

The Impact of Thermal Modeling on Limiting RF-EMF*

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ABSTRACT

The paper quantitatively assesses the relationship between specific energy absorption rates (*SAR*) of radio frequency (RF) electromagnetic fields (EMF) and resulting intracorporal tissue temperature changes (ΔT) at whole body exposure of a small person to resonant RF EMF. Applied thermal modeling allowed accounting also for dynamic thermoregulatory responses. As expected from physical laws the correlation of all local *SAR* values and ΔT data was fairly good. However, at local level *SAR* proved to be only weakly associated with ΔT . Even if averaged, over any 10 g tissue the ratio $\Delta T_{10g}/SAR_{10g}$ still varied by almost two orders of magnitudes. Blood perfusion was found to play a major role in affecting local temperature changes and caused even net cooling. The results demonstrate that local *SAR* is a poor surrogate for local temperature change, and that conventional static thermal modeling underestimates body core temperature. Results demonstrated that recommended reference levels of RF EMF fail to reliably prevent from exceeding yet legally binding basic restrictions not only with regard to whole-body *SAR* but also with regard to whole-body temperature rise (ΔT). Consequently, from a legal point of view general presumption of conformity is no longer justified. While thermal basic restrictions were exceeded if related to the whole-body averaged value, compliance could not be excluded with regard to body-core related values. Further results might allow improving EMF limiting in terms of relating it more closely to the basic health-relevant parameter which is tissue temperature change.

Keywords: Electromagnetic Fields; Radio Frequency; Health Risks; Tissue Heating; Specific Absorption Rate

1. Introduction

Existing regulations and guidelines for limiting exposures to non-ionizing electromagnetic fields (EMF) such as from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) or the Institute of Electrical and Electronics Engineers (IEEE) aim at defining basic limits for those induced intracorporal quantities which primarily generate health-relevant biological effects. For pragmatic reasons in a second step reference values are derived by numerical modeling linking measurable external field parameters to intracorporal basic quantities [1-4].

For biophysical reasons the frequency range of non-ionizing EMF (up to 300 GHz) can be divided into two basic sections governed by quite different but well established interaction mechanisms.

In the extremely low frequency (ELF) range electric and magnetic fields have to be assessed separately although both induce intracorporal electric field strengths

(and in turn electric current densities), however, with different pathways. Induced electric field strengths may cause the primary biologic effect, namely cellular excitation, provided stimulation thresholds are exceeded. Progress in numerical simulation and digital anatomical modeling allowed more reliably assessing the relationship between magnetic reference levels and basic restrictions which in the meanwhile resulted in doubling former magnetic field reference levels (e.g. at power frequency from 100 μ T to 200 μ T) without challenging the basic restriction [1].

In the radio frequency (RF) range, the situation is somewhat more difficult. While there is widespread consensus that the basic interaction mechanism is tissue heating by absorbed RF EMF energy, until recently the obvious basic biologic quantity, namely induced intracorporal tissue temperature change (ΔT), could not be evaluated with sufficient accuracy, and consequently not reliably linked to external EMF parameters. Therefore, so far, the intracorporal specific rate of RF EMF energy absorption (*SAR*) is chosen as surrogate for the primary

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parameter ΔT that is responsible for established biologic effects [5,6]. In the meanwhile, progress in numerical simulation and digital anatomical modeling allowed demonstrating that RF EMF reference values are not conservative enough to justify presumption of conformity with basic restrictions in any case. Studies reported up to 45% excess of basic restrictions at exposure scenarios of persons with small body height such as children or undersized adults [7-15].

Limiting EMF exposure by basic restrictions and reference levels is based on three essential requirements:

a) knowledge of the primary health-relevant interaction mechanisms for identifying basic intracorporal quantities;

b) knowledge of the frequency-dependent dose response as an indispensable requirement for extrapolation to other exposure conditions and limit setting in the entire frequency range;

c) knowledge of the relationship between basic intracorporal quantities and measurable external field parameters (reference levels).

This paper quantitatively assesses the relationship of EMF-induced intracorporal tissue temperature changes and SAR with particular consideration of dynamic thermoregulation.

2. Method

Numerical investigations were made in a two-step approach. In a first step, the intracorporal SAR distribution has been calculated by the commercial software package CST Studio Suite [16] based on finite integration technique (FIT) [17] at the numerical anatomical model DIZZY of an 8-year-old boy (1.4 m, 26 kg) segmented into $2 \times 2 \times 2$ mm voxels [18]. In a second step the calculated SAR distributions were used for thermal simulation which was based on the bioheat equation [19] which had been further improved by accounting for additional and time-dependent thermoregulatory processes. These were heat-dependent changing metabolic rate A , blood perfusion and vasodilatation B , heat exchange S via tissue/air interfaces at the skin and within the lung, and by heat transfer due to insensible water loss and sweating [7]. This resulted in the following improved bioheat equation

$$\frac{\partial T(\mathbf{r}, t)}{\partial t} = \frac{1}{\rho(\mathbf{r})C(\mathbf{r})} \times \left[(\nabla K(\mathbf{r}) \nabla T(\mathbf{r}, t)) + A(\mathbf{r}, T) - S(\mathbf{r}, T) - B(\mathbf{r}, T)(T(\mathbf{r}, t) - T_b(t)) + \rho(\mathbf{r}) \cdot SAR(\mathbf{r}, t) \right]$$

with the spatial vector \mathbf{r} in m, the time t in s, the specific heat capacity C in $\text{Ws}/(\text{K} \cdot \text{kg})$, the mass density ρ in kg/m^3 , the thermal conductivity K in $\text{W}/(\text{m} \cdot \text{K})$, the

metabolic rate A in W/m^3 , the heat loss at tissue/air interface voxels S in W/m^3 , the blood flow coefficient B in $\text{W}/(\text{K} \cdot \text{m}^3)$, and the absorbed energy rate SAR in W/kg .

After initially calculating the steady-state starting condition, induced tissue temperature changes were determined as a function of time over 60 min to assure ΔT reached the new steady-state. Dielectric tissue parameters were derived from the Cole-Cole model [20-22], thermal parameters were taken from the literature [23,24].

The association between SAR and tissue temperature change ΔT has been quantitatively investigated for a worst-case scenario with plane-wave whole-body RF EMF exposure at resonance frequency and at reference level as defined by exposure limits [2,3].

3. Results

The resonance frequency of the used 1.4 m tall child model at plane wave RF EMF exposure was defined by peaking whole-body SAR (SAR_{WB}). It was found at 90 MHz. The results showed that reference level RF EMF induce an SAR_{WB} of 0.098 W/kg which exceeds the basic restriction 0.08 W/kg by 23%. Thermal modeling demonstrated that the temperature increase ΔT_{WB} , averaged over the entire body (including extremities outside the temperature equilibration body-core zone) is only 0.031 K (Table 1). It has to be noted that hot-spots encountered at the extremities make the whole-body averaged temperature increase ΔT_{WB} by 61% larger than the body-core temperature increase ΔT_{BC} which is averaged over head and trunk only. Consequently, the blood temperature increase which is equivalent to the change of body core temperature ΔT_{BC} , amounted to only 0.022 K which is 27% lower than ΔT_{WB} .

If SAR would be used as a surrogate for temperature increase, the relationship of both quantities SAR and ΔT would be needed to be known. Based on whole-body averages the ratio $\Delta T_{WB}/SAR_{WB}$ was 0.31 K/(W/kg) while $\Delta T_{BC}/SAR_{BC}$ was 0.37 K/(W/kg). To investigate the variability of the relationship between local ΔT and SAR, vertical profiles of slice-averages of horizontal cross sections SAR_{slice} and related temperature changes ΔT_{slice} were determined. Figure 1 shows that both vertical

Table 1. Characteristic values of RF-EMF induced heating in the DIZZY child model.

Region of interest	SAR_{av}	ΔT_{av}	$\Delta T_{av}/SAR_{av}$
	W/kg	K	K/(W/kg)
Whole body	0.098	0.031	0.31
Head & trunk	0.061	0.022	0.37
Extremities	0.159	0.044	0.27

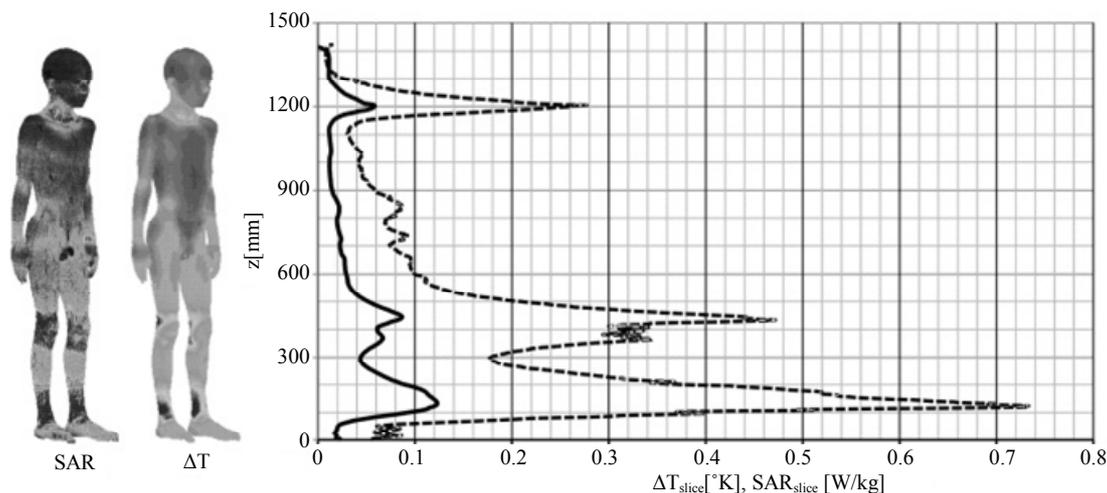


Figure 1. Height profiles of slice-averaged values of SAR_{slice} and ΔT_{slice} with surface distributions of SAR and ΔT at the child model.

profiles are fairly similar. However, while their overall correlation was very good (correlation coefficient 0.987) the ratio $\Delta T_{\text{slice}}/SAR_{\text{slice}}$ varied considerably, in particular up to 6.7-fold in the head region and up to 2.3-fold in the remaining body region, respectively. The ratio peaked at the skull because of weak local absorption (low SAR_{voxel}) and heat transfer from the cerebrospinal fluid and brain regions causing an over-proportional temperature increase. The overall span of the ratio $\Delta T_{\text{slice}}/SAR_{\text{slice}}$ amounted to almost one order of magnitude (0.177 to 1.486).

At voxel level, the association between SAR_{voxel} and ΔT_{voxel} was weaker than at slice-averaged values, but still fairly good (correlation coefficient 0.808). However, detailed analysis of the 3.1×10^6 voxel-values showed that local variations of SAR_{voxel} and ΔT_{voxel} values are rather high. The maximum voxel-values were 4.03 W/kg and 0.24°K, respectively. Interestingly, if drawn one over the other the distribution exhibits a complex structure indicating that the relationship between SAR_{voxel} and ΔT_{voxel} is governed by physiologic heat transfer mechanisms. To demonstrate this, results are presented one over the other (in both versions) for the extremities and the temperature-regulated body core (head and trunk). **Figure 2** shows that the temperature elevation within the temperature-controlled body-core region is clearly lower than at the extremities. In addition, since physiological heat transfer tends to decrease ΔT_{voxel} in voxels with higher absorption rate (heat sources) and to increase ΔT_{voxel} at voxels with lower SAR (heat sinks) the distribution exhibits a two-tear structure which is clearly seen in the head and trunk (torso) data (**Figure 2**). At local level enforced heat dissipation by increased blood circulation can even lead to negative heat balance and negative values of ΔT_{voxel} (net cooling). Please note that the chosen

logarithmic presentation does not allow including negative values; these were omitted.

The role of blood perfusion was investigated by analyzing differently perfused tissues such as muscle and fat. **Figure 3** shows that due to its higher water content and better perfusion muscle exhibits higher SAR_{voxel} but smaller ΔT . Almost the same temperature elevations were found in fat tissue at lower SAR_{voxel} . Due to lower heat dissipation, the same amount of absorbed energy induced higher temperature elevations in fat compared to muscle tissue. Consequently, overall, the distribution associated with fat tissue is shifted towards lower values of SAR_{voxel} (**Figure 3**).

If SAR was a good proxy for ΔT , the ratio of both quantities should be fairly constant. However, this is clearly not the case. This is reflected already by the ratio of medians $\Delta T/SAR$ of the entire fat and muscle tissue. The ratio was 1.85-fold higher at fat compared to muscle tissue with 0.5 K/(W/kg) and 0.27 K/(W/kg), respectively.

The ratio of voxel-values $\Delta T_{\text{voxel}}/SAR_{\text{voxel}}$ varied even more. Ideally, it should be independent on SAR . In fact, it is not. It is systematically decreasing with increasing SAR_{voxel} (**Figure 4**). The overall span is extremely large and amounts to about 4 orders of magnitudes. Evaluated over the whole body, the ratio may exhibit even negative values (which for logarithmic presentation are cut off in **Figure 4**). The ratio $\Delta T_{\text{voxel}}/SAR_{\text{voxel}}$ ranges from -20 K/(W/kg) to at most 45 K/(W/kg) which is 145-fold higher than the ratio 0.31 K/(W/kg) of whole-body averaged values.

Since recommended basic restrictions of RF EMF exposure are based on spatial averages over any 10 g tissue (SAR_{10g}), the distribution of SAR_{10g} has also been analyzed. Compared to SAR_{voxel} the correlation of all values

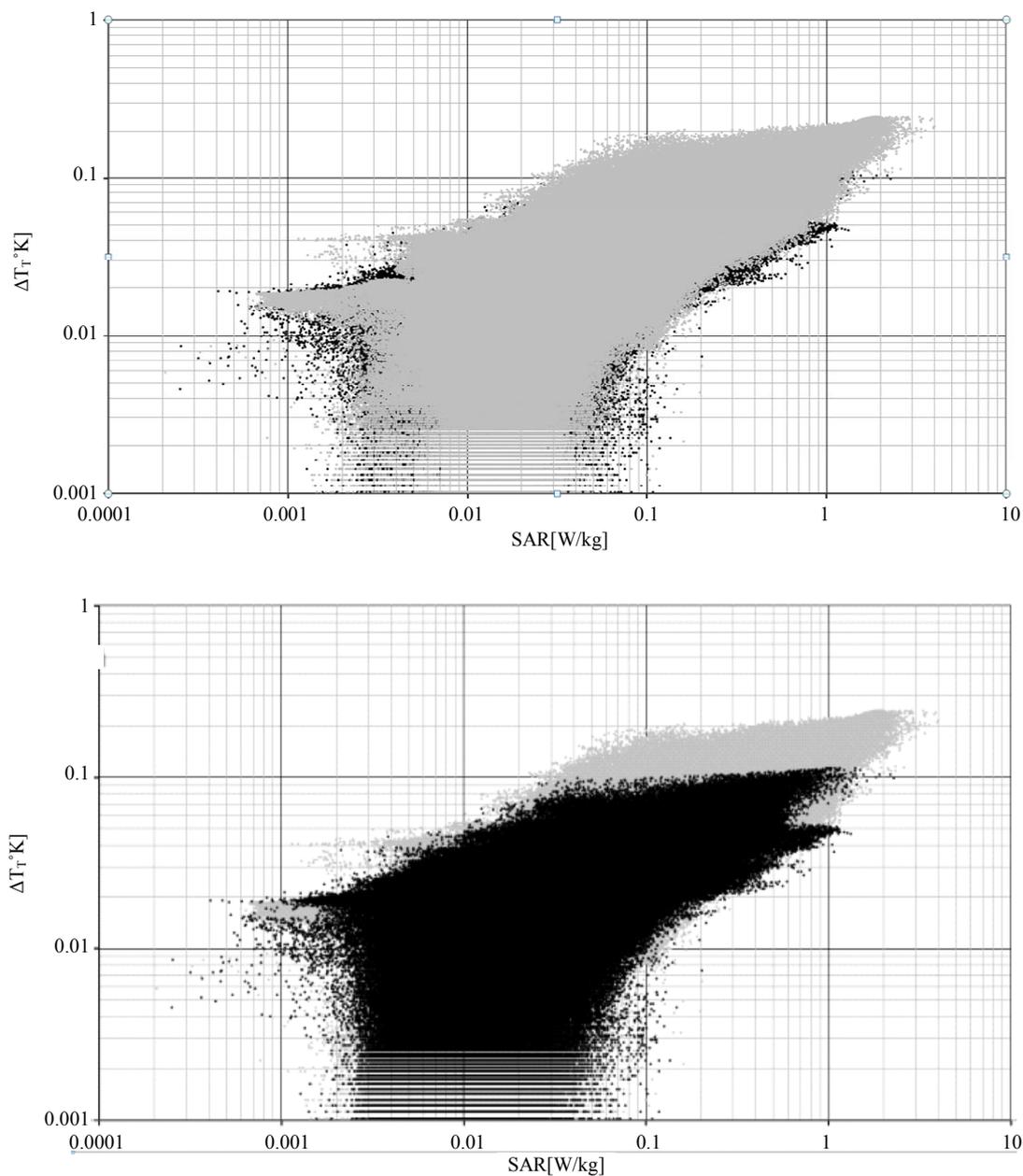


Figure 2. Region-specific voxel-values ΔT over SAR at the child model; extremities over torso (above) and torso over extremities (below); torso (black), extremities (grey).

SAR_{10g} and ΔT_{10g} improved to 0.977, and variability became smaller. The maxima of SAR_{10g} and ΔT_{10g} were 1.19 W/kg and 0.186°C, respectively. Due to averaging, no (local) negative values of temperature changes were found anymore. However, within the body the ratio $\Delta T_{10g}/SAR_{10g}$ still varied considerably. It exhibited a span of almost two orders of magnitudes reaching from 0.11 K/(W/kg) up to a maximum of 9.63 K/(W/kg). The maximum $\Delta T_{10g}/SAR_{10g}$ was still 38.3-fold higher than the ratio of whole-body averages $\Delta T_{WB}/SAR_{WB}$ while the minimum was 2.4-fold lower.

4. Discussion

Any modeling is inherently suffering from unavoidable simplifications and numerical restrictions. This leads to deviations from the real world, and consequently to uncertainties. Sources of uncertainty are discretization, meshing, computational space limitation, boundary conditions, physical tissue properties, and computational algorithms, both for EMF interaction, heating and thermal regulation. To minimize uncertainties, a high spatial resolution of 2 mm was chosen, which among others allowed minimizing staircase effects; meshing was made

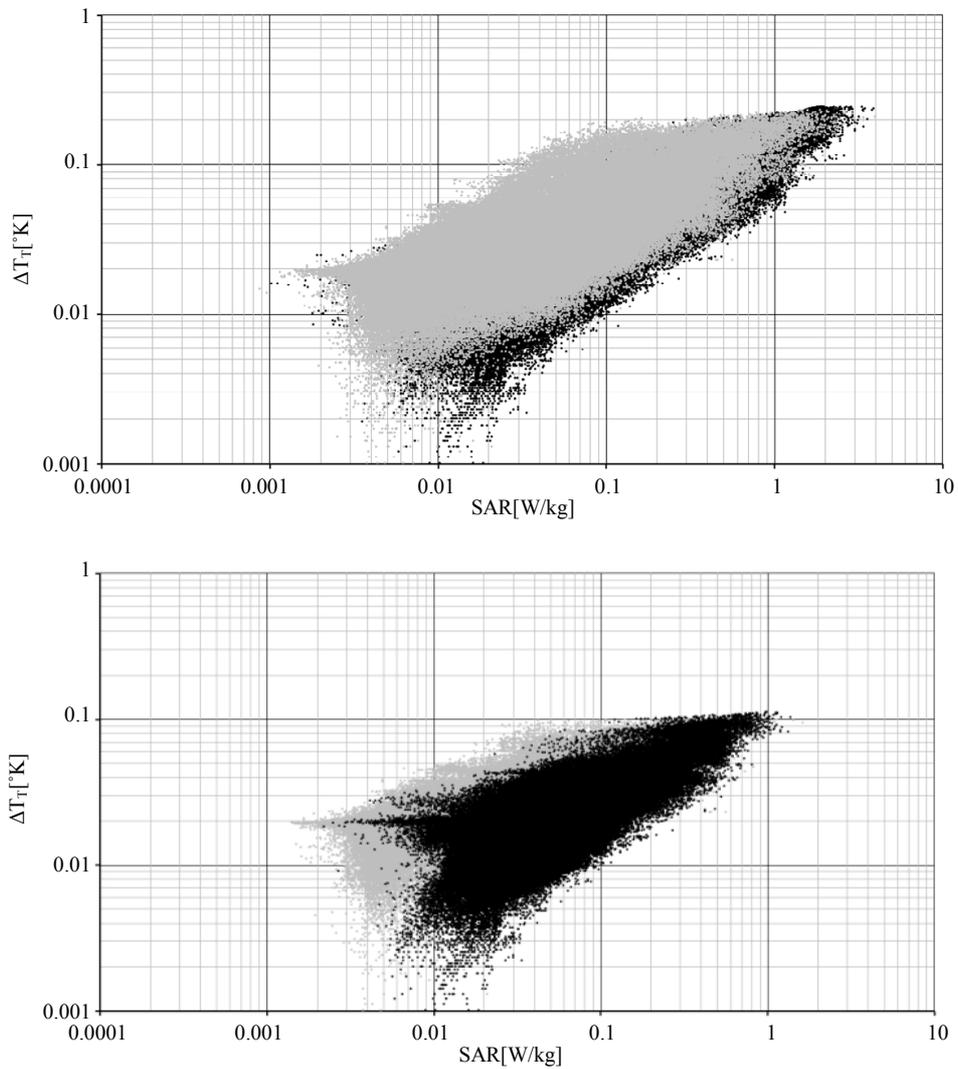


Figure 3. Tissue-specific voxel-values ΔT over SAR at the head and trunk region of the child model, fat over muscle (above) and muscle over fat(below); muscle (black), fat tissue (grey).

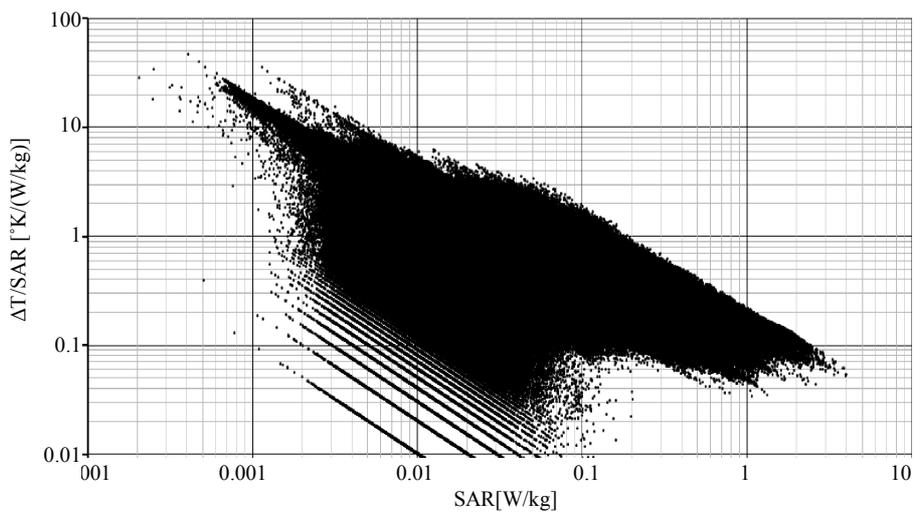


Figure 4. Voxel-related ratio $\Delta T/SAR$ over SAR at the child model.

such as to avoid compromising the high spatial resolution, boundaries were non-reflective and isothermal. This allowed limiting uncertainty to about 1% in accordance to [25]. The uncertainty with regard to tissue properties is caused by their measurement itself, extrapolation from animal tissue to humans and interpersonal variability. The related uncertainty can be estimated to about 10% - 15% for physical and about 10% for thermal parameters, respectively [20-22]. The uncertainty of the numerical algorithm was minimized by carefully setting the termination criteria and can be estimated to less than 5% [16].

The overall performance of the numerical SAR estimation was validated by using the test model as defined in the standard EN 62311 [26] which resulted in a deviation of EMF-induced quantities of 2.8%. Thermal modeling was validated by simulating experiments with provoked body heating caused by exposure to 450 MHz EMF [27]. The deviation from experimental results remained below 20%. This includes overall uncertainties of numerical modeling and those of the experimental approach [28].

In the rationale of recommended guidelines the objective of EMF limitation is declared to prevent from excess heating, in particular from whole-body heating exceeding 1°C [1,3]. The presented results with improved thermal modeling shows, that rather than whole-body-heating the body core temperature rise ΔT_{BC} of 0.022°C is almost low enough to allow concluding that this goal is met in cases of whole body exposure to reference values even in excess of present SAR_{WB} limits. The low temperature elevation is not surprising since in case of induced heat, thermoregulation aims at keeping body's core temperature constant. However, this does not exclude higher temperature rise at local level. Based on the initial bioheat equation, Bakker *et al.* [8] reported a maximum local temperature rise of 1°C. By accounting for dynamic thermoregulatory mechanisms in our study the maximum voxel temperature rise is somewhat lower with a ΔT_{voxel} of 0.24°C. It should be noted that locally averaged values are generally lower than voxel-values. The ΔT_{10g} value which was encountered at the extremities was at most 0.18°C.

One particular finding of this study was that good correlation of the entire voxel data of ΔT_{voxel} and SAR_{voxel} is not sufficient to take SAR as a surrogate for temperature increase. In fact this does not already indicate that local SAR was a good proxy, neither for ΔT at voxel level nor at 10 g average level. The reason is that of course good correlation of the entire data is not surprising and follows already from the bioheat equation. However, biological thermoregulation and tissue-specific heating cause the large variance in the relationship between SAR and ΔT at local level which increases with decreasing averaging volume down to voxels. However, in spite of their fairly good overall correlation even averages over any 10 g

tissue still exhibit considerable variance. These results challenge conclusions drawn from previous thermal modeling suggesting that averaging SAR over a volume such as 10 cm³ (10 g) would be a better predictor of tissue temperature rise although statistically not significantly correlated with ΔT_{10g} tissue [30,31].

The presented results demonstrate that local temperature rise is strongly dependent on the intensity and dynamics of tissue perfusion. Since body-core temperature is regulated by thermal control mechanisms such as vasodilation and insensible water loss, SAR-attributed temperature changes are smaller in body core regions compared to extremities.

Taking local SAR as proxy for local ΔT is conservatively ignoring any heat dissipation and thermoregulation and, hence, implicitly assuming adiabatic heating. However, it does not account for heat dissipation to low SAR-regions which could heat sensible regions even higher than expected. Therefore, if reduction factors were not conservatively chosen, this approach is not necessarily conservative in any case.

The results confirmed that RF EMF reference levels do not prevent small people from exposures exceeding the basic restriction. In this particular case the excess was 23%. This finding is in agreement with the literature reporting overexposures up to 45% [7-15].

In its statement to its guidelines for limiting exposure to RF EMF ICNIRP acknowledged such results and argued, the excess of recommended basic restrictions would be negligible compared to the large reduction factor 50 chosen for the general public [29]. However, while such an argument is acceptable in scientific discussions on health risks, it is inadequate from a legal point of view, since legal restrictions need to be met anyway and do not leave room for further negotiation.

Therefore, such a non-compliant relationship challenges the presumption of conformity with basic restrictions when meeting reference levels. In our case the excess of basic SAR restrictions also leads to exceeding the implicit basic thermal restriction 0.02°C as derived from the objective to prevent from heating above 1°C by applying the reduction factor 50. The excess of the temperature limit was 52% with regard to the whole-body average and 12% with regard to the body-core temperature, respectively. It needs to be noted that the latter remains within the uncertainty range and would not already proof noncompliance.

It has to be stressed that calculation with the initial bioheat equation [19] revealed that the thermal basic restriction was exceeded by only 20% by ΔT_{WB} while ΔT_{BC} remained in compliance with it. The reason for this is that the bioheat equation does not allow dynamic changes of the blood temperature. Consequently, constant blood temperature overestimates cooling and subsequently re-

sults in lower body-core temperatures.

The encountered non-compliance between reference values and basic restrictions requires either adapting reference values and/or basic SAR_{WB} restrictions.

The presented study demonstrates that thermal modeling allows gaining better insight into the relationship between SAR and the objectives of health protection. A potential change from SAR to the biological more relevant quantity ΔT would require further studies on the impact of worst-case scenarios with regard to environment, biology and interpersonal variance.

5. Conclusions

Thermal modeling performed on a small person (child) exposed to resonance frequency (90 MHz) EMF by accounting for time-dependent thermoregulatory processes showed, that in spite of the fairly good correlation between overall data of SAR_{10g} and ΔT_{10g} , local SAR_{10g} values are only weakly associated with local tissue temperature changes. Therefore, local SAR_{10g} is no adequate surrogate to quantitatively assess local tissue temperature changes.

The fact that reference levels do not justify assumption of conformity in any exposure scenario poses a legal problem and requires a solution.

The results confirmed the reported excess of whole-body basic SAR_{WB} restrictions at plane wave EMF exposure of undersized people at reference levels. They demonstrated also that also deduced thermal basic restrictions might be exceeded if related to the whole-body average. However, compliance could not be excluded with regard to body-core averaged temperature rise.

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