Correlation of psSAR and tissue specific temperature for 7T pTx head coils - a large scale simulation study

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Target audience: Basic researchers interested in managing RF safety of transmit coil arrays at ultrahigh fields (UHF)

Purpose: Currently, peak spatial SAR10g (psSAR10g) is the basic safety measure for transmit coil arrays. Appropriate limit values for psSAR10g can be found in safety standards, e.g. IEC 60601-2-33. But there is limited knowledge about the correlation of psSAR10g with local tissue temperature which determines the risk of tissue damage according to the thermal dose concept[1]. Previous work in this field[2] mostly compared SAR and temperature distributions for individual RF excitation modes. In the present study we performed thermal simulations for a large set of steering conditions, i.e. amplitudes and phases of the driving voltages of the transmit channels of a 7T 8-channel transmit head coil array, in order to determine the maximum steady state temperatures of different tissue types. To this end, a fast implementation of Pennes' Bioheat Equation on a GPU was developed which allows to perform >1000 simulation runs in a reasonable time.

Methods:

Model: 8-channel decoupled loop array with external shield operating at 300 MHz (s. Fig1.) using 'Ella' as head model. All tissue parameters for EM and thermal modeling were taken from the ITIS database[4,5].

Fig.1: Coil model with 'Ella' (shield not shown).

EM simulations: XFDTD 6.4 (Remcom Inc.), equidistant mesh (2mm), 8 million FDTD cells, CW excitation, 3D data sets of complex valued E, H and J field vector amplitudes were extracted for each of the 8 driving and 16 decoupling ports.

Co-simulation: Tuning, matching and decoupling of coil elements were performed by using T-type matching circuits and decoupling capacitors. Intrinsic coil losses were included in the matching circuit by an additional resistor to achieve realistic quality factor ratios.

Field superposition: For each 8-component, complex valued driving voltage vector $|u\rangle$ all electromagnetic field components (**E**, **H** and **j**) are calculated by superposition of all 24 3D field data sets using the complex valued weighting factors from co-simulation.

Voltage vectors: Voltage vectors $|u\rangle$ were chosen as eigenvectors of a subset of Q-matrices $\mathbf{Q}(\mathbf{r}) = \langle \mathbf{j}^*(\mathbf{r})\mathbf{E}(\mathbf{r})\rangle_{10g}$ obtained from a data compression method similar to the 'Virtual Observation Points' (VOPs)[3]. With $\mathbf{Q}(\mathbf{r}) = \mathbf{Q}_v$ the global maximum of $\langle u|\mathbf{Q}_v|u\rangle$ is given by the largest overall eigenvalue λ_{max}. For a given vector $|u\rangle$ an upper limit of psSAR10g is given by 2ρ psSAR10g $< \lambda_{max}/R + \max\{\langle u|\mathbf{Q}_{vop(i)}|u\rangle\}_{i=1,nvop}$. For the model under investigation and for R = 20 we obtained 873 Q-matrices relevant for psSAR10g determination. At 8 W (4W) of total forward power the voltage vectors corresponding to the largest eigenvalues of these 873 individual Q-matrices result in psSAR10g values spanning almost continuously from about 4 to 20 W/kg (2 to 10 W/kg).

Thermal modelling: Pennes' Bioheat Equation[1] (PBS) was implemented on exactly the same FDTD mesh as the EMF calculation. This was done to avoid any discretization artifacts, when the heat generation terms $\mathbf{j}^*_{x,y,z}(\mathbf{r})\mathbf{E}_{x,y,z}(\mathbf{r})/2$ do not match with the right tissue type. A numerically stable GPU code was written using the OpenACC framework of the PGI Accelerator compiler suite (The Portland Group, Beaverton, OR). To ensure steady state conditions always 1 h of heating was simulated which takes about 5 minutes on a GPU with 4GB of RAM. Maximum steady state temperatures were determined for four groups of tissue types: (i) muscle, skin and fat, (ii) tissues of the central nervous system, (iii) bone and cartilage and (iv) eye tissues. Furthermore, the following model assumptions were made: There are no systemic effects, i.e. the blood temperature was kept always constant at 37°C. For head coils this can be justified since the total absorbed power is low compared to the total metabolic heat generation rate. The heat dissipation into surrounding air is supposed to be negligible. This is a conservative assumption, taking into account that the patient head is often supported by thermally insulating pads. The same assumption is made for internal air, i.e. heat transfer via air filled body compartments is neglected. Further, the perfusion rate is (conservatively) assumed to be constant, i.e. does not increase with temperature.

Results and Discussion: From Fig. 2 it turns out that care has to be taken when using psSAR10g as a predictor for peak tissue temperatures. Certain steering conditions produce higher tissue temperatures at psSAR10g = 10W/kg than others at psSAR10g = 20W/kg. This is mainly due to the different positions of local SAR hot spots resulting in different temperatures since tissue distribution and perfusion have a significant influence. From the extrapolating lines in Fig. 2 one may conclude that in worst case scenarios tissue temperatures of about 41.5°C (muscle, skin, fat), 41.2°C (bone, cartilage) and 40.5°C (CNS, eye) can be reached when fully exploiting the psSAR10g = 20W/kg limit. Nevertheless, when fixing e.g. the total forward power to 8W, the peak steady state temperature of brain and eye tissue is <39.5°C which would allow the safe operation of the coil when using the thermal dose concept.

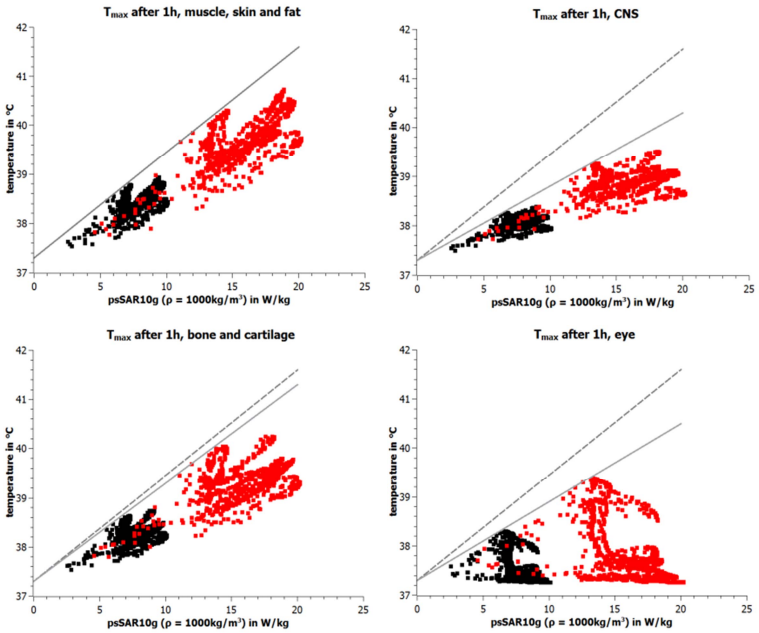

Fig.2: Peak steady state temperatures in dependence of psSAR10g for 4 tissue groups. Overall 2×873 different voltage vectors were used, total forward power: 8 W (red squares) or 4 W (black squares). Solid lines: upper limit extrapolation. Dashed lines: Extrapolating line for muscle, skin and fat.

Conclusion: A fast implementation of Pennes' Bioheat equation was developed which is capable to perform thermal simulations for thousands of different driving conditions of transmit coil arrays. Further, a scheme was presented to construct driving voltage vectors which cover a large range of psSAR10g values at fixed overall input power. Results obtained for a broad range of steering conditions indicate that psSAR10g is not an ideal measure to rely on for patient safety. Nevertheless, constraints for the safe operation of a transmit array coil can be found, e.g. to limit the brain and eye temperature to 39.5 °C which would allow a scan time of more than 2 hour according to the thermal dose concept[1]. We believe that the methods developed in this study represent a widely usable test bed to define robust operating constraints for transmit coil arrays at ultrahigh fields which would allow the safe use of these coils.

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