Fast Whole-Body Temperature Estimation for Real-Time MRI Safety Assurance

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Target audience: anyone interested in RF safety and specifically in fast temperature calculation.

Introduction: Currently 10g average SAR is the quantity most used to assess RF safety with respect to localized heating, even though temperature through time (i.e., thermal dose) has a much more direct relationship to risk. However, temperature is usually not computed at all due to the complexity of the methods and to the computation time requirements. For this reason, recently some fast calculation methods have been proposed [1-5]. One method [3] allows rapid calculation of the temperature throughout the body during time-varying SAR absorption, by convolving the precomputed temperature increase of the body for a unit power SAR segment with the sequence of power levels used in the MRI scan. Here this method is combined with a method for considering effect of SAR on core body temperature to demonstrate real-time prediction for an actual MRI exam requiring several different imaging sequences with high-SAR levels and numerous different SAR distributions due to re-positioning of the body in the scanner.

Methods: The temperature during a MRI exam of the spine requiring high-SAR sequences while imaging regions from the cervical, thoracic, and lumbar spine was calculated. The temperature (T) over time was estimated using the Pennes Bioheat Equation:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) - W \rho_{bl} c_{bl} (T - T_{bl}) + Q + \rho SAR(t) \qquad (1)$$

where c is heat capacity, W blood perfusion rate, k thermal conductivity, ρ material density, the subscript bl indicates values for blood, and Q the heat generated by metabolism. The parameters $\rho, c, W, \rho_{bl}, c_{bl}$, and Q in equation (1) were time invariant (ensuring conservative temperature prediction), while the core body temperature T_{bl} was allowed to increase [6].

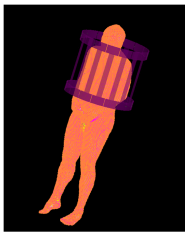

Figure 1: Geometry of the problem. During the entire exam, the subject was positioned at 6 different locations for various imaging sequences.

The patient was placed in 6 different positions during the exam. *Before the exam:* For each of these positions the electromagnetic fields and the corresponding SAR distribution, as generated with a birdcage coil operating at 128 MHz (Figure 1), were calculated with a 3D numerical simulator (XFDTD, Remcom). Each SAR distribution has different power levels and distributions through space and time: hence, the term $SAR(t)$ in eq. (1) can be written as $SAR(t) = \sum_{m=1}^{M} SAR_m(t)$ for M different SAR distributions. To accelerate the calculation, the time dependent term $SAR_m(t)$ is expressed in terms of a fundamental rectangular function $SAR_{m,0}(t)$ having positive amplitude at time t=0 and no amplitude for t<0 or t>Δt such that $SAR(t) = \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{c_{m,n}}{c_{m,0}} SAR_{m,0}(t - n\Delta t)$. Here Δt=30s. The constants $c_{m,n}$ were estimated as the the whole body SAR (SAR_{wb}) averaged over the n[th] time interval

$$c_{m,n} = \frac{1}{\Delta t} \int SAR_{wb}(t) dt \qquad (2)$$

And $c_{m,0}$ is the SAR_{wb} corresponding to $SAR_{m,0}(t)$. The tissue response $T_{m,0}(t)$ for the spatial distribution of the single short segment $SAR_{m,0}(t)$ was calculated with a finite difference method. *During the exam:* The temperature increase at any time during the series of SAR levels was calculated by convolving the temperature increase curve with the sequence of N scaled pulses, as shown in Figure 2, according to the formula $T_m(t) = \sum_{n=1}^{N} \frac{c_{m,n}}{c_{m,0}} T_{m,0}(t - n\Delta t)$. Due to the linearity of Eq. 1, the temperature increase is given by: $T(t) = \sum_{m=1}^{6} T_m(t)$ (6). The accuracy of the method was validated by comparing the calculated temperature distribution with the full finite difference method where the power levels have not been averaged over each Δt according to eq. (2).

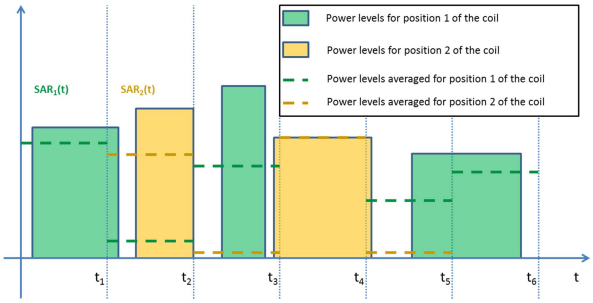

Figure 2: Schematic of the power levels for two different real-time SAR distributions (solid bars), and the levels averaged over time segments having duration Δt (dashed lines).

Results and Discussion: The proposed method provides an accurate calculation of the temperature in a short time, capable of calculating the temperature rise from a 1 hour exam in less than 2 minutes, while the computation time for the full finite difference method is more than one hour. The method was implemented with an in-house C++ code on a personal computer having 8 GB of RAM and 3 GHz CPU processor. The method can be further accelerated with parallel computing implementation, but it already provides results in a time short enough to allow real-time temperature prediction during an MRI exam. The results obtained with the fast computation method predict a maximum temperature increase less than 1% from that of the full finite difference method (Figure 3).

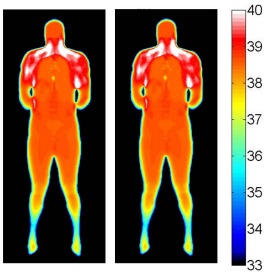

Figure 3: Comparison between the temperature distribution at the end of the exam calculated with full FD method (left) and the fast impulse response prediction (right).

References:

1. Carluccio G *et al.*, IEEE TBME, 60:6:1735-1741, 2013. 2. D Shrivastava, JT Vaughan, 2009, J Biomech Eng., Jul;131(7):074506. 3. Carluccio G *et al.*, Proc. 21st ISMRM, p. 4425. 4. Borup *et al.*, IEEE MTT, 32:4:355-360, 1984. 5. Collins CM *et al.*, JMRI, 19:650-656, 2004. 6. Carluccio G *et al.*, Proc. 21st ISMRM, p. 4433.