Simulation of SAR Induced Heating in Infants undergoing 1.5 T Magnetic Resonance Imaging

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Abstract—RF absorption in patients undergoing MRI procedures poses a major safety risk due to resulting heating in the tissue. In order to stay below permitted temperature limits the SAR has to be quantified and limited. Based on the model of an infant inside a birdcage coil we have investigated the SAR distribution in the body at 1.5 T. Thermal simulations could thus be performed to establish a relationship between the limits of SAR and temperature. Results show a thermal hotspot in the neck region caused by high local absorption. The temperature limits in this local area were exceeded after 7 min of excitation within regulatory SAR limits. For a long-term exposure critical organs in the body’s core also undergo thermal stress beyond limitations. This indicates the need for constraints in regard to long MR procedures to consider the temporal aspect of heating.

Clinical relevance—This work establishes a relationship between SAR and temperature in infants undergoing MRI and shows potential risks of long-term procedures due to induced thermal stress.

I. INTRODUCTION

The diagnostic method of magnetic resonance imaging (MRI) is a well-established technique for the visualization of a wide range of diseases and is recommended for use in numerous diagnoses on neonates and infants [1],[2]. Due to its advantages of high resolution combined with excellent soft tissue contrast, this method stands out from the alternatives like ultrasound or computed tomography. With regard to these young patients, the absence of ionizing radiation is of particular importance, as potential long-term radiation damage is avoided. During an MRI scan, the patient is exposed to radio frequency (RF) pulses, which are essential for imaging but have the side effect of causing unwanted energy absorption and induced heating of the tissue. This power can be quantified by the specific absorption rate (SAR). To ensure a low-risk examination, the SAR as well as the temperatures are generally limited by standards [3]. Compliance with these SAR limits is intended to ensure that no temperature limits are exceeded which may cause physiological or sensory effects.

In this work, the temperature rise in the body of an infant as a result of the excitation with a dedicated birdcage coil at 1.5 T is investigated. The formation of local skin temperature hotspots, as well as critical organs, are monitored with respect to the applicable SAR limits.

II. METHODS

To investigate the heat induced in the body of infants during an MR procedure, a detailed setup of the patient and the excitation coil was modeled. The absorbed power was calculated by SAR simulation based on the Finite Integration Technique (FIT) [4]. Subsequently thermal simulations were performed using Pennes’ Bioheat Equation [5] and were evaluated in the tissue over time.

A. Modeling

A birdcage coil was modeled with its geometries for imaging infants. It consists of 16 runs and features a total length and diameter of 26 cm. As a low-pass design, on each rung two capacitors were placed to tune the coil to the Larmor frequency of 63.8 MHz. The birdcage coil was driven in quadrature and an RF shield with a diameter of 28.4 cm and a length of 36.6 cm was used as a reference point for both excitation ports. The structure was complemented by two additional hollow cylinders of FR-4, which typically serve as support for birdcage and shield, having a length of 1 m and a wall thickness of 2 mm.

A heterogeneous voxel model based on an 8-week-old female infant (Helmholtz Zentrum Munich [6]), was used to simulate the absorbed power distribution and consecutive temperature rise in the human body. The infant model has a length of 56.8 cm and a mass of 4 kg. With a voxel resolution of 0.85 x 0.85 x 4 mm (X,Y,Z) a total of 67 pre-segmented tissue types are described. The electromagnetic parameters of the tissues were generated from parameterized Cole-Cole models [7]-[9] and the required thermal parameters were taken from the database of the IT’IS Foundation [10]. The parameters were adapted and assigned to the particular segmentation of the model. The well established Pennes’ Bioheat Equation [4], [11],[12] was used to model the influence of the absorbed power on the temperature change over time $\frac{\partial T}{\partial t}$ as

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) + \rho \text{SAR} + R_B (T_B - T) + Q_M \quad \text{(II.1)}$$

with the density $\rho$, heat capacity $c$, thermal conductivity $\kappa$ and metabolic heat generation term $Q_M$. Blood perfusion in the tissue was modeled by the parameter $R_B$ with a blood temperature $T_B$ of 37°C and can be seen as a compensation mechanism, while SAR as an additive term contributes to a...
temperature increase. The ambient temperature was modeled conservatively at 24 °C without convective effects from air flows. The infant model was positioned head centered for a typical brain examination, as shown in the cross-sectional views in Fig. 1.

![Fig. 1. Head centered position of the infant model inside the birdcage coil. Sagittal and coronal cross-sectional views.](image)

**B. SAR Simulations**

Full-wave electromagnetic simulations were performed using the Finite Integration Technique (FIT) [4] in the time domain using the simulation environment CST-Studio Suite (Dassault Systèmes, France). Based on a convergence analysis with respect to the electric field in the infant and the computational resolution used, a mesh of 6 million cells was chosen. The SAR distribution was calculated in the simulation volume from the power loss and the norm-relevant SAR values in the infant model were extracted. In detail these are the SAR averaged over the whole-body (SAR\(_{\text{body}}\)), the effective partial body (SAR\(_{\text{part}}\)), the head (SAR\(_{\text{head}}\)) and the maximum local value (SAR\(_{\text{local}}\)) averaged over a 10 g element according to IEC 62704-1 [13]. The maximum permitted SAR limits [3] in normal operation mode and an averaging time of 6 min were considered and correspond to Table I. By comparing the calculated SAR values with their regulatory limits, it is possible to specify the maximum permitted RF input power. The SAR simulations, as presented in a previous study [14], show particular high absorption in the neck region, reaching levels about four times as high as the head average. Despite homogeneous excitation, the absorption shows an asymmetric profile, with a hotspot at the left neck curvature. The position of this hotspot is essentially preserved when varying the model position in the transversal plane, although its absolute intensity may fluctuate. The absorption takes place within the body volume inside of the coil and decreases rapidly inward from the periphery towards the inside of the body. These SAR distributions are also comparable to results from Malik et al. [15].

**C. Thermal Simulations**

The dynamic temperature distribution due to the excitation was calculated using a numerical approximation of the before mentioned bioheat equation. Regulatory limits are specified for the maximum permitted temperatures in the human body [3], as listed in Table II. The local tissue temperature \(T_{\text{local}}\) must not exceed 39 °C and no patient’s core body temperature \(T_{\text{core}}\) must increase by more than 0.5 °C. An equilibrium state of temperature in the infant model was calculated, which establishes itself through the body’s own thermal parameters without any RF excitation. This is shown in frontal and cross-sectional views in Fig. 3 and was used as the initial distribution for the excitations. A maximum of 37.6 °C was reached in the area of the heart, 37.3 °C in the brain tissue and a minimum of 36 °C at the toes. Due to the absence of air circulation, there was an additional heat radius around the body. A continuous-wave (CW) excitation amplitude was used, which has been shown to be accurate for thermal simulations without relying on the exact MR sequence [16] with an identical time-average SAR level. At its full saturation of SAR\(_{\text{local}}\) = 10 W/kg, the other regulatory limits were not yet reached, with them being at values of SAR\(_{\text{body}}\) = 1.04 W/kg, SAR\(_{\text{head}}\) = 2.6 W/kg and SAR\(_{\text{part}}\) = 1.91 W/kg. Thus SAR\(_{\text{local}}\) represents the first of the regulatory SAR limits reached and will therefore be used as the critical value, having the most restrictive effect on the excitation.

![Fig. 2. SAR in the head centered infant model with a normalized 1 W input power. Frontal, coronal and sagittal views.](image)

<table>
<thead>
<tr>
<th>(T_{\text{core}})</th>
<th>(T_{\text{local}})</th>
<th>(\Delta T_{\text{core}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>39 °C</td>
<td>39 °C</td>
<td>0.5 °C</td>
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</tbody>
</table>

**TABLE II**

TEMPERATURE LIMITS FOR NORMAL OPERATION MODE [3].

<table>
<thead>
<tr>
<th>SAR(_{\text{body}})</th>
<th>SAR(_{\text{part}})</th>
<th>SAR(_{\text{head}})</th>
<th>SAR(_{\text{local}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 W/kg</td>
<td>2–10 W/kg</td>
<td>3.2 W/kg</td>
<td>10 W/kg</td>
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</tbody>
</table>

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The excitation amplitudes were scaled to result in SAR\textsubscript{local} levels of 10 W kg\textsuperscript{-1}, 7.5 W kg\textsuperscript{-1}, 5 W kg\textsuperscript{-1} and 2.5 W kg\textsuperscript{-1}, representing fractions of the SAR limit exhaustion. The temperature profile in the infant model was calculated under the exposure to the SAR levels over a period of 60 min. The maximum local temperature, as well as that of the brain and lungs, as critical tissues, were monitored. Both the temperature evolution and time points of exceeding critical limits were evaluated.

III. RESULTS

The increase in temperature over time for different excitation amplitudes in the infant model is presented in Fig. 4. The local SAR hotspot (see Fig. 2) resulted in the strongest temperature increase in this area. Along the neck and back area of the head, the heat spread, penetrating into deeper parts of the head over time. Other body regions which also received significant heating, but are not visible in the cross-sectional view to some extent, are spots along the upper arms at 38°C and the eyes at 37.9°C, each after 10 min of excitation with SAR\textsubscript{local} = 10 W kg\textsuperscript{-1} (SAR\textsubscript{head} = 2.6 W kg\textsuperscript{-1}). The brain, as well as the lung tissue, also experienced temperature rises, which developed from the hotspot in the outermost tissues to the interior. Whereas the temperature of the heart remained almost unchanged by the excitation. The temperature rise at the neck resulting from the hotspot is shown in detail in Fig. 5 for the selected excitations over a period of 60 min. A flattening heating was observed, resulting from the interaction of SAR and compensatory processes as perfusion and thermal conduction. The critical value of 39°C was exceeded in the observed time at both values of 10 W kg\textsuperscript{-1} and 7.5 W kg\textsuperscript{-1} for SAR\textsubscript{local}. This occurred after a time of \( t = 7 \) min and \( t = 15 \) min, respectively. An increase to more than 40°C occurred for the 10 W kg\textsuperscript{-1} continuous excitation after 30 min. The SAR of the two weaker excitations was sufficiently low that no rise of \( T_{\text{local}} \) to over 39°C was achieved within one hour. For the brain and lung tissue, the excitations with SAR\textsubscript{local} values of 5 W kg\textsuperscript{-1} and 2.5 W kg\textsuperscript{-1} have not exceeded the limit of a 0.5°C increase. For the 10 W kg\textsuperscript{-1} excitation, brain tissue reached this limit after 11 min and lung tissue after 24 min. The 7.5 W kg\textsuperscript{-1} excitation showed an exceedance for brain tissue after 21 min and for lung tissue after 60 min. The limit exceedances are summarized by Fig. 6. The local temperature limit of 39°C was exceeded first before the deeper tissues, brain and lung, experienced an increase of 0.5°C. By reducing the excitation from 10 W kg\textsuperscript{-1} to 7.5 W kg\textsuperscript{-1}, the time intervals until the limits were exceeded, are approximately doubled.

IV. DISCUSSION

The influence of SAR on heat generation in the body of an infant in undergoing an 1.5 T MRI was assessed and evaluated. The simulation results indicated that a local SAR hotspot is developed and the limit for this is reached significantly earlier than one of the more global limits. With regard to the physiologically relevant temperature, it was shown that after a certain period of time temperature limits were exceeded even if the SAR limits were respected. The
that the intensity of the local hotspot can vary depending on the exact excitation and patient conditions as well as their positioning. In this respect, further simulations in the scope of worst-case assumptions of the parameters or even a sensitivity analysis would be beneficial. Although this would increase complexity, it provides insight into which parameters in particular need to be most precisely defined.

In addition, initial results suggest that the relative absorption profile from a heterogeneous to a homogeneous model varies only slightly at this field strength, allowing geometrically realistic phantoms to be used for profound validation.

Apart from a general reduction of the permitted SAR, this work shows that there is no imperative equivalence between SAR and temperature limits and the importance of special constraints in the case of long-term RF-expositions. These would more strongly emphasize the temporal aspect of heating by MR sequences. With no further restrictions on short SAR limit exhausting scans, this would ensure a low-risk examination without significant thermal effects.

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REFERENCES


