Comprehensive RF Safety Concept for Parallel Transmission MR

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Target audience

RF engineers and MR physicists

Introduction

Achieving RF safety in parallel transmission is challenging, due to the freedom in tailoring the RF transmit (Tx) fields. A comprehensive RF safety concept for parallel transmission (pTx) MRI systems requires verifying the SAR limits[1] before the scan[2] and supervising the RF signal during the scan.[3] Using a pre-calculated safety margin overestimates the actual SAR, resulting in an increased scan time. SAR supervision systems[4,5,6] overcome this problem, but do not detect all RF situations that are potentially unsafe for the patient. We developed, implemented, and verified a new comprehensive RF concept for the supervision of patient safety that combines real-time global SAR and local SAR supervision with real-time RF supervision. This new concept allows for a significantly increased permissible RF duty cycle, improves the detection of SAR limit violations and patient-unsafe conditions, and reduces the number of false-positive scan interruptions.

Methods

The new RF safety concept was developed and integrated on a 3 T MRI scanner (Achieva, Philips Healthcare, Best, The Netherlands) equipped with an 8-channel parallel Tx/Rx body coil,[7] and was verified experimentally. Each Tx/Rx RF coil element has its own pick-up coil (PUC)[8] connected to a monitor, which samples the measured signal and sends the data for processing to the supervision system. The concept we propose can be achieved by: I. Predicting the pTx SAR prior to each scan and initiating the scan only, when the SAR limits are met. II. Measuring the system matrix A_{sys} (the coupling among Tx coil elements) for active decoupling and mapping actual B_1^+ to adjust to the prescribed B_1^+, thus ensuring that the predicted SAR matches the actual SAR. III. Supervising patient safety during the scan and, in case of a hazardous situation, aborting the scan.
As a one-time prerequisite, we carried out finite-difference time-domain SAR simulations[9,10] (XFDTD from REMCOM Inc., State College, PA, USA) for the 3 T eight-channel body coil[8] at a 5 mm grid resolution. To improve computational efficiency, the number of applied Q-matrices was reduced by using a model compression approach.[6,11-13]
The described SAR supervision was tested in experiments with a spherical water phantom located in the isocenter. Corresponding Q-matrices were selected for the SAR prediction and supervision. On one hand, B_1^+ shimming was performed based on maps measured with DREAM.[14] For a fast gradient echo scan, variation of TR and α resulted in a predicted global SAR (SAR_{WB}) of <4 W kg^{-1} and a local SAR (SAR_L) of <15 W kg^{-1}. On the other hand, spatially selective RF pulses were applied exciting a disc-shaped 2D region of 5 cm diameter. A spiral k-space trajectory (numerical field-of-excitation of 32×32 pixels) was used for the pulse calculation algorithm based on Lagrange multipliers.[15] Here, variation of TR (7–170 ms) and α (20°–100°) resulted in a predicted SAR_{WB}<4 W kg^{-1} and a SAR_L<8 W kg^{-1}.
Furthermore, the described RF safety concept was tested on healthy volunteers. The system matrix A_{sys} and SAR were analyzed in intentionally introduced fault scenarios. For all test cases, a safe, low-SAR fast gradient echo scan was used, driving the body coil in quadrature excitation and active decoupling.[16] The normalized root-mean-square error (NRMSE) was calculated for the diagonal element of A_{sys} acquired at the beginning and end of the test. SAR deviations resulting from the following list of intentionally induced fault situation were investigated: (a) The volunteer moved the arms from resting on the body to next to the body. (b) The volunteer moved the body closer to the right side of the body coil. (c) The patient table was moved 10 cm in feet–head direction. (d) The phase of one Tx channel was changed by 17° when shortening the electrical length of the coaxial cable. (e) The amplitude and phase of Tx channel 1 was increased by 25% and 10°, respectively. (f) Tx channel 1 amplitude was set to zero.

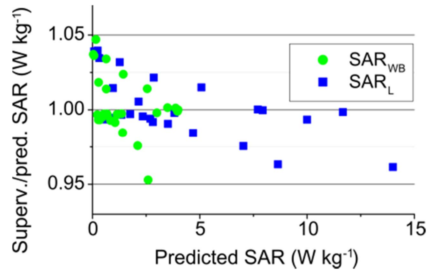

Figure 1: Validation of predicted and calculated SAR from pick-up coil (PUC) samples. For various RF shimming and local excitation experiments using a water-filled sphere, the deviations from the predicted SAR are shown for the global SAR_{WB} and the 10 g averaged local SAR_L.

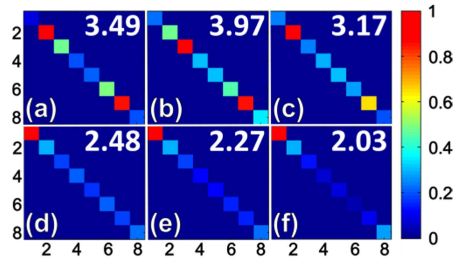

Figure 2: Normalized system matrices. Plots of diagonal elements of the normalized system matrices and (NRMSE) normalized root-mean-square error (upper right) for the 6 cases (a–f).

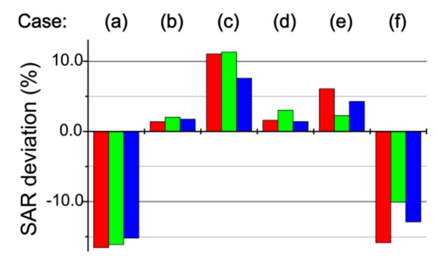

Figure 3: SAR deviation (%) for the global whole body SAR (red), the local torso SAR (green), and the extremities SAR (blue) for the 6 cases.

Results and Discussion

The results demonstrate the functioning of the supervision system, the complete RF transmit chain, and the PUC monitoring chain (Fig. 1). The maximum deviation between the predicted and calculated SAR values was ±5% for the global whole body SAR and ±4% for the local SAR, and resulted from calibration and hardware imprecision. For the intentional fault situations (a)–(f), Fig. 2 shows A_{sys} and the NRMSE of its diagonal elements, whereas Fig. 3 shows the deviations of the global SAR, local torso SAR, and extremities' SAR. For cases (a)–(c), multiple diagonal elements of A_{sys} changed, while only a single matrix element changed significantly for the other cases, so coil "external" and coil "internal" variations can be distinguished, and are supported by higher NRMSE values for cases (a)–(c) and lower values for cases (d)–(f). While the predicted SAR is correct for cases (d)–(f), it is incorrect for the remaining cases, because the electromagnetic-field simulations used by the SAR supervision no longer fit the actual SAR of the scan situation. Therefore, for cases (d)–(f), a scan would still be safe if the SAR limits are met; for the other cases, the predicted SAR deviates from the actual SAR. While the supervision SAR is reduced by about 15% in case (a), the local extremity SAR generally increases when extremities are moved closer to the coil elements.

Conclusion

We present a novel safety concept and experimentally demonstrate safe scanning in pTx. The concept represents an important step towards the safe operation of pTx systems, and is also applicable for field strengths above 3 T.

References

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