calculated from the PUC sample monitoring.

Results

Experimental Verification of SAR Prediction and Supervision

A wide range of global and local SAR values was tested for RF shimming and local excitation with varied repetition times and flip angles. The global and local predicted SAR correlate very well with the supervision SAR for a wide range of RF Tx signal amplitudes and duration variations (Fig. 2). This result demonstrates the functioning of the RF signal generation and amplification as part of the RF Tx chain, the monitoring of the PUC signals, and their processing by the supervision system. The averaged supervision SAR of all individual RF pulses only differs from the supervision SAR of all PUC samples within the range of numerical rounding errors. The largest standard deviation among all RF pulses of a scan is $7.0\cdot10^{-3}$. The maximum difference between predicted and calculated SAR values is ±5% for the global SAR and ±4% for the local SAR. The errors result from calibration and hardware imprecision.

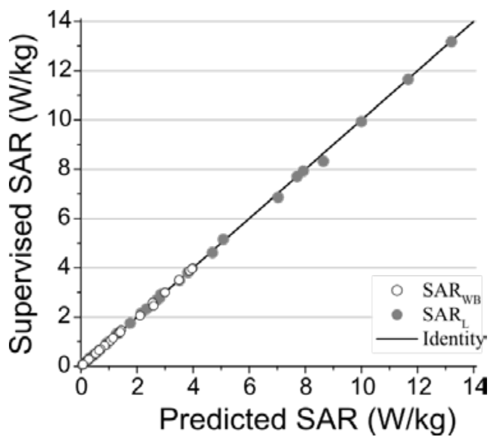

Fig. 2: Validation of predicted and calculated SAR from pick-up coil (PUC) samples. For various RF shimming and local excitation experiments using a water-filled sphere, the global SAR_{WB} and the 10g averaged local SAR_L are shown. The predicted SAR_{WB} (open circles) and SAR_L (grey circles) based on the demand RF waveforms are compared with those calculated from the sampled RF signals acquired via the PUCs.

DISCUSSION

A key issue for the safety of pTx imaging systems is the correct prediction the actual SAR prior to the scan, the supervision of the SAR limits, and the abortion of the scan in case of hazardous situations for the patient. This is achievable by various approaches including RF and SAR monitoring.

Fast and accurate SAR prediction is important for the compulsory safety check before each scan. Using preprocessed numerical simulation data helps to significantly reduce SAR computation times. To ensure accuracy, which means that the predicted SAR matches the actual SAR applied to the patient during the scan, hardware and software measures are used. Using circulators is one way to improve the correspondence between SAR simulation and experiment. Furthermore, the SAR-related system parameters need to be adapted during the preparation phases to establish the essential correspondence between electromagnetic field simulations and the actual scan situation with the patient in the magnet.

Summary:

- Achieving RF patient safety is particularly challenging for parallel transmit systems with local transmit coils at high main field strength.
- For RF and SAR simulations, the availability of a variety of different bio-mesh models is desirable.
- Different patient safety approaches exist for parallel transmission systems.
- SAR prediction before the scan and RF/SAR monitoring during the scan is one possibility to achieve RF patient safety for parallel transmit systems.
- Further research efforts are necessary in the area of patient modeling and selection.

Acknowledgments

I would like to thank H. Homann, P. Vernickel, U. Katscher, K. Nehrke, S. Krueger, S. Weiss, B. Annighoefer, and P. Börnert for their contributions, and P. Harvey, J. vd. Brink, H. Dingemans, G. Mens, Z. Zhai, and M. Morich for technical support.

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