Predicting Long-term Temperature Increase from Time-Dependent SAR Levels with a Single Short-term Temperature Response

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Introduction: Currently, 10g SAR is the quantity used most often to assess safety with respect to local tissue heating during MRI, although the 10g averaging is cumbersome and time-consuming to perform and by itself SAR is a quantity with limited direct relation to risk. While temperature increase has a much more intuitive and direct relationship to risk it is typically not calculated at all due to the associated complexity and time requirements. To improve the prospects for more valuable real-time safety assessment based on rapid temperature-based predictions, fast methods for temperature computation [1] and measurement [2] have been recently proposed an demonstrated for fairly simple (boxcar-type) heating time courses. In a patient exam, typically a series of sequences with very different power levels and Specific energy Absorption Rate (SAR) levels (and possibly different SAR patterns) are applied. By taking advantage of the linear nature of heat equations, it should be possible to predict temperature increase over an entire patient exam after characterizing the temperature response to only brief period of heating for each SAR pattern. Here we present a new method for extremely rapid prediction of temperature increase for time-varying SAR levels after calculating the tissue response to a short SAR pulse.

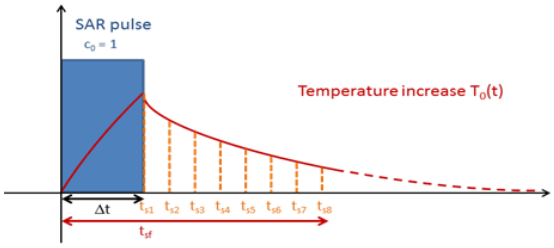

Figure 1: In this work, characterization of temperature response from a single application of heating of duration Δt includes sampling of temperature decay at regular intervals until exponential decay can be assumed.

Methods: For a given SAR distribution, increase of temperature (T) over time can be estimated using various methods, including 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. Assuming that the parameters $\rho, c, W, \rho_{bl}, c_{bl}, Q$ in equation (1) are time invariant, the time dependent term $SAR(t)$ can be decomposed into a sequence of short pulses applied sequentially, such as

$$SAR(t) = c_1 SAR(t_1) + c_2 SAR(t_2) + c_3 SAR(t_3) + \ldots \quad (2)$$

where each single $SAR(t_i)$ short pulse has duration Δt and spatial distribution but can be scaled with the use of the constants c_i. In order to predict the temperature increase after a number of arbitrary pulses of duration Δt, it is necessary to first characterize the tissue response to a single SAR application of duration Δt having a scaling factor c_0. In this work, we characterize this response over time with numerically-calculated values sampled at times t_{si} (Figure 1) until the temperature decays exponentially, whereafter it is fit with an exponential prediction in order to reduce the time required for characterization, since the acceleration rate of subsequent predictive method is equal to the total heating time (t_h) divided by the time of the final sample (t_{sf}). The curve representing the characterized impulse response $T_0(t)$ is equal to the sampled data for $t < t_{sf}$ and the (exponential) predicted curve for $t_{sf} < t < t_f$. Once the response to one period of heating has been characterized (by any method), the temperature at any time during the series of SAR levels can be calculated by convolving the temperature response curve with the sequence of N scaled pulses, as shown in Figure 2, according to the formula $T_n(t) = \sum_{n=1}^{N} c_n / c_0 T_0(t - n\Delta t)$ (3).

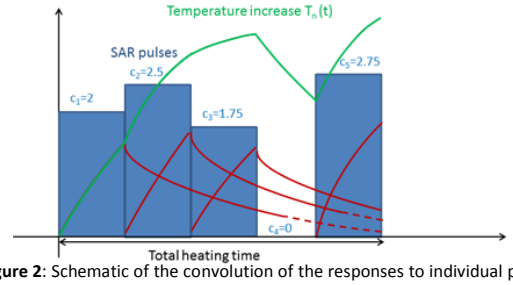

Figure 2: Schematic of the convolution of the responses to individual periods of differing SAR (red) to compute the resulting temperature(green).

Even though the method has presented here when applied to Pennes' bioheat equation, it can be used to every bioheat model where the relationship between SAR and temperature is linear, such as more complicated models where blood temperature T_{bl} is not time invariant [3]. The method is also very useful to compute Cumulative Equivalent Minutes at 43 degrees C (CEM43), a measure of thermal dose that can be used to estimate risk to specific tissue types [4], since the method allows the rapid prediction of the temperature throughout an entire patient exam. This method could also utilize characterizations based on measured temperature response to a single SAR pulse [2], with the experimentally measured data replacing the numerically calculated data used here. Operating in this way, it may be possible to predict maximum temperature increase without the specific knowledge of the SAR spatial distribution and of the parameters distribution in the tissues, such as c, W, k, ρ, but with the only assumption that they are time invariant and that the relationship among them is linear.

Results: The method provides an accurate prediction of the temperature increase in a short time. In the case where characterization of temperature response to a single heating period can occur *a priori* (e.g., for a birdcage oil loaded with an available body model) temperature prediction for the entire imaging period is instantaneous, as soon as required patient-specific power levels for the exam are known. In the case where a more subject-specific characterization requires one tenth of the total imaging time, there would be an effective acceleration rate $R = 10$. For the case of a quadrature surface coil adjacent the occipital lobe with the series of sequences described in Fig. 2, the rapidly-predicted temperature distribution and that calculated with a full numerical method appear in Fig. 3e and 3d, respectively. In this specific case, the temperature computation is also many times faster than 10g SAR determination. Importantly, the maximum accuracy is achieved in the voxels with the highest temperature increase: in the case of Fig. 3 the difference is less than 1%. In Fig. 3f the rapidly-predicted CEM43 distribution is also shown.

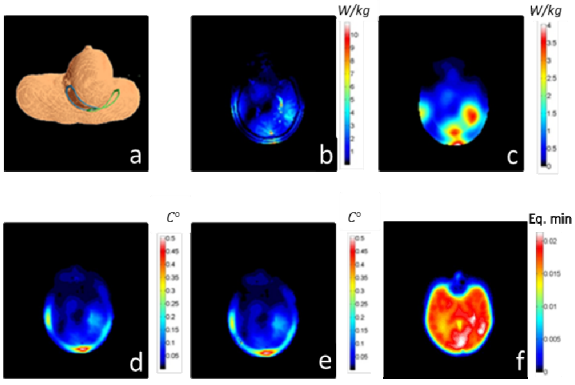

Figure 3: plots of (a) the geometry of the model used for temperature calculations, (b) the unaveraged SAR distribution, (c) the 10g average SAR distribution, (d) the temperature increase computed entirely with a finite difference algorithm, (e) the temperature increase calculated with the proposed fast method, (f) computation of the cumulative equivalent minutes at 43 degrees C (CEM43).

References: 1) Carluccio G *et al*., Proc. 20th ISMRM, p. 3844 2) Cao Z *et al*., Proc. 21st ISMRM 2012, p. 312 3) Shrivastava and Vaughan J Biomech Eng. 2009;131:074506 4) Yarmolenko *et al*., Int. J. Hyperthermia, June 2011;27:320