A simple and conservative method to include variation of core blood temperature with Pennes' bioheat equation

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Introduction: Computation of temperature increase due to Specific energy Absorption Rate (SAR) can provide information more relevant to safety than SAR alone. One of the most commonly-used models to describe temperature increase due to SAR absorption is the Pennes' bioheat equation. As it was first developed to describe very localized heating, one limitation of the Pennes' equation in its original form is the assumption of constant value of blood temperature. While this is expected to be appropriate in cases of high local or regional heating but relatively-low whole-body SAR [1] Some models have been recently proposed [2], which try to overcome this limitation. In this work we present a simple, conservative model to include variation of blood temperature due to whole-body SAR absorption.

Figure 1. Model used for Numerical simulations.

Methods: Pennes' bioheat equation is given by:

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

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 blood temperature term T_{bl} is computed with a simplified version of a previous model for core body temperature in MRI [3] by making conservative assumptions, such as not including the cooling contribution of respiration and by the increase in perfusion rate of skin with body temperature.
The model considers heat absorbed by whole-body SAR (SAR_{wb}) and heat transfer between the blood and the skin, where heat is lost to the air. The SAR_{wb} is redistributed between the skin and body core according to the weight percentage w_{sk} of skin, typically about 10%

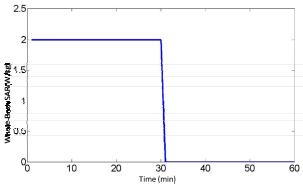

Figure 2. Time course of whole-body SAR.

$$SAR_{bl} = (1 - w_{sk}) W_b \, SAR_{wb} \qquad (2)$$
$$SAR_{sk} = w_{sk} W_b \, SAR_{wb} \qquad (3)$$

where W_b is the mass of the subject. The differential equations describing the time dependent blood temperature increase are:

$$\frac{dT_{bl}}{dt} = \frac{Q_{bl} + SAR_{bl} - A\,K_{blsk}\,(T_{bl} - T_{sk})}{(1 - w_{sk}) C_b W_b} \qquad (4)$$

$$\frac{dT_{sk}}{dt} = \frac{Q_{sk} + SAR_{sk} + A\,K_{blsk}\,(T_{bl} - T_{sk}) - A\,K_{ska}(T_{sk} - T_a)}{w_{sk} C_b W_b} \qquad (5)$$

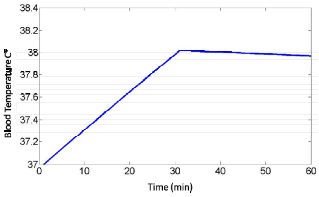

Figure 3. Core blood temperature over time.

where Q_{bl} and Q_{sk} represent the heat generated by metabolism, A is the body surface area, C_b the average heat capacity of the body, T_a the air temperature, K_{blsk}, K_{ska}, the heat conductance respectively between body core and skin, and between skin and air. The computed blood temperature T_{bl} can be either directly used in Pennes' bioheat as a time dependent parameter, or as an external excitation for fast temperature computation methods [4]. In this case, blood temperature can be written

$$T_{bl} = \Delta T_{bl} + T_{bl0} \qquad (6)$$

where T_{bl0} is the equilibrium blood temperature before external SAR application, and ΔT_{bl} the time-dependent blood temperature increase. Replacing eq. (6) in eq. (1), the term $W \rho_{bl} c_{bl} \Delta T_{bl}$ can be summed to the SAR spatial distribution and the sum can be considered as the total excitation. The method has been tested with a body-size 8 channel stripline array (Fig. 1) when producing a whole-body SAR equal to 2 W/kg for 30 minutes. The blood temperature evolution was computed over 60 minutes, including a 30 minute cool-down period, as shown in Fig. 2. The spatial temperature distribution in the body has been computed with a simulator based on finite-difference analysis.

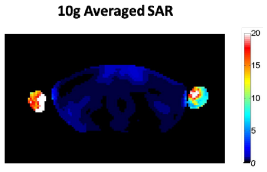

Figure 4. Spatial SAR distributions.

Results: Fig. 3 shows the blood temperature increase, with a linear increase during the first 30 minutes, and a gradual reduction when no power is applied. Fig. 4 shows the 10 g averaged SAR distribution. Fig. 5a shows the spatial temperature distribution by using the Pennes' bioheat equation with the time-invariant blood temperature in a cross-section of the body after 30 minutes with the heating time-course of Fig. 2, while Fig. 5b shows the spatial temperature distribution with the blood temperature time dependence here presented. The comparison between the images of the first row and the ones of the second of Fig. 5 confirm that the presented method provides a solution more conservative than the classic Pennes' bioheat equation, particularly useful in applications with high RF power excitation.

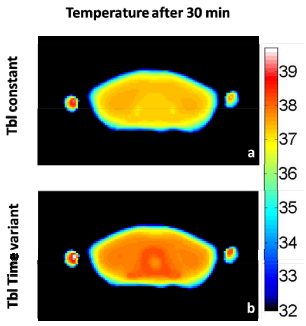

Figure 5. Spatial Temperature distributions.

References:
[1] CM Collins et al., JMRI, 2004, vol. 19, pp. 650-656
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[4] G Carluccio et al., 2011; ISMRM, Montreal; p. 3844