On the worst case temperature rise in a one-dimensional tissue model exposed to radiofrequency radiation

Theodoros Samaras[1], Andreas Christ[2] and Niels Kuster[2]

[1]Department of Physics, Aristotle University of Thessaloniki,
GR-54124 Thessaloniki, Greece (theosama@auth.gr)
[2]Foundation for Research on Information Technologies in Society (IT'IS),
Zeughausstrasse 43, CH-8004 Zürich, Switzerland
(christ@it is.ethz.ch, kuster@it is.ethz.ch)

1. INTRODUCTION

The standards and guidelines for limiting electromagnetic exposure are based to a large extent on the thermal biological effects induced to the tissues. However, the basic restrictions are given in terms of field or energy quantities instead of temperature rise.

Recently the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has issued a statement on the protection of patients that undergo MRI examination [1]. This document has the purpose to provide information on levels of exposure and health effects from magnetic and radiofrequency (RF) electromagnetic fields associated with the use of MR diagnostic devices, and on precautions to be taken to minimize health hazards and risks to patients and volunteers undergoing MR examinations. Nevertheless, it describes and considers the health effects that may appear due to whole-body or localized RF heating, and, therefore, can be used as a starting point for a realistic restriction of temperature rise.

According to the document, for localized heating, it seems reasonable to assume that adverse effects will be avoided, with a reasonable certainty, if temperatures in localized regions of the head are less than 38°C, of the trunk less than 39°C, and in the limbs less than 40°C. Therefore, these values give an indication of the limitations that can be considered for the temperature rise due to localized electromagnetic energy absorption.

The present study aims at determining the physiological and physical parameters at specific local exposure situations that may lead to the worst-case temperature rise inside the tissues. The cases studied refer only to limbs and trunk exposure.

2. METHODOLOGY

2.1. Model Description

A 1D model of a tissue slab was used for the study (Fig. 1), which can be a good approximation, as long as the surface curvature radii are not less than 0.1m for a cylinder and 0.15m for a sphere [2], [3]. This can be considered as a condition fulfilled in most cases of local exposure for a standard adult. The 1D model has already been used in the field of RF exposure in a homogeneous [4]-[6] or layered [7] configuration.

The stratification of tissue layers, i.e. the succession of tissues depending on the anatomical site and their thickness, were chosen according to the cases described in [8], because it had been shown that for these configurations the achieved SAR from plane-wave irradiation was maximum, which is expected to result in an increased thermal load in the tissues. The incident power was scaled upwards in the electromagnetic simulation, in order to achieve a maximum averaged SAR of 1.6W/kg for 1g [9] and 2W/kg for 10g [10].

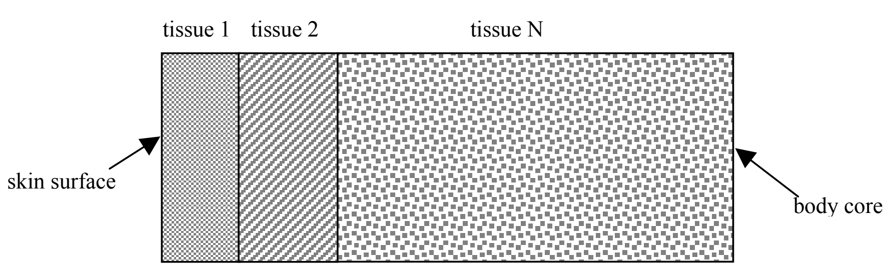


Fig. 1. Schematic diagram of the tissue model

Table 1 contains the thermophysiological and physical properties of the tissues that appear in the various cases. The values are taken from a list taking into account several literature sources. The values for metabolic heat generation are taken from [11]. It is assumed that the properties are constant with time, i.e. the temperature rise is not large enough to trigger local thermoregulation mechanisms, which change blood flow or metabolic heat rate.

Table 1: Thermal properties of tissues in the layered model

Tissue	Thermal conductivity (W/m K)	Specific heat (J/kg K)	Blood flow (W/m^3 K)	Metabolic heat generation* (W/m^3)
skin	0.35	3437	7170	1620
fat	0.25	2524	1671	300
muscle	0.53	3546	1969	480
bone	0.40	1289	2936	610
breast	0.50	2524	1692	300
intestine	0.56	3653	70521	9500
heart (muscle)	0.54	3720	64441	9600
kidney	0.52	3745	270000*	48000
lung	0.44	3625	17698	1700

*based on values in [11]

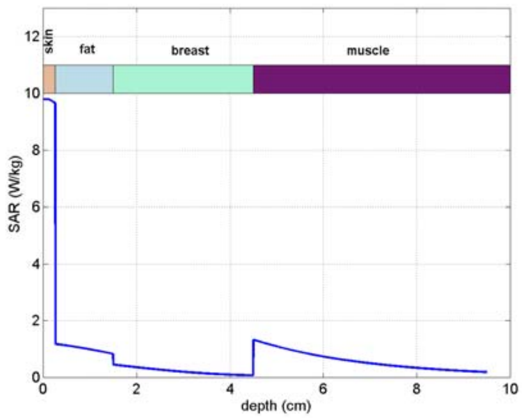
The calculation of the electromagnetic energy absorption in the layered model was based on the transmission line theory and performed in an analytical fashion. This allowed for an enormous number of cases to be examined, in order to find the worst ones from the point of view of the maximum averaged SAR. Temperature computations, on the other hand, were carried out with the finite-difference time-domain (FDTD) method. A uniform grid with a space step of 0.05mm was used.

2.2. Environmental Conditions

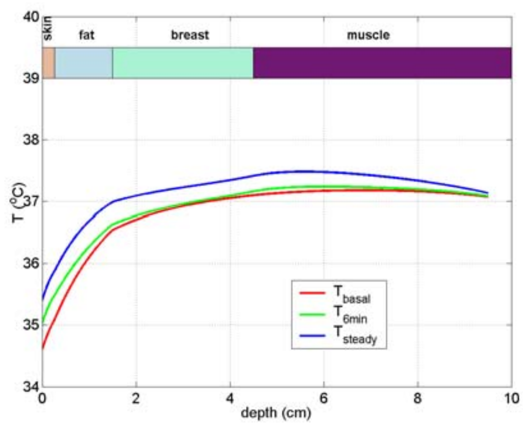
The environmental conditions assumed for the simulations impose the thermal boundaries on the top layer of the model. Initially, the skin was free to convect and radiate heat to the air, so that the basal temperature distribution for the tissues was calculated. The basal temperature was close to 37°C in the deeper tissue layers and lower in the superficial tissues. The combined heat transfer coefficient (for natural convection and radiation to air of 22°C) from the skin was taken at 7 W/(m^2 K). Then, two different situations were simulated during RF exposure, namely those of heat exchange (free convection, radiation) and insulation. The latter is the condition for which no heat is removed from the skin of the body and can occur when the temperature of the surroundings is equal to or greater than the body temperature, or when an insulating material is in contact with it. In such cases, thermoregulation is mainly achieved with evaporation through sweating and/or blood perfusion changes; these mechanisms were not included in the model. At the other end of the model, i.e. toward the inner body, it was assumed that there is heat advection at a very high rate of 70 W/(m^2 K) from the body core temperature, assumed at 37°C.

3. RESULTS

The results are examined in terms of the temperature achieved after 6 minutes of irradiation and at steady state, which was reached for most cases within 30 minutes. In this way, all averaging times considered in the two standards, ranging from 6 to 30 minutes, are taken into account. Fig. 2 shows the case of frontal thorax illumination at 450MHz for the ICNIRP case. The SAR distribution and the resulting temperatures in the model before and after RF irradiation are shown. The role of fatty (breast) tissue is indicated in the higher temperature rise at the beginning of the muscle layer (Fig. 2b), since its low thermal conductivity does not allow heat to diffuse to the skin surface and the environment. A different pattern of temperature distribution is obtained at 5.8GHz (Fig. 3), for which the superficial energy absorption (Fig. 3a) results in a fast temperature rise in the surface tissues (Fig. 3b). The maximum temperature rise in any tissue for all cases examined and for the condition of heat exchange from the skin are shown is Fig. 4. The maximum of temperature rise maximum at high frequencies was located in the skin, with one exception, where it took place in the fat tissue. The omission of heat exchange with the environment gave higher temperature rises (Fig. 5), always in the skin. These results indicate that, unless some thermoregulation mechanism is activated, e.g. increase in blood perfusion, to counteract the effect of the induced thermal load, the temperature rise within 6 minutes can exceed the restrictions set in [1] for the trunk.

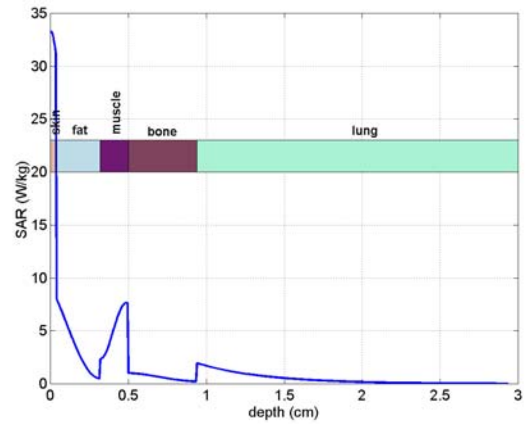


(a)

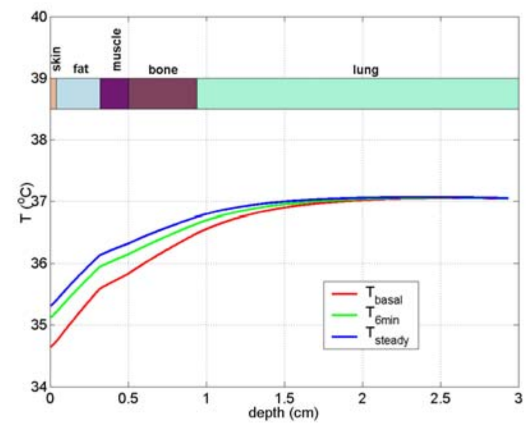


(b)

Fig. 2. Irradiation the thorax front at 450MHz (ICNIRP)



(a)



(b)

Fig. 3. Irradiation the thorax front at 5.8GHz (ICNIRP)

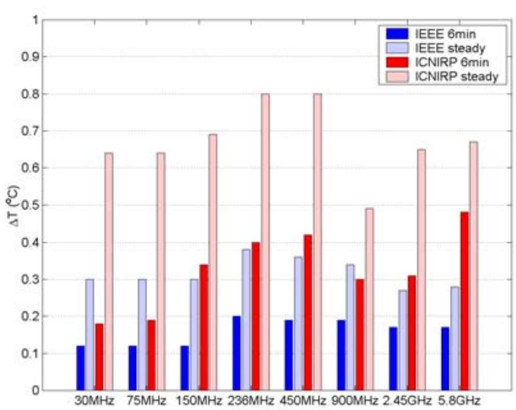


Fig. 4. Maximum temperature rise in the model for natural (free) convection on the skin

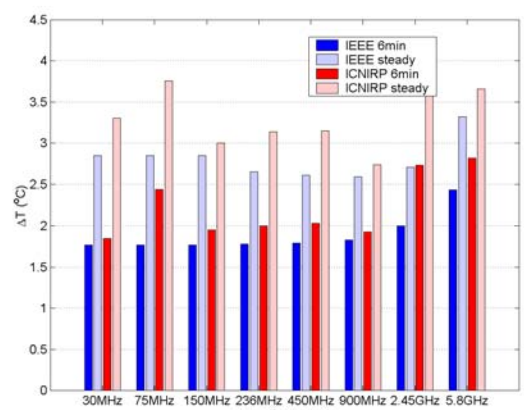


Fig. 5. Maximum temperature rise in the model for adiabatic conditions on the skin

4. CONCLUSIONS

The results of the study have shown that, in terms of worst-case temperature rise, the IEEE standard is more conservative than the ICNIRP guidelines, i.e. when the basic restriction for SAR of either is reached, the former results in a lower temperature rise than the latter. Fatty tissue can act as an isolation layer, as already observed in [7], leading to higher temperature rises in the tissue layers on either of its sides, depending on the energy absorption pattern. The obstruction of heat transfer from the model to the environment leads to a temperature rise in the skin, irrespective of the plane-wave frequency. The maximum temperature rise recorded in such a situation nearly 5 times larger than the one in the case of free convection and radiation.

5. REFERENCES

[1] ICNIRP Statement, “Medical magnetic resonance (MR) procedures: protection of patients”, Health Physics, vol. 87, no. 2, pp. 197-216, 2004.

[2] Z. F. Cui and J. C. Barbenel, “The influence of model parameter values on the prediction of skin surface temperature: I. Resting and surface insulation”, Phys Med Biol, vol. 35, pp. 1683-1697, 1990.

[3] Z. F. Cui and J. C. Barbenel, “The influence of model parameter values on the prediction of skin surface temperature: II. Contact problems”, Phys Med Biol, vol. 36, pp. 1627-1620, 1991.

[4] P. J. Riu, K. R. Foster, D. W. Blick and E. R. Adair, “A thermal model for human thresholds of microwave-evoked warmth sensations”, Bioelectromagnetics, vol. 18, pp. 578–583, 1996.

[5] K. R. Foster, A. Lozano-Nieto and P. J. Riu, “Heating of tissues by microwaves: A model analysis”, Bioelectromagnetics, vol. 19, pp. 420–428, 1998.

[6] K. R. Foster and L. S. Erdreich, “Thermal models for microwave hazards and their role in standards development”, Bioelectromagnetics, vol. 20, pp. 52–63, 1999.

[7] F. Gustrau and A. Bahr, “W-band investigation of material parameters, SAR distribution, and thermal response in human tissue”, IEEE Transactions on Microwave Theory and Techniques, vol. 50, pp. 2393-2400, 2002.

[8] A. Christ, A. Klingenböck and N. Kuster, “Interim Report: Dependence of Electromagnetic Energy Absorption Upon Human Body Tissue Composition in the Frequency Range of 30-5800MHz”, Tech. Rep., Foundation for Research on Information Technologies in Society (IT’IS), Zurich, CH, Feb. 2004.

[9] IEEE Std C95.1-1999, “IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz”, IEEE, NY, 1999.

[10] ICNIRP Guidelines, “Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz),” Health Phys., vol. 74, no. 4, pp. 494–522, 1998.

[11] P. Bernardi, M. Cavagnaro, S. Pisa and E. Piuzzi, “Specific Absorption Rate and temperature elevation in a subject exposed in the far-field of Radio-Frequency sources operating in the 10–900-MHz range”, IEEE Transactions on Biomedical Engineering, vol. 50, no. 3, pp. 295-304, 2003.