Method for monitoring safety in parallel transmission systems based on channel-dependent average powers

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Introduction: RF safety is a prerequisite to be able to fully exploit the capabilities of parallel transmission. Because of the technical challenges in waveform monitoring and uncertainties in the models and simulations, several approaches have been proposed that circumvent some of the difficulties by making conservative assumptions [1]. Although such conservative approaches can be safer and easier to implement, they usually come with a substantial overestimation of the SAR, depending on the type of assumptions being made [1]. In this abstract, we present a method for monitoring the SAR based on the average power for each channel of a Tx array. It is still conservative in the sense that the phases are ignored so that constructive interference of the E-fields is assumed everywhere. The calculation however depends only on the average power of each pulse so that their shape is irrelevant and real-time amplitude monitoring is not required. We prove that this computation actually constitutes an upper bound of the SAR that would be obtained if the true waveforms, but still ignoring the phases, were taken into account and show numerically that it yields a mild 20-30% overestimation of that result.

Theory: Let $f_i(t)$ denote the desired waveforms to be played on channel #i of a Tx array (N is the number of channels available). We assume constructive interference of the E-fields everywhere and hence take $f_i(t)$ to be real and positive. With these assumptions, the true SAR at point **r** will be:

$$SAR(\vec{r}) \le \frac{\sigma(\vec{r})}{2\rho(\vec{r})}\frac{1}{T}\int_0^T\left(\sum_{i=1}^{N} f_i(t)\left\|\vec{E}_i(\vec{r})\right\|\right)^2 dt = \frac{\sigma(\vec{r})}{2\rho(\vec{r})}\frac{1}{T}\left(\sum_{i=1}^{N}\left\|\vec{E}_i(\vec{r})\right\|^2\int_0^T f_i(t)^2 dt + 2\sum_{i\neq j}^{N}\left\|\vec{E}_i(\vec{r})\right\|\left\|\vec{E}_j(\vec{r})\right\|\int_0^T f_i(t) f_j(t) dt\right). \qquad (1)$$

By calling P_i the average power of the pulse: $\frac{1}{T}\int_0^T f_i^2(t)dt = P_i$, and by using the Cauchy-Schwarz inequality we obtain the following:

$$rhs\ of\ eq.(1) \le \frac{\sigma(\vec{r})}{2\rho(\vec{r})}\left(\sum_{i=1}^{N}\left\|\vec{E}_i(\vec{r})\right\|^2 P_i + 2\sum_{i\neq j}^{N}\left\|\vec{E}_i(\vec{r})\right\|\left\|\vec{E}_j(\vec{r})\right\|\sqrt{P_i P_j}\right). \qquad (2)$$

The upper bound derived above depends only on the average power and not on the RF shapes. Only the monitoring of the average power would then be required if the power thresholds on the different channels were set according to this result. The equality in (2) holds when the waveforms $f_i(t)$ have identical shapes and differ only by a multiplicative constant. For static RF-shimming, this shows that the monitoring of the average power is sufficient and that the real-time monitoring of the RF amplitude is not required if the phases are ignored. Using this new method, the question that remains is by how much do we overestimate the true SAR result?

Methods: We performed full-wave simulations at 297 MHz (7 T) with the finite element method (HFSS, Ansoft, Pittsburgh, PA) to return electric and magnetic fields corresponding to the eight different channel excitations of our Tx array coil. An eight-tissue human head model was placed in the centre of the coil [2]. Using these maps, we designed pulses based on a 1 up to 5-spokes k-space trajectory [3] to homogenize the FA (target of 10°) over a central slice of the brain (1 spoke sinc pulse duration = 0.7 ms, time-bandwidth product = 4.2). For each optimized pulse, we did three types of SAR calculations (global and peak 10g). The first method consisted of using the rhs of eq. (1), therefore ignoring the phase information but still considering the actual waveforms ("the real-time amplitude monitoring method"). The second method used the rhs of eq. (2) and therefore used only the average power information ("the average power monitoring method"). Last, we calculated the true SAR by taking into account all the amplitude and phase information.

Results and Discussion: Fig. 1 shows the overestimation factor (SAR of method x)/(True SAR) for the two different methods. For both methods, the global SAR was always more overestimated than the peak 10g SAR with ranges of 4-5.7 and 2.5-5 respectively. One can notice that for 1 spoke, the results returned by the two methods are equal, which is simply due to the fact that the waveforms among the different channels are the same up to a multiplicative constant. Fig. 2 provides the relative overestimation of the two methods versus the number of spokes for the global and peak 10g SAR. As the number of sub-pulses increases, there is more possibility of differing in shapes thereby yielding a larger overestimation. With 5 spokes, the relative overestimations of the average power monitoring method with respect to the real-time amplitude monitoring one peaked only at 27 % and 19 % for the global SAR and peak 10g SAR respectively. Although not shown, roughly similar numbers were found for spiral trajectories.

Conclusion: We have derived an upper bound of the SAR that can be used for monitoring RF safety in parallel transmission systems. Such bound is very fast to compute since it depends only on the pulse average powers and not on the actual RF waveforms. Furthermore we have shown that the real-time monitoring of the amplitude of the waveforms (not the phase) during a scan seems to yield a very modest gain in the power thresholds compared to the approach based on the monitoring of the average power only. Although with this method the overestimation of the true SAR is still significant, so that it leaves room for improvement, this cost seems reasonable at the present time considering the uncertainties in the models and the importance of the topic in terms of patient safety.

References: [1] I. Graesslin et al. in Proc. of the 16th ISMRM meeting, p 74 (2008). [2] N. Boulant et al. in Proc. of the 18th ISMRM meeting, p 1788 (2010). [3] S. Saekho MRM 2006;55:719-724.

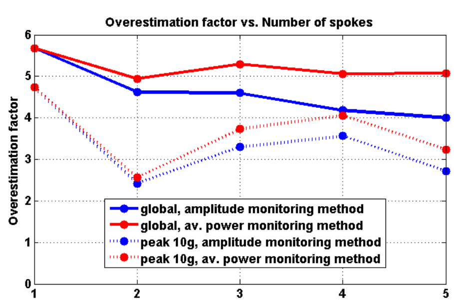

Fig. 1: In blue: ratio between the SAR calculated using the real-time amplitude monitoring method and the true SAR. In red: ratio between the SAR calculated using the average power monitoring method and the true SAR. Solid lines: results for the global SAR. Dotted lines: results for the peak 10g SAR.

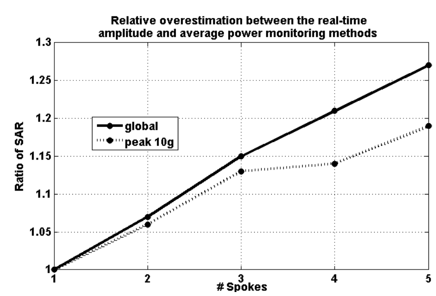

Fig. 2: Ratio between the SAR calculated using the average power monitoring method and the real-time amplitude monitoring method (solid line: result for the global SAR, dotted line: result for the peak 10g SAR).