On the SAR averaging nature of parallel excitation pulses and its impact on conservative worst-case analysis

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INTRODUCTION: RF power absorption in the human body and the associated heating of tissue is a critical issue and a limiting factor for parallel transmission applications. Besides the challenges of determining the electric fields inside the patient, further safety arrangements are necessary to detect unwanted behaviour of the RF system. If no additional hardware is available to monitor the RF phases, e.g. pick-up coils [1], a common approach is to perform a conservative worst-case analysis that either estimates the worst maximum local SAR that might occur in the object by comparing all possible phase combinations of the n different transmitter coils [2, 3] or by summing the magnitudes of the n electric field vectors. In both approaches the RF power is to be limited such that even in the case of absolutely constructive interference of the electric fields, the local SAR limits are not exceeded. During a parallel excitation experiment, the phases and amplitudes of an RF pulse vary continuously, which leads to a temporal averaging of the deposited energy. Assuming that RF amplitudes can be measured correctly, the aim of this work is to investigate if this worst-case analysis is appropriate for parallel excitation pulses at 3T in the abdomen.

METHODS: In this study FDTD-based electromagnetic field simulations [4] were performed for an 8-channel whole body TX array and a human whole body phantom [5] at 3T. Based on the simulated magnetic fields, small tip angle parallel excitation pulses were calculated using a conjugate gradient method. Eight different excitation patterns and 4 different acceleration factors were considered. For SAR calculation the simulated electric fields were weighted by the corresponding pulses: for real SAR the vector character of the complex electric fields was considered, while for worst-case analysis SAR phases and directions of the electric field vectors were neglected and the magnitudes were summed up. In a second step, the malfunction of the RF system was simulated by adding a random phase for each coil element. The additional phases were assumed to be constant during the RF pulse and were chosen randomly and equally distributed over an interval of +/-60°. This procedure was repeated 100 times. With regard to IEC SAR standards [6] the SAR was averaged over a 10cm³ volume. For the excited slice the maximum local SAR in worst-case analysis (WCSAR) and the real maximum local SAR (RCSAR) were determined for each pulse. In addition WCSAR and RCSAR were evaluated for different static coil combinations: departing from quadrature mode 1000 random coil combinations were generated by adding random amplitudes (+/-100%) and phases (+/-60°).

RESULTS AND DISCUSSION: The static coil combinations show a wide variety of WCSAR-to-RCSAR ratios being in the range of 1.4 to 11.8. The results are plotted against standard deviation of B1 in Fig.1. They indicate that for static coil combinations or for single time steps during a parallel excitation pulse, RCSAR may be close to, as well as far from what is estimated by worst-case analysis, depending on amplitude and phase settings. For the designed and correctly executed parallel excitation pulses, however, WCSAR-to-RCSAR ratios are in the narrow range of 2.6 and 4.6 as the coloured bars in Fig. 3 show. The ratio depends on the pulse and tends to increase with acceleration. Additionally the markers in Fig.3 show the ratio of the WCSAR calculated for the originally designed pulse to the RCSAR that results from the malfunction of the RF system. For pulses for which the original WCSAR-to-RCSAR ratio is only about 2 or 3, the erroneous RF pulse rather decreases than increases maximum local SAR. For pulses with large ratios both effects can occur, but the ratio never falls below 2. As Fig.2c shows, SAR estimation according to worst-case analysis may pretend to exceed the local SAR limits of 10 W/kg [5] while neither for the correct (Fig.2a) nor for the incorrect RF pulse (Fig.2b) the limit is exceeded.

CONCLUSIONS: Due to the varying phase settings during a parallel excitation pulse, conservative worst-case analysis is too strict. Therefore it is possible to relax RF power limits that are based on this worst-case analysis.

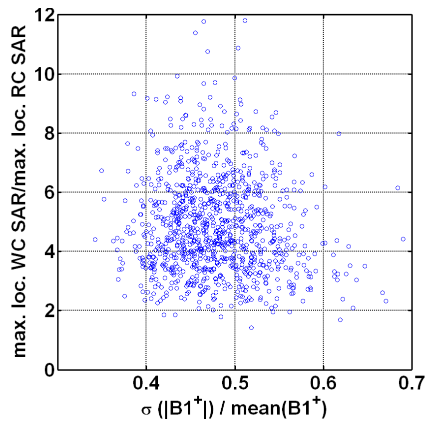

Fig. 1 Ratio of worst-case analysis maximum local SAR and real maximum local SAR for different static coil combinations plotted against standard deviation of B1+ normalized to mean B1+

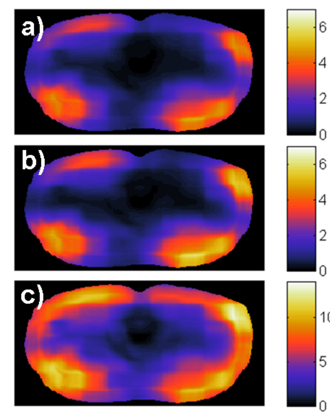

Fig. 2 SAR distribution in excited slice for exc. pattern 2 & acceleration 3
a) SAR for designed pulse
b) SAR for erroneous RF pulse
c) worst-case analysis SAR

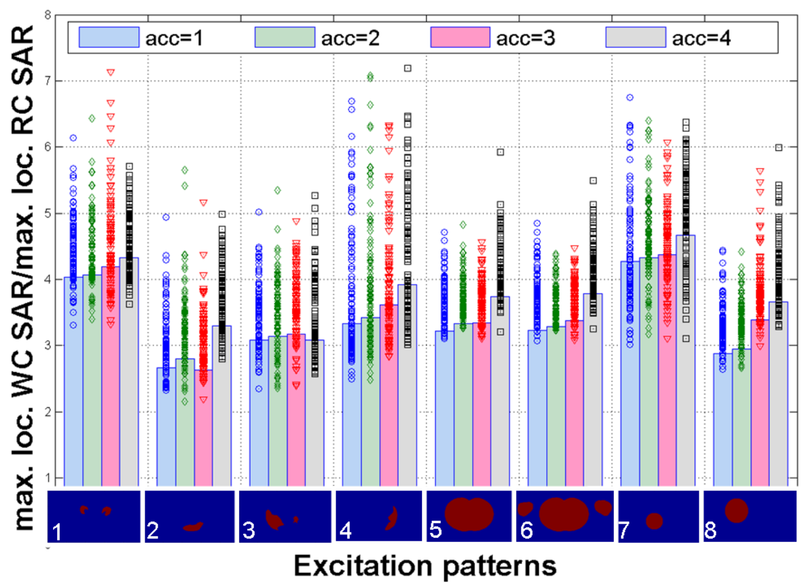

Fig. 3 Ratio of worst-case analysis maximum local SAR of the designed pulse to real maximum local SAR of i) the correctly executed PEX pulses (coloured bars) or ii) the erroneously executed RF pulses (O, ◊, ∇, □)

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