Research Article

Effect of adverse environmental conditions and protective clothing on temperature rise in a human body exposed to radiofrequency electromagnetic fields¹

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Abstract

This study considers the computationally determined thermal profile of a finely discretized, heterogeneous human body model, simulating a radiofrequency electromagnetic field (RF-EMF) worker wearing protective clothing subject to RF-EMF exposure, and subject to various environmental conditions including high ambient temperature and high humidity, with full thermoregulatory mechanisms in place. How the human body responds in various scenarios was investigated, and the information was used to consider safety limits in current international RF-EMF safety guidelines and standards. It was found that different environmental conditions had minimal impact on the magnitude of the thermal response due to RF-EMF exposure, and that the current safety factor of 10 applied in international RF-EMF safety guidelines and standards [ICNIRP, 1998; IEEE, 2005] for RF-EMF workers is generally conservative, though it is only narrowly so when workers are subjected to the most adverse environmental conditions.

Keywords: radiofrequency safety standards; RF-EMF worker; temperature rise; protective clothing; occupational safety

INTRODUCTION

This paper considers thermal effects on radiofrequency (RF) electromagnetic field (EMF) workers operating in adverse environmental conditions, and the appropriateness of limits set in international RF-EMF safety standards and guidelines. A range of RF-EMF and

environmental exposure scenarios were thus considered. This follows our initial paper [Moore et al., 2015], which described the development and validation of computational methods employed in this study. That paper described thermal computational methods, based on the well-known Pennes' equation [Pennes, 1948]. Those methods also included thermoregulatory effects, influence of clothing, and the possibility of a change in core blood temperature; the human body model was based on the 'Duke' member of the virtual family dataset [Christ et al., 2010]. Since the results from this paper were specific to Duke, it is important to note that Duke was the model of a 34-year-old male, 1.74 m tall. Further parametric details of the model were provided in Moore et al. [2015], including a metabolic rate of 119.5 W. It was also assumed that Duke represents a healthy thermoregulatory system, similar to RF-EMF workers.

Our interest in RF-EMF workers is due in part because safety guidelines are less stringent for those occupationally exposed, compared to the general public. The International Commission for Non-Ionizing Radiation (ICNIRP) provides the rationale for the relaxed guidelines: "The occupationally exposed population consists of adults who are generally exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions" [ICNIRP, 1998]. However, this also raises the possibility of greater risk. For example, an RF-EMF worker may need to wear a protective uniform that may not be appropriate for certain weather conditions. In hot and humid conditions, the effectiveness of sweating and evaporation will be reduced when workers wear heavily insulated protective clothing that may cover much of the body.

Whenever a person is exposed to RF-EMF, currents and fields will be induced inside the body that will heat tissue due to dielectric losses. In the setting of international safety standards, exposure limits only consider the magnitude of the temperature rise due to RF-EMF. This strategy provides minimal consideration of environmental conditions affecting the person, such as ambient temperature (T_a) and relative humidity (RH), and also clothing that the person is wearing. The impact of these environmental inputs is taken into account through the setting of an additional ‘safety factor,’ a quantity that is the ratio of the exposure level causing an adverse health effect to the corresponding allowable exposure limit. (For a fuller description and definition of terms, see IEEE [2005] and the discussion in ICNIRP [1998].) However, the numerical choice of safety factor is not well justified [ICNIRP, 1998]. This raises the question of whether a given rise, which has no adverse effect in a comfortable environment, may possibly lead to thermal distress or tissue damage in a thermally stressful environment. Thus, an alternative strategy for setting RF-EMF exposure limits may be to consider environmental conditions, either on a temporal or durational basis.

The need to consider protective clothing and its role in the possible compromise of the body’s thermoregulatory system was emphasized in Taylor’s review [2015]. His research team studied various scenarios, including occupational conditions for firefighters and military personnel, and also motorcycle riders who surprisingly exhibited metabolic heat production when riding, which was similar to a person standing at rest. Measurements showed that for moderately adverse conditions (around 35-44 °C and 40-60% RH), hyperthermic states were induced for some of the study participants due in large part to their heavily insulated clothing, though generally only after lengthy study periods of one-and-a-half to three hours. Measurements on persons wearing protective clothing used by firefighters suggested core body temperature elevations of around

0.9-1.4 °C after 90 min at 30 °C and 38 RH. Taylor [2015] emphasized that more demanding physical work, a topic in our future studies, will increase the likelihood of hyperthermia. Clothing may also increase the body's metabolic rate especially if it restricts joint movement when working.

MODELS AND METHODS

Major components of the computational model were outlined in Moore et al. [2015], describing the generation of computational mesh, discretization of the bioheat equation, incorporation of the thermoregulation mechanism, and clothing model imposed as a boundary condition. To briefly summarize the thermal solver, an unstructured polyhedral finite volume mesh was generated from the adult male Duke model. Custom software based on the Insight Segmentation and Registration Toolkit (ITK) [Yoo et al., 2002], Visualization Toolkit (VTK) [Schroeder et al., 2006], and OpenFOAM [Weller et al., 1998] libraries was implemented to convert the voxel model into a mesh model and assign thermal properties to each cell in the mesh. This mesh was comprised of approximately 4 million cells having a spatial resolution of approximately 3 mm. A custom OpenFOAM solver for the bioheat equation incorporating the thermoregulation model of Fiala et al. [1999] was used, performing temporal discretization using the Crank-Nicolson method with a time step size of 10 s. The arterial blood temperature was determined using the approach of Hirata et al. [2007]. The clothing model was based on Wissler and Havenith [2000], who described both heat and mass transport through a clothing ensemble that could be comprised of an arbitrary number of layers, and was implemented as a custom boundary condition.

XFDTD [Remcom, 2016] was used for the electromagnetic solver to determine the Specific Absorption Rate (SAR) (W/kg), using Duke with a 2 mm cubical mesh.

VALIDATION

Validation of our thermal modeling environment was performed in Moore et al. [2015]. That exercise focused on the thermoregulatory response over a 4 h period to changing environmental conditions and compared the calculated results to the measured data of Stolwijk and Hardy [1966]. As the focus of this paper is the thermal response to various RF-EMF exposure scenarios, we continued the validation process, this time using an exact analytical solution to verify the thermal response to RF-EMF. We compared our thermal calculations to results for an infinite ‘muscle’ cylinder exposed to a 2.45 GHz plane wave with incident power flux density $S_{inc} = 1,000 \text{ W/m}^2$ [Bardati et al., 1980; Bernardi et al., 1980]. The peak temperature increase due to the exposure was up to around 5 °C. The cylinder had radius $r = 50 \text{ mm}$, electrical conductivity $\sigma = 2.21 \text{ S/m}$, relative permittivity $\epsilon_r = 47$, material density $\rho = 1070 \text{ kg/m}^3$, blood temperature $T_b = 37 \text{ °C}$, convective heat-transfer coefficient $h = 8.37 \text{ W/(m}^2\text{.°C)}$, specific heat capacity $c = 3140 \text{ J/(kg.°C)}$, thermal conductivity $k = 0.502 \text{ W/(m.°C)}$, heat-sink strength from tissue volume by blood perfusion $b = 1674 \text{ W/(m}^3\text{.°C)}$, metabolic heat production $A_0 = 1005 \text{ W/m}^3$, and $T_a = 24 \text{ °C}$. SAR was calculated using an analytic formulation for the electric field, E (rms Vm^{-1}), presented in Bardati et al. [1980], and then used the formula $\text{SAR} = \sigma |E|^2 / \rho$. This validation

exercise was successful with our thermal profile precisely matching that of Figure 7 in Bardati et al. [1980], examined both part-way through exposure after 10 min and at steady state (see Fig. 1).

MAIN ANALYSES AND RESULTS

In order to assess the effect of RF-EMF, a series of environmental conditions was chosen, ranging from relatively comfortable to extreme. Emphasis was placed on choosing scenarios that would be representative of harsh conditions in order to consider the appropriateness of current safety standards. Results are presented in Table 1 and images are presented in Figure 2 for one of the scenarios. The RH was considered at three levels: 40%, 60%, and 80%; the ambient temperature was between 28 °C and the value that produced a ‘heat index’ of 55 °C. The heat index took into account T_a and RH, and provided what is called the human-perceived equivalent temperature or ‘apparent temperature.’ For each scenario, the heat index was specified using a calculator at the U.S. National Oceanic and Atmospheric Administration (NOAA) website (www.srh.noaa.gov/epz/?n=wxcalc_heatindex). The scenarios were limited to have a heat index of no more than 55 °C, a threshold that when exceeded, the environmental conditions are considered ‘extreme danger’ by NOAA, and where heat stroke is imminent. It is unnecessary for RF-EMF safety guidelines and standards to consider environmental conditions above that threshold since the conditions are already deemed unsafe.

All of the results including temperature, sweat rate, and evaporative loss were recorded when the calculations reached steady state, a state reached in no more than 2 h after the body model, which, initially in the thermoneutral state, was subject to given environmental conditions. For the sake of brevity, only temperature is presented here in tabular form. The RF-EMF exposure was set to be a vertically polarized plane wave directed to the front of the body, with a frequency of 1 GHz in most scenarios.

The first scenario presented is the thermoneutral case (model code ‘T’), which is defined as the steady-state temperature profile of an unclothed person standing at rest (metabolic rate 119.5 W), subject to $T_a = 28\text{ }^{\circ}\text{C}$ and 40% RH [Moore et al., 2015].

In all of the other scenarios, clothing consisted of pants and a two-layer ensemble (shirt and jacket, and socks and boots) elsewhere on the body consisting of a 1 mm air space adjacent to the skin, a single layer of permeable outerwear, a second 1 mm air space, and a single layer of PVC coated outerwear. This clothing was chosen to simulate protective clothing worn by an RF-EMF worker.

The ‘base-line’ scenarios (B1–7) had no RF-EMF exposure. The next scenarios in Table 1 (S1-1–S3-7) had increasing RF-EMF exposure: reference level (25 W/m^2), 0.4 W/kg whole-body average (WBA) SAR, and 4 W/kg WBA SAR. The definition and setting of the reference level and WBA SAR limit (0.4 W/kg) for ‘occupational’ exposure is in ICNIRP [1998], and ‘controlled’ is in IEEE [2005]. The values in brackets represent the change in temperature with and without the addition of RF-EMF. A WBA SAR of 4 W/kg is discussed in IEEE [2005] as being a threshold for behavioral disruption in laboratory animals including nonhuman primates, and has a potentially adverse effect in humans. In ICNIRP [1998], the 4 W/kg level is further discussed as forming the basis “... for an occupational exposure restriction of 0.4 W/kg,

which provides a large margin of safety for other limiting conditions such as high ambient temperature, humidity, or level of physical activity.” It is important to examine this latter statement and how well the 4 W/kg level can accommodate varying environmental conditions. The ability to handle physical activity will be considered in future papers.

The final scenario in Table 1 is presented for considering the influence of frequency (F1-5). Middle-of-the-range adverse environmental conditions were chosen (38 °C, 60% RH). The thermal effects that arise from a 1 GHz dipole antenna positioned vertically 2 mm from the left ear, with the feed-point adjacent to the ear canal, were evaluated in another scenario. However, even at the localized SAR limit, the resultant average tissue temperature changes were insignificant and the results have not been presented.

DISCUSSION

The limitations of our thermal modeling environment were discussed in Moore et al. [2015], including the estimation of blood temperature and fidelity of key parameters such as sweating distribution. The validation study in that paper examined the accuracy of the calculations for subjects exposed to elevated ambient temperature and humidity over a two-hour period. Our results presented here for workers were therefore limited to that length of time, when steady state had already been reached. Our conclusions were also restricted to the scenario of

an RF-EMF worker standing at rest, wearing clothing that consisted of pants and a two-layer ensemble (shirt and jacket, and socks and boots) elsewhere on the body.

The human body's core temperature is normally tightly regulated to within less than 1 °C, with changes of more than 2 °C indicative of loss of thermoregulatory function [Taylor, 2006]. Our results presented in the last column of Table 1 show that the maximum change was 1.4 °C at 4 W/kg (above thermoneutral, comparing models S3-5 and T), indicating a safety factor of more than 10 at the current limit of 0.4 W/kg.

The addition of clothing (in this case protective clothing) by a naked person increased the core temperature by about 0.3 °C and average skin temperature by 0.7 °C (compare models T and B-1). The effect of clothing created a trapped microclimate that was warmer and contained more water vapor than the external environment. The addition of clothing would affect heat transfer and evaporation loss [Taylor, 2006]. For various environmental conditions and for the clothed model with no RF-EMF exposure, the temperature fluctuated in the core by 0.3 °C, in the skin by 0.4 °C, and up to 0.7 °C in the eyes and testes (compare models B1 to B7 in Table 1), with the higher heat indices associated with higher elevations of regional temperature, as expected.

When RF-EMF exposure resulted in 4 W/kg WBA SAR ($S_{inc} = 623.9 \text{ W/m}^2$), the core temperature increased by up to 0.9 °C (compared to no RF-EMF: see core temperature values for S3-1,4,6); however, skin temperature showed a reduction due primarily to evaporation loss, similarly noted in the human volunteer study by Adair et al. [1998] (reduction in back and chest skin temperatures during exposure to an incident field of up to $S_{inc} = 240 \text{ W/m}^2$ at 450 MHz at an ambient temperature of 31 °C) and in the computational study by Nelson et al. [2013] (reduction

in weighted-average skin temperature during exposure to an incident field of up to $S_{inc} = 80 \text{ W/m}^2$ at 100 MHz at an ambient temperature of 31 °C). In our study, evaporation loss was found to be more pronounced as RF-EMF exposures increased, which coincided with increasing rates of sweat. For example, the evaporative loss of a clothed standing person in an ambient temperature of 28 °C and 40% RH was 75 W and sweat rate was around 1.5 g.min^{-1} when there was no RF-EMF exposure (model B-1). Under the same ambient environmental conditions and for an RF-EMF exposure that resulted in 4 W/kg WBA SAR (total RF induced load of 290 W), the evaporative loss increased to 395 W and sweat rate increased to around 12 g.min^{-1} (model S3-1).

Various environmental conditions did not greatly influence the magnitude of localized temperature change due to SAR. For example, even at 4 W/kg WBA SAR, the biggest difference in temperature increase was no more than 0.1 °C (compare eye temperature change values in S3-1 to S3-7). The biggest difference (-0.4 °C) occurred in temperature losses in the skin due to sweating – a sweat rate of around 16 g.min^{-1} at 42.5 °C and 40% RH (model S3-3) compared to around 13.5 g.min^{-1} at 28 °C and 80% RH (model S3-6).

The largest temperature changes occurred in the eye, up to an increase of 2.4 °C (S3-1,2,4,6), and a peak temperature of 39 °C (S3-3). This peak was below the retrolental temperature of 41 °C that is recognized as being required for the rapid onset of thermally induced cataracts [Elder, 2003]. With a WBA SAR of 4 W/kg, the point SAR in the retrolental area was around 22 W/kg.

The scenario with the highest temperatures was for an RF-EMF exposure of 4 W/kg WBA SAR, 42.5 °C T_a , and 40% RH (S3-3). Average temperatures reached 39 °C in the eyes, 38.9 °C in the marrow, 38.5 °C in the brain, and 38.4 °C in the core. Such elevated localized

temperatures in the S3 models, especially when environmental conditions were adverse (such as for S3-3), suggested that the safety factor of 10 at the current limit of 0.4 W/kg applied, but only narrowly. The frequency with the highest temperature changes due to RF-EMF was 3 GHz where there was a 0.5 °C increase in the eyes and a 0.4 °C in the testes (model F4). At 6 GHz it was slightly lower at 0.3 °C in both of those tissues (F4). Thus, it appears important to further investigate various exposure scenarios at 3 GHz in future studies. The core temperature change was 0.1 °C for 100 MHz (F-1) and 1 GHz (F-3).

The calculations in this study were performed using a specific model of a 34-year-old 1.74 m tall male, with a set metabolism and thermoregulatory performance. Considering the well-being of RF-EMF workers allows us to focus on a restricted range of possible models, although comprehensive evaluation still requires that future studies consider effects for women, persons of different body shapes and sizes, and a range of thermoregulatory functions, especially as the latter can change with age up to retirement age. Such a need is emphasized by studies such as Adair et al. [2001], which provided measured data for four men and three women, 31–69 years of age, weighing 66.9–99.1 kg, which we observed were parameters that fit within the possible range for RF-EMF workers. The subjects were exposed to 45 min of RF-EMF at 2450 MHz at an incident power density of up to 700 W/m² (14 times above the limit specified in ICNIRP [1998]) and conducted in ambient temperatures up to 31°C. Adair et al. [2001] documented the range of responses exhibited by the participants, including the range of sweating rates and body temperature values, a valuable source for data on inter-subject variability. Despite the difference in exposure conditions, Adair et al. [2001] also provided an opportunity for a check of our calculations, and their study found an average core-body temperature increase of around 0.15 °C

(estimated using measurements made in the esophagus) following an estimated whole-body exposure of 1 W/kg, which was close to our findings.

CONCLUSIONS

In this paper we sought to consider the extreme scenario of an RF-EMF worker wearing protective clothing subject to adverse environmental conditions and subject to a high level of RF-EMF exposure, and to consider whether SAR limits set in RF-EMF safety guidelines and standards are appropriate for these conditions. We did not consider environmental conditions above a heat index of 55 °C since those conditions are deemed unsafe.

It was generally found that different environmental conditions had minimal impact on the magnitude of the thermal response due to RF-EMF exposure, and the current safety factor of 10 applied in international RF-EMF safety guidelines and standards [ICNIRP, 1998; IEEE, 2005] for RF-EMF workers is conservative. However, average temperature in the eye did reach 39 °C for the most adverse conditions. This suggests that the safety factor of 10, while conservative in most situations, is only narrowly appropriate when workers are subject to the most adverse environmental conditions.

The greatest variation occurred in the skin where temperature changes were due in part to sweating, and the change was a temperature loss. The greatest temperature increase was in the eyes. When the 1 GHz far-field exposure resulted in a WBA SAR of 4 W/kg, the average

temperature increased in the eyeball by the same amount (2.3-2.4 °C) in all scenarios, regardless of the ambient conditions. While noteworthy, the temperature in the eye remained below that associated with cataract formation.

Development of safety limits has been based on studies that showed that WBA SAR of 4 W/kg is a threshold for behavioral disruption in laboratory animals including nonhuman primates. Here we found that core body temperature increased by 0.8-0.9 °C when the body model was subject to a 1 GHz far-field exposure under all environmental conditions considered. This supports the notion that 4 W/kg is a suitable ceiling under which WBA SAR limits should be derived.

In future studies, we aim to simulate the work environment of an RF-EMF worker with multiple RF-EMF sources and elevated metabolic rates (consistent with climbing a structure or other work-related activities) and consider different exposure scenarios, especially for RF-EMF exposure at 3 GHz. To gain an improved understanding of the effect of adverse conditions for all persons, using body models for women and those of different shapes and sizes is necessary, in addition to needing to consider the varying health of the thermoregulatory system.

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Figure 1: Comparison of thermal profile on center-line (front to back) of cylinder.

Figure 2: Profiles of **A**: SAR (unaveraged) (W/kg), and **B**: resultant temperature change (°C), for the right half-head for model S2-5. Effects are greatest on the face as the incident field is directed to the front of the body.

Table 1: Thermal changes in key tissues and the core for a range of environmental scenarios

Model code	Model type ^a	Ambient temp. (Ta) (°C)	Relative Humidity (RH)	Heat index (°C)	RF-EMF ^b	Tissue					
						Skin	Eyes	Testes	Marrow	Brain	Core ^c
Average temperature (°C)											
T	Thermoneutral (no clothing)	28	40%	27.7	No exposure (SAR = 0 W/kg)	34.5	35.9	36.1	36.5	37.0	37.0
B-1	Base-line scenarios (clothing and no exposure)	28	40%	27.7	No exposure (SAR = 0 W/kg)	35.2	36.0	36.6	36.9	37.2	37.3
B-2		35	40%	37.2		35.5	36.4	37.0	37.1	37.4	37.5
B-3		42.5	40%	55.0		35.6	36.7	37.3	37.3	37.6	37.6
B-4		28	60%	29.5		35.2	36.0	36.7	36.9	37.2	37.3
B-5		38	60%	55.0		35.5	36.5	37.1	37.2	37.5	37.6
B-6		28	80%	32.1		35.3	36.0	36.7	36.9	37.3	37.3
B-7		34.7	80%	55.0		35.4	36.4	37.0	37.1	37.5	37.5
Average temperature (°C)											
(± average temperature change due to SAR (°C))											
S1-1	Influence of RF-EMF at the reference level	28	40%	27.7	1 GHz at reference level (S _{inc} = 25 W/m ²)	35.2 (0.0)	36.1 (+0.1)	36.7 (+0.1)	37.0 (+0.1)	37.3 (+0.1)	37.3 (0.0)
S1-2		35	40%	37.2		35.4 (-0.1)	36.5 (+0.1)	37.0 (0.0)	37.2 (+0.1)	37.5 (+0.1)	37.5 (0.0)
S1-3		42.5	40%	55.0		35.5 (-0.1)	36.8 (+0.1)	37.3 (0.0)	37.4 (+0.1)	37.6 (0.0)	37.7 (+0.1)
S1-4		28	60%	29.5		35.2 (0.0)	36.1 (+0.1)	36.8 (+0.1)	37.0 (+0.1)	37.3 (+0.1)	37.4 (+0.1)

S1-5		38	60%	55.0		35.5 (0.0)	36.6 (+0.1)	37.2 (+0.1)	37.3 (+0.1)	37.6 (+0.1)	37.6 (0.0)
S1-6		28	80%	32.1		35.2 (-0.1)	36.1 (+0.1)	36.8 (+0.1)	37.0 (+0.1)	37.3 (0.0)	37.4 (+0.1)
S1-7		34.7	80%	55.0		35.4 (0.0)	36.5 (+0.1)	37.1 (+0.1)	37.2 (+0.1)	37.5 (0.0)	37.6 (+0.1)
S2-1		28	40%	27.7		35.2 (0.0)	36.3 (+0.3)	36.8 (+0.2)	37.1 (+0.2)	37.4 (+0.2)	37.4 (+0.1)
S2-2		35	40%	37.2		35.4 (-0.1)	36.7 (+0.3)	37.1 (+0.1)	37.3 (+0.2)	37.5 (+0.1)	37.6 (+0.1)
S2-3		42.5	40%	55.0		35.5 (-0.1)	37.0 (+0.3)	37.4 (+0.1)	37.5 (+0.2)	37.7 (+0.1)	37.7 (+0.1)
S2-4	Influence of RF-EMF at the occupational WBA SAR limit of 0.4 W/kg	28	60%	29.5	1 GHz at WBA SAR limit ($S_{inc} = 62.4 \text{ W/m}^2$)	35.2 (0.0)	36.3 (+0.3)	36.9 (+0.2)	37.1 (+0.2)	37.4 (+0.2)	37.4 (+0.1)
S2-5		38	60%	55.0		35.4 (-0.1)	36.8 (+0.3)	37.3 (+0.2)	37.4 (+0.2)	37.6 (+0.1)	37.7 (+0.1)
S2-6		28	80%	32.1		35.2 (-0.1)	36.3 (+0.3)	36.9 (+0.2)	37.1 (+0.2)	37.4 (+0.1)	37.5 (+0.2)
S2-7		34.7	80%	55.0		35.3 (-0.1)	36.6 (+0.2)	37.2 (+0.2)	37.3 (+0.2)	37.6 (+0.1)	37.6 (+0.1)
S3-1	Influence of RF-EMF at WBA SAR of 4 W/kg	28	40%	27.7	1 GHz at WBA SAR of 4 W/kg ($S_{inc} = 623.9 \text{ W/m}^2$)	33.6 (-1.6)	38.4 (+2.4)	37.5 (+0.9)	38.6 (+1.7)	38.2 (+1.0)	38.2 (+0.9)

S3-2	35	40%	37.2		34.0 (-1.5)	38.8 (+2.4)	37.8 (+0.8)	38.8 (+1.7)	38.3 (+0.9)	38.3 (+0.8)	
S3-3	42.5	40%	55.0		34.2 (-1.4)	39.0 (+2.3)	38.2 (+0.9)	38.9 (+1.6)	38.5 (+0.9)	38.4 (+0.8)	
S3-4	28	60%	29.5		33.5 (-1.7)	38.4 (+2.4)	37.5 (+0.8)	38.6 (+1.7)	38.2 (+1.0)	38.2 (+0.9)	
S3-5	38	60%	55.0		34.0 (-1.5)	38.9 (+2.4)	38.0 (+0.9)	38.8 (+1.6)	38.4 (+0.9)	38.4 (+0.8)	
S3-6	28	80%	32.1		33.5 (-1.8)	38.4 (+2.4)	37.5 (+0.8)	38.6 (+1.7)	38.2 (+0.9)	38.2 (+0.9)	
S3-7	34.7	80%	55.0		33.9 (-1.5)	38.7 (+2.3)	37.9 (+0.9)	38.8 (+1.7)	38.3 (+0.8)	38.3 (+0.8)	
F-1				100 MHz at WBA SAR limit ($S_{inc} = 23.6 \text{ W/m}^2$)	35.4 (-0.1)	36.5 (0.0)	37.2 (+0.1)	37.4 (+0.2)	37.6 (+0.1)	37.7 (+0.1)	
F-2	Influence of frequency at WBA SAR limit of 0.4 W/kg	38	60%	55.0	500 MHz at WBA SAR limit ($S_{inc} = 61.4 \text{ W/m}^2$)	35.4 (-0.1)	36.6 (+0.1)	37.2 (+0.1)	37.4 (+0.2)	37.6 (+0.1)	37.6 (0.0)
F-3					1 GHz at WBA SAR limit ($S_{inc} = 62.4 \text{ W/m}^2$)	35.4 (-0.1)	36.8 (+0.3)	37.3 (+0.2)	37.4 (+0.2)	37.6 (+0.1)	37.7 (+0.1)
F-4					3 GHz at WBA SAR limit ($S_{inc} = 111.2 \text{ W/m}^2$)	35.5 (0.0)	37.0 (+0.5)	37.5 (+0.4)	37.3 (+0.1)	37.6 (+0.1)	37.6 (0.0)

F-5	6 GHz at WBA SAR limit ($S_{inc} = 252.5 \text{ W/m}^2$)	35.5 (0.0)	36.8 (+0.3)	37.4 (+0.3)	37.3 (+0.1)	37.6 (+0.1)	37.6 (0.0)
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^a All models are of a clothed person, with the clothing is as per an RF-EMF worker, and the metabolic rate as per a standing person. For thermoneutral the body model is unclothed and standing.

^b In all scenarios the RF-EMF exposure is set to be a vertically polarized plane wave directed to the front of the body model.

^c 'core' is defined as the temperature of the blood in the circulation and its value obtained at a point in the pulmonary artery (Lefrant 2003).

^d This and further values for S_{inc} were given by XFDTD after setting the WBA SAR to the value shown

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Figure 1

Figure 2

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