

Underestimation Error in Estimating ‘True’ Local SAR in Perfused Tissues in High and Ultra-High Field MRI

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Target Audience All MR personnel including MR manufacturers, Clinicians, Researchers, Patients, Human Research Subjects, and Regulatory Bodies.

Purpose ‘Excessive’ in vivo heating, that may be produced in humans due to radiofrequency (RF) power deposition from RF coils during imaging at high and ultra-high fields, is a safety concern^{1,2}. Regulatory bodies around the world have specified local and global specific absorption rate thresholds that should not be exceeded to keep the heating within safe limits³. Safe SAR thresholds have been estimated by simulating ‘gold’ standard Pennes bioheat transfer equation (BHTE)^{3,4}.

Developing an RF coil and determining its safe operation (i.e., when the coil produces local SAR hot spots within allowable SAR thresholds) requires developing validated electromagnetic (EM) models of the coil. Validation requires ‘measuring’ local SAR in relevant perfused tissue geometries. Traditionally, local SAR ($\sim C_p \frac{dT}{dt}$) is estimated by measuring the rate of change of local temperature with time (dT/dt) using fluoroptic probes and multiplying it with the specific heat of tissue (C_p). This approach underestimates the true local SAR (SAR_{true}) in a local vasculature dependent manner and is valid only when the temperature of the heated tissue is equal to the temperature of the surrounding blood, as shown below. Mechanistic bioheat transfer models are needed to determine true SAR values.

Current international RF safety guidelines limit the maximum local SAR to 20 W/kg per 10 gram of tissue in the head and trunk, and 40 W/kg per 10 gram of tissue in the extremities averaged over any six minutes of power deposition. The maximum whole-head average SAR is limited to 3.2 W/kg of head weight and the maximum whole body average SAR to 4 W/kg of body weight averaged over any six minutes of power deposition. The maximum whole-body average SAR of 4 W/kg can be delivered for up to 60 minutes. The guidelines expect that this amount of RF energy deposition will result in safe in vivo temperature changes (i.e., core temperature $\leq 1^{\circ}\text{C}$ and local temperature change $\leq 3^{\circ}\text{C}$, assuming core body temperature of 37°C), as simulated using the Pennes BHTE^{3,4}.

Methods Equation 1 below presents the traditional ‘gold’ standard Pennes BHTE. Equation 1 was rearranged as equation 2 to clearly depict the relationship between the ‘true’ (SAR_{true}) and ‘measured’ local SAR ($SAR_{estimated}$) as a function of the thermal diffusion (first term on the right hand side of eq. 2B) and blood perfusion (second term on the right hand side of eq. 2B) related terms. Thermal diffusion related term can be neglected compared to the other terms if the time rate of change of measured temperatures (dT/dt) is nearly linear. Neglecting thermal diffusion, the $SAR_{estimated}$ and SAR_{true} can be related as presented in equation 3. Equation 3 clearly shows that the estimated SAR underestimates true SAR and approaches it only when the temperature of the heated tissue is equal to the temperature of the blood.

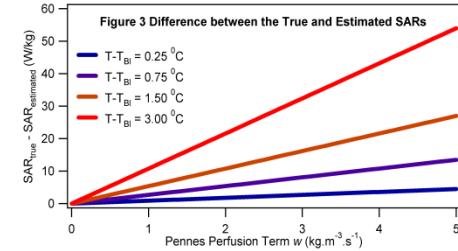
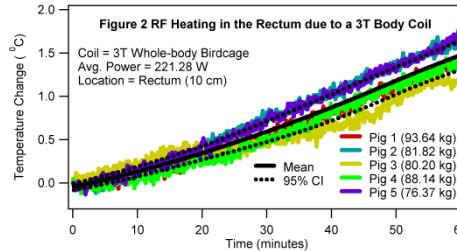
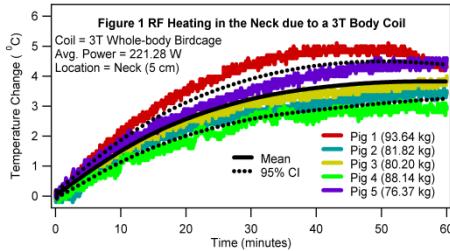
$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T - w C_p [T - T_{Bi}] + Q \quad (\text{eq. 1})$$

$$C_p \frac{\partial T}{\partial t} = \frac{1}{\rho} (\nabla \cdot k \nabla T) - \frac{w C_p}{\rho} [T - T_{Bi}] + \frac{Q}{\rho} \quad (\text{eq. 2A}) \quad \rightarrow \quad SAR_{estimated} = \frac{1}{\rho} (\nabla \cdot k \nabla T) - \frac{w C_p}{\rho} [T - T_{Bi}] + SAR_{true} \quad (\text{eq. 2B})$$

$$SAR_{estimated} \approx -\frac{w C_p}{\rho} [T - T_{Bi}] + SAR_{true} \quad (\text{eq. 3A}) \quad \text{or} \quad \rightarrow \quad SAR_{true} - SAR_{estimated} \approx \frac{w C_p}{\rho} [T - T_{Bi}] \quad (\text{eq. 3B})$$

Blood perfusion in a healthy mammalian muscle and skin may vary from $1\text{-}5 \text{ kg.m}^{-3} \cdot \text{s}^{-1}$ ⁴ in response to heating⁵. The difference between local tissue temperature and core rectal temperature (i.e., assumed as blood temperature in Pennes model) in perfused tissues was measured by exposing five human sized anesthetized swine ($N=5$, mean animal weight = 84.03 kg, SD = 6.85 kg) to an hour long RF power deposition from a 3T body coil in a clinical scanner. The RF heating was produced due to a turbo spin echo (TSE) sequence (whole body average SAR = 2.65 W/kg, SD = 0.22 W/kg) with the pig head in the isocenter. Temperatures were recorded as a function of time using fluoroptic probes in the sub-cutaneous layer of the scalp; 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm deep in the brain after the dura; 5 cm deep and 4.5 cm proximal from the end of the skull, 5 mm lateral to the midline (simulated hot region); and 10 cm deep in the rectum for ~1 hour before the RF exposure started, for ~1 hour during the RF exposure, and for 0.75 hour after the RF exposure stopped. Temperatures in the scalp were measured by placing a fluoroptic probe in the sub-cutaneous layer with an 18G catheter. Temperatures in the brain were measured by drilling an ~18G hole into the swine cranium perpendicular to the coil plane 45 mm away from the back of the skull and 5 mm lateral to the midline and slipping fluoroptic probes through the dura to appropriate depths. Temperature in the neck was measured by placing a fluoroptic probe at the appropriate depth using an 18G catheter. The pigs were kept anesthetized using 1.5–2.5% Isoflurane in 50% air – 50% O_2 during the experiment. The animals’ respiratory rate, end tidal CO_2 , and the % inspired/expired anesthetic agent were recorded manually every 30 minutes. The number of animals was chosen as $N = 5$ since a minimum of 4.0 animals was required to have $>95\%$ power with $P < 0.01$ (two-sided). The animal experiment protocol was approved by the Institutional Animal Care and Usage Committee of the University.

Results and Discussion Figures 1 and 2 present the local tissue temperature change in the hot region and rectum, respectively. Figures show that the difference between local tissue temperature and core rectal temperature (i.e., assumed as blood temperature in Pennes model) in perfused tissues may approach up to 3°C (or more for higher SAR) within first 15 minutes. Figure 3 presents the difference between the true and estimated SARs as a function of the blood perfusion and the difference between the local tissue and blood temperatures. Results show that the local SAR estimated by the conventional method ($SAR_{estimated} = C_p \frac{dT}{dt}$) may be significantly lower than the true SAR (SAR_{true}) and the difference between the two may approach or exceed ‘safe’ SAR limits. Mechanistic bioheat transfer models that can accurately account for the effect of blood flow are needed to determine true SARs.



Summary Conventional measurement of local specific absorption rate (SAR) in perfused tissues underestimates true SAR as a function of local tissue perfusion and the temperature difference between local tissue and blood. Accurate estimation of local SAR is needed to build and operate RF coils within safe SAR thresholds.

Acknowledgments R01 EB007327, R01 EB 006835, P41-EB015894. **References** 1) D. Shrivastava et al., Magn. Reson. Med. (2014). 2) D. Shrivastava and J. T. Vaughan, J Biomech Eng 131 (7), 074506 (2009). 3) IEC, International Electrotechnical Commission 60601-2-33-ed3.0b (3rd Ed3.0b) (2010). 4) H. H. Pennes, J Appl Physiol 85 (1), 5-34 (1998). 5) C. W. Song, A. Lokshina, J. G. Rhee, M. Patten and S. H. Levitt, IEEE Trans Biomed Eng 31 (1), 9-16 (1984).