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Kære Anders

Som aftalt før jul fremsender Energistyrelsen materiale vedrørende det forventede eksponeringsniveau i forbindelse med udrulning af 5G. Materialet kan bruges som beredskab og baggrundsviden, når Energistyrelsen offentliggør 5G-handlingsplanen d. 18. februar. Energistyrelsen vil fortsat henvise spørgsmål af sundhedsmæssig karakter, herunder om ikke-ioniserende stråling, til Sundhedsstyrelsen.

Beregningerne er foretaget af mobiloperatørerne og viser effekttætheden for de elektromagnetiske felter fra mobilbranchens basestationer i 2025. Beregningerne viser, at den samlede effekttæthed for de elektromagnetiske felter fra mobilbranchens basestationer i 2025 – efter udbygningen af 5G – stadigvæk vil være væsentligt lavere end de fælleseuropæiske grænseværdier.

Det skal bemærkes, at mobiloperatørernes oplysning om, at ICNIRP er ved at udvikle en ny beregnings- og målemetode for 5G, er forkert. ICNIRP er derimod ved at kigge nærmere på MMW (Milli Meter Waves) eksponering, det vil sige eksponering i det høje frekvensbånd: 6 GHz – 300 GHz. Den nuværende ICNIRP Guideline fra 1998 går allerede helt op til 300 GHz, men erfaringen de seneste par år har vist, at grænseværdierne for det højere frekvensområde er lidt mangelfulde.

Med venlig hilsen / Best regards

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Energistyrelsen

Danish Energy Agency - www.ens.dk
- part of the Danish Ministry of Energy, Utilities and Climate

Energistyrelsen

Effekttætheden for de elektromagnetiske felter fra mobilbranchens basestationer i 2025 - efter udbygningen af 5G - sammenlignet med forholdene i 2019.

Kontor/afdeling
THG / Center for Tele

Dato
5. februar 2019

J nr. xxx

/

I forbindelse med udarbejdelsen af 5G handlingsplanen har Energistyrelsen anmodet den danske teleindustri om at estimere niveauet for den samlede effekttæthed for de elektromagnetiske felter fra mobilbranchens basestationer i 2025, hvor 5G forventes at være udbygget i Danmark.

Det fremgår af vedlagte notat, at mobilbranchen estimerer, at den samlede elektromagnetiske effekttæthed fra mobilbranchens basestationer i 2025 vil være en faktor 1,1 til 1,2 set i forhold til i dag.

Det højeste eksponeringsniveau af den almene befolkning af elektromagnetiske felter fra mobilbranchens basestationer er i dag mellem 10 og 100 gange lavere end de fælles europæiske grænseværdier.

Samlet set betyder det således, at den samlede effekttæthed for de elektromagnetiske felter fra mobilbranchens basestationer i 2025 – efter udbygningen af 5G – stadigvæk vil være væsentligt lavere end de fælleseuropæiske grænseværdier.

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Januar 2019

Elektromagnetisk effekttæthed

Den danske Teleindustris faktuelle bidrag til Energistyrelsen, inden 5G handlingsplan skal offentliggøres.

Formålet med dette dokument er, at estimere den samlede elektromagnetiske effekttæthed fra telebranchens radioudstyr i år 2025, sammenlignet med i dag. Dette understøttes af den estimerede udbygning af fremtidens mobilteknologi, herunder 5G, startende fra 2020 frem til 2025.

Teknologierne udvikler sig hurtigt, og derfor er der betydelig usikkerhed forbundet med at estimere udbygningsplanerne 5 år frem. Derudover vides ikke præcist, hvornår den enkelte teleoperatør vælger at påbegynde 5G udrulningen. Beskrivelsen skal ses som et samlet bud fra Teleindustrien på tværs af de danske teleoperatører.

Forudsætninger

Tidshorisonten er år 2020 – 2025.
Det antages at 700 MHz og 3500 MHz frekvenserne har været i udbud, og at de er en del af teleoperatørernes frekvensspektrum fra år 2020.

Det vil sige at teleoperatørerne har brugsretten over følgende frekvensbånd: 700, 800, 900, 1800, 2100, 2300, 2600 og 3500 MHz.

Det antages, at der i kommende frekvensauktioner ikke indgår dækningsforpligtelser, der påvirker operatørernes udbygningsplaner.

Nuværende situation og forventet udvikling

I 2019 råder teleoperatørerne over følgende teknologier:

2G: Telenor, TDC og Telia

3G: Telenor, TDC, 3 og Telia

4G: Telenor, TDC, 3 og Telia

Teleoperatørerne planlægger i større eller mindre grad 5G i 2019 og vil sandsynligvis påbegynde udrulningen af denne teknologi i 2020. På vejen mod 2025, vil 2G og 3G systemerne udfases, således operatørerne i 2025 primært vil drive 4G og 5G systemerne.

Årsagen til nedlukningen af de ældre systemer skyldes hovedsageligt 3 ting: for det første - at imødekomme en støt stigende trafikmængde på cirka 30% om året (som 4G og 5G bedre kan håndtere), for det andet - at imødekomme de støt stigende kundeforventninger om højere datahastigheder og lavere svartider og endeligt for det tredje - at kunne fjerne omkostningerne til drift og vedligehold af 2G og 3G systemerne. Dette for at kunne investere besparelserne i 5G.

Der er bred enighed blandt teleoperatørerne om, at 5G først udbygges på eksisterende antennepositioner, som i dag anvendes for 2G, 3G og 4G. Fra 2020 vil 5G indledningsvist blive sendt i 700 og 3500 MHz båndene, hvor 700 MHz vil blive anvendt til at give dyb indendørsdækning i byerne og stor areal-dækning på landet. 3500 MHz frekvensbåndet vil blive anvendt i mindre og større byer til at øge datahastighederne og kapaciteten.

Det estimeres, at de danske teleoperatører vil have størstedelen af de eksisterende antennepositioner opgraderet med 5G i 2025. Yderligere estimeres det, at teleoperatørerne frem mod 2025 øger antallet af helt nye antennepositioner med 15-25% af det i 2019 eksisterende antal. Dette billede ligger ikke langt fra Verizons estimat på 25% [Verizon Executive Briefing, 5G: The First Three Years, december 2018, side 5].

Teleoperatørernes udbygning med nye positioner forventes efterhånden også at ske i form af nye små antennepositioner (small og pico cells). De er anderledes, da deres effekttæthed er markant lavere og medfører kortere rækkevidde. Det vil kræve flere små antennepositioner med kortere fysisk afstand, og deres samlede effekttæthed vil være mere jævnt fordelt. Small cells benyttes allerede i dag til 4G.

Mange af disse nye antennepositioner vil blive delt mellem operatørerne således, at landskabet og bybilledet ikke vil ændre sig nævneværdigt på grund af dette.

Estimat på den samlede effekttæthed i forhold til i 2019

Den uafhængige kommission ICNIRP udarbejder grænseværdier, som de danske myndigheder tilslutter sig. Teleoperatørerne i Danmark følger disse grænseværdier og anbefalinger. På nuværende tidspunkt ligger effekttætheden fra mobilmasternes antenner meget langt under de fastsatte grænseværdier.

Teleoperatørerne forventer, at der samlet frem mod 2025 vil ske en begrænset stigning i effekttætheden. Teleoperatørerne estimerer, at den samlede elektromagnetiske effekttæthed fra teleoperatørernes telekommunikationsudstyr i 2025 vil være en faktor 1,1 til 1,2 set i forhold til i dag. Det vil sige, at den samlede gennemsnitlige effekttæthed i 2025 estimeres at stige 10-20% i forhold til 2019.

ICNIRP er i gang med at udvikle en ny beregningsmodel og målemetode for 5G effekttæthed, og teleoperatørernes estimat er udarbejdet, inden ICNIRP har offentliggjort disse nye standarder og retningslinjer.

Der vil generelt blive benyttet flere frekvenser på antennepositionerne, men det vil være mere effektive teknologier, der kan udnytte de lavere signalniveauer. Desuden forventes nye terminaler med bedre følsomhed, som kan sikre en god brugeroplevelse ved et lavere modtaget signalniveau end i dag.

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11 July 2018

Draft

ICNIRP Guidelines

GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC AND ELECTROMAGNETIC FIELDS

(100 kHz TO 300 GHz)

Appendix A: Review of Studies on Dosimetry

International Commission on Non-Ionizing Radiation Protection

1. INTRODUCTION

This appendix provides additional dosimetry information that is directly relevant to the derivation of the radiofrequency exposure restrictions that form the basis of these guidelines. As described in the main document, the operational adverse health effects (OAHETs) resulting from the lowest radiofrequency exposure levels are due to temperature rise (nerve stimulation is discussed and protected against within the low frequency guidelines; ICNIRP 2010). Accordingly, this appendix details the choice of metrics used to restrict temperature rise to the operational adverse health effect thresholds described in the main document, the methods used to derive these restrictions (including, where relevant, the associated uncertainty), the spatial and temporal averaging regimes used to represent temperature rise, as well as the derivation of the restriction values themselves. The OAHETs considered are 1 °C body core temperature rise for whole body exposure, and 5 °C and 2 °C local temperature rise for local exposure of 'Type-1' and 'Type-2' body tissue respectively.

2. QUANTITIES AND UNITS

Detailed explanations for the basic quantities, i.e., $\boldsymbol{E}$, $\boldsymbol{H}$, $\boldsymbol{J}$, I, T, and t are found elsewhere (see ICNIRP, 2009). In this section, the other quantities, i.e., *SAR*, *SA*, S_{inc}, S_{tr}, H_{inc}, and H_{tr} are detailed.

It is noted that radiofrequency basic restrictions and reference levels are based on the adverse health effects caused by the lowest radiofrequency exposure levels; these are thermally mediated. Thermal effects are measured with energy or power. Therefore, squared values of $\boldsymbol{E}$, $\boldsymbol{H}$, and I are considered for time or spatial integration, or where summation of multiple frequencies is applied. The following equation is an example of the spatial average of $\boldsymbol{E}$ over a volume V;

$$E_{spatial\_average} = \sqrt{\frac{1}{V}\int_v |\boldsymbol{E}(r)|^2 dr} \qquad \text{(Eqn. 2.1),}$$

where r is the location in the volume of the integration ($\mathrm{V} = \int_v dr$).

2.1. SPECIFIC ABSORPTION RATE (*SAR*) AND SPECIFIC ABSORPTION (*SA*)

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SAR is defined as the time derivative of the incremental energy, δW, absorbed by or dissipated in an incremental mass, δm, contained in a volume element, δV, of a given density ρ, and is expressed in watts per kilogram (W kg^{-1}):

$$SAR = \frac{\delta}{\delta t}\left(\frac{\delta W}{\delta m}\right) = \frac{\delta}{\delta t}\left(\frac{\delta W}{\rho \delta V}\right)$$ (Eqn. 2.2).

Electrical properties of the biological tissues or organs are generally considered as dielectric lossy material and magnetically transparent because the relative magnetic permeability (μ_r) is 1. Therefore, the SAR is usually derived from the following equation;

$$SAR = \frac{\sigma |\boldsymbol{E}|^2}{\rho}$$ (Eqn. 2.3),

where σ is conductivity (S m^{-1}), **E** is the internal electric-field and ρ is density (kg m^{-3}) of the tissue.

SAR is strongly correlated with tissue temperature elevation. Under the adiabatic condition where no heat diffusion occurs, SAR and temperature elevation are directly related as follows;

$$SAR = C\frac{dT}{dt}$$ (Eqn. 2.4),

where C is heat capacity (J kg^{-1} °C^{-1}) of the tissue, T is temperature (°C) and t is the duration of the exposure (s). Eqn. 2.4 is not applied to actual cases because a large amount of heat energy rapidly diffuses during the exposure. However, the adiabatic temperature elevation formula is useful for brief exposure scenarios where heat diffusion is not significant.

SA is derived as the time integral of the SAR during the time from t_1 to t_2:

$$\mathrm{SA} = \int_{t_1}^{t_2} SAR(t)dt$$ (Eqn. 2.5).

For the adiabatic condition, temperature elevation is simply related to the SA as follows:

$$\Delta T = {}^{SA}\!/_{C}$$ (Eqn. 2.6).

SAR is used as a basic restriction in these guidelines. The SAR basic restrictions are defined as the spatially averaged values, i.e., whole body average SAR and SAR$_{10\mathrm{g}}$. The whole body average SAR is not the average value over the whole body, but the total power absorbed in the whole body divided by the whole body weight:

$$\text{Whole body average SAR} = \frac{(Total\,power)_{WB}}{(Total\,weight)_{WB}} = \frac{\int_{WB} \sigma |\boldsymbol{E}|^2 dv}{\int_{WB} \rho dv}$$ (Eqn. 2.7).

SAR$_{10\mathrm{g}}$ is defined as the total power absorbed in a 10 g cubic volume divided by 10 grams:

$$SAR_{10\mathrm{g}} = \frac{(Total\,power)_{V_{10g}}}{(Total\,weight)_{V_{10g}}} = \frac{\int_{V_{10g}} \sigma |\boldsymbol{E}|^2 dv}{\int_{V_{10g}} \rho dv}$$ (Eqn. 2.8).

A 10 g volume (V_{10g}) is generally defined as a $2.15[\mathrm{cm}] \times 2.15[\mathrm{cm}] \times 2.15[\mathrm{cm}]$ cube, based on the assumption that the tissue has the same mass density as water, or 1000 kg m^{-1}.

2.2. TRANSMITTED POWER DENSITY (S_{TR}) AND TRANSMITTED ENERGY DENSITY (H_{TR})

The transmitted power and energy densities are newly introduced in the guidelines for basic restrictions above 6 GHz, where the radiofrequency power or energy absorption is confined within very superficial regions of the body; e.g., the penetration depths are approximately 1 cm and 0.4 mm at 6 GHz and 300 GHz, respectively; $\mathrm{SAR}_{10\mathrm{g}}$ is no longer an appropriate surrogate for local temperature elevation at such frequencies.

The power and energy absorption are confined within the body surface. Therefore, the transmitted power and energy densities are defined at the body surface;

$$S_{\mathrm{tr}} = \iint_A dxdy \int_0^\infty \rho(x,y,z) \cdot SAR(x,y,z)\, dz / A \qquad \text{(Eqn. 2.9),}$$

where the body surface is at $z = 0$, and A is the averaging area (in m^2). Considering heat diffusion, a 2 [cm] × 2 [cm] (below 30 GHz) or 1 [cm] × 1 [cm] (above 30 GHz) square is used for the averaging area of the transmitted power and energy density basic restrictions.

A more rigorous formula for transmitted power density is based on the Poynting vector ($\boldsymbol{S}$);

$$S_{\mathrm{tr}} = \iint_A \mathrm{Re}[\boldsymbol{S}] \cdot \boldsymbol{ds} / A = \iint_A \mathrm{Re}[\boldsymbol{E} \times \boldsymbol{H}^*] \cdot \boldsymbol{ds} / A \qquad \text{(Eqn. 2.10),}$$

Where Re[X] is the real part of a complex value 'X', and $\boldsymbol{ds}$ is the integral variable vector with the normal direction of the integral area A.

As well as the relationship between SAR and SA, the transmitted energy density is derived as the temporal integration of the transmitted power density:

$$H_{\mathrm{tr}} = \int_{t_1}^{t_2} S_{\mathrm{tr}}(t)\, dt \qquad \text{(Eqn. 2.11).}$$

2.3. INCIDENT POWER DENSITY (S_{INC}) AND INCIDENT ENERGY DENSITY (H_{INC})

The incident power and energy densities are used as the reference levels in the guidelines. The incident power density is defined as the absolute strength of the Poynting vector:

$$S_{\mathrm{inc}} = |\boldsymbol{E} \times \boldsymbol{H}^*| \qquad \text{(Eqn. 2.12).}$$

In the case of the far-field or transverse electromagnetic (TEM) plane wave, the incident power density is derived as;

$$S_{\mathrm{inc}} = EH = \frac{E^2}{Z_0} = Z_0 H^2 \qquad \text{(Eqn. 2.13).}$$

where Z_0 is the characteristic impedance of free space, i.e., 377 Ω. The above equation is also used for the evaluation of the equivalent incident power density.

S_{inc} is also related to S_{tr} using the reflection coefficient R:

$$S_{\mathrm{tr}} = (1 - |R|^2) \cdot S_{\mathrm{inc}} \qquad \text{(Eqn. 2.14).}$$

Similar to the relationship between SAR and SA, the incident energy density is derived as the temporal integration of the incident power density:

$$H_{\mathrm{inc}} = \int_{t_1}^{t_2} S_{\mathrm{inc}}(t)\, dt \qquad \text{(Eqn. 2.15).}$$

In near-field exposure scenarios, the components of the Poynting vector are not real values but complex ones. Detailed investigation for the definition of the incident power density relevant to radiofrequency safety may be necessary for such cases. However, the reactive near-field is limited to within close proximity to the radiofrequency source above 6 GHz.

Furthermore, for cases of oblique incidence of the radiofrequency wave, Li et al. (2018) have shown that the incident power and energy densities averaged over the body surface or boundary surface can underestimate the transmitted power and energy densities in some cases, e.g., transverse magnetic (TM) wave at the incident around the Brewster angle (the angle of

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incidence at which there is no reflection of the TM wave). They also found that normal incidence is always the worst case regarding temperature elevation if the incident and energy power densities are averaged over the area normal to the Poynting vector.

In the guidelines, the basic restrictions and reference levels are derived from investigations assuming normal incidence to the multi-layered human model as the worst-case modeling, which means that the definitions used in these guidelines may be extremely conservative.

3. RELEVANT BIOPHYSICAL MECHANISMS

3.1. WHOLE BODY EXPOSURE

3.1.1. Relevant quantity

Health effects due to whole body exposure are related to body core temperature elevation. It is, however, difficult to predict body core temperature elevation based on exposure of the human body to radiofrequency EMFs.

Body core temperature depends on the whole body thermal energy balance. Radiofrequency energy absorbed by the body is transferred to the body core via blood flow, which can activate thermoregulatory responses to maintain the body core temperature (Adair & Black, 2003). This means that the time rate of the energy balance is essential for the body core temperature dynamics. Whole body average SAR is used as the physical quantity relating to body core temperature elevation.

The relationship between the total energy absorption and the body core temperature is in general independent from frequency. However, at frequencies higher than a few GHz, core temperature does not elevate as much as with the same level of whole body average SAR at lower frequencies because of heat transfer from the body surface to air, including the effect of vasodilation in the skin (Hirata et al 2013). The power absorption is confined within skin surface tissues where localized temperature elevation is more significant than the body core temperature elevation (Laakso and Hirata, 2011). It has also been reported that infrared radiation (IR) exposure can cause significant body core temperature elevation (Brockow et al., 2007). Infrared radiation refers to electromagnetic waves with frequencies between those of radiofrequency EMF and visible light. This means that the penetration depth of IR is very small or comparable to the high GHz radiofrequency EMFs (or millimeter waves). For conservative reasons, therefore, ICNIRP set equal whole body average limits for frequencies both above and below 6 GHz. This is especially important for cases of multiple-frequency exposure of both higher and lower frequencies. Thus, the applicable frequency is the entire frequency range considered in the guidelines.

3.1.2. Temporal averaging considerations

If the adiabatic condition is considered, the body temperature continues to increase until the exposure to radiofrequency EMF is terminated. However, this does not occur because thermoregulation and heat exchange with the environment work to reduce this temperature increase to a point where an equilibrium or steady-state is achieved.

The definition of the time constant of body core temperature is not clear. However, under simplified conditions that produce a reasonable estimate of the time constant (e.g. assuming a first order lag), temperature dynamics can be described as follows;

$$T(t) = T_0 + \left(T_\infty - T_0\right)\left(1 - e^{\frac{-t}{\tau}}\right) \qquad \text{(Eqn. 3.1),}$$

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where T is the temperature as a function of time t, T_0 and T_∞ are the initial and steady-state temperature respectively, and τ is the time constant. In this case, the time constant corresponds to the time taken from the initial temperature to reach 63% of the steady-state temperature. In these guidelines, the time to reach a steady-state of 80-90% of the equilibrium temperature, from the initial temperature, is considered for guideline setting; this is almost two times the time constant in Eqn. 3.1.

Further, the time needed to reach the steady-state body core temperature depends on the level of heat load, which in this case relates to the whole body average SAR. Hirata et al., (2007b) numerically simulated the body core temperature elevation of a naked body exposed to plane wave exposure at 65 MHz and 2 GHz, and reported that in both cases it takes at least 60 minutes to reach a 1°C body core temperature rise for whole body average SARs of 6 to 8 W kg^{-1}. This time is also dependent on the sweating rate, with strong sweating increasing this time by 40-100 minutes (Hirata et al., 2008b and Nelson et al. 2013). Consequently, the time to reach the steady state temperature rise due to whole body exposure to radiofrequency EMFs below 6 GHz is 30 minutes or longer.

As described above, power absorption is confined within the surface tissues at frequencies above 6 GHz. This may lead to thermoregulatory response initiation time being reduced. However, the time needed for the steady state temperature rise is not significantly affected by this, and so is not taken into account. It is thus reasonable to keep the averaging time above 6 GHz the same as that below 6 GHz, because there is no quantitative investigation on the time constant of body core temperature elevation above 6 GHz.

3.1.3. Whole body average SAR needed to raise body core temperature by 1°C

Thermoregulatory functions are activated if a human body is exposed to significant heating load, which often results in non-linear relations between whole body average SAR and body core temperature elevation.

Adair and colleagues have experimentally investigated body core temperature (via esophageal temperature measurements) during whole body exposure. They have reported no or minor increases of the esophageal temperature (<0.1°C) during the whole body exposure at 100 MHz, 220 MHz, and 2450 MHz, with whole body average SAR ranging from 0.54 to 1 W kg^{-1} in normal ambient temperature conditions, from 24°C to 28°C (Adair et al., 2001; Adair et al., 2003; Adair et al., 2005).

They also reported a relatively high body core temperature elevation (0.35°C) for whole body exposure at 220 MHz with a whole body average SAR of 0.675 W kg^{-1} in a hot ambient temperature (31°C) condition, although this was found in only one person and the mean of the body core temperature elevations (6 persons) was not significant. There is no data on body core temperature elevation for whole body exposure to radiofrequency EMF above 6 GHz. The only available data are on IR radiation (Brockow et al., 2007). The conservativeness for whole body exposure at higher frequencies is discussed in the main text.

There are two main factors affecting body core temperature rise due to radiofrequency exposure: sweating and body-surface to mass ratio.

Evaporative heat loss due to sweating reduces body core temperature efficiently, and needs to be accounted for when estimating body core temperature rise due to EMF. For example, Hirata et al., (2007b and 2008b) reported that 4.5 W kg^{-1} is required to increase the body core temperature by 1 °C for a person with a lower sweat rate, such as an elderly person, while 6 W kg^{-1} is required for a person with a normal sweat rate. The decline of sweat rate in elderly people is primarily due to degradation of thermal sensation (Nomura et al., 2014).

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Similarly, heat exchange between the body surface and external air is also very important. Hirata et al (2009a) found that the steady state body core temperature elevation due to whole body radiofrequency EMF exposure is proportional to the ratio of the (whole body) power absorption to the surface area of the body. The ratio of the mass to the surface area is smaller for smaller-dimension bodies such as children. This is why the basal metabolic rate in the child is larger than the adult; greater SAR is required to maintain constant body core temperature due to the higher body-surface-area-to mass ratio.

This coincides with the finding that smaller persons have a lower body core temperature rise for the same whole body average SAR. For example, Hirata et al. (2008b) numerically evaluated the body core temperature elevation in a 3-year-old child model and found that their body core temperature elevation was 35% smaller than that of an adult female model for the same whole body average SAR. They concluded that the higher ratio of the child's surface area to body mass causes more effective cooling, due to thermal convection between body surface and the external air. Consequently, the body core temperature rise in the child is smaller than that of the adult at the same whole body average SAR.

Addressing the issue more broadly, theoretical modelling and generalization from experimental research across a range of species has shown that within the 100 kHz to 6 GHz range, whole body average SARs of at least 6 W kg^{-1}, for exposures of at least 1 hour at moderately high ambient temperature (28°C), are necessary to increase body core temperature by 1°C (Hirata et al., 2013).

3.1.4. Considerations for fetus exposure

The body core temperature of the fetus is heavily dependent on that of the mother, with body core temperature of the fetus typically 0.5°C higher than that of the mother (Asakura, 2004). This relationship is not changed significantly by radiofrequency EMF exposure of the mother at 26 week gestation, as reported by Hirata et al., (2014). In the frequency range from 40 MHz to 500 MHz, they computed fetal temperature, taking the thermal exchange between mother and fetus into account, and reported that the fetal temperature rise was only 30% higher than that of the mother, even when the power absorption was focused around the fetus. This suggests that at frequencies below 6 GHz, EMF exposure to the mother will result in a similar (or slightly larger) body core temperature elevation in the fetus relative to that of the mother.

Further, considering the frequency characteristics of the SAR distribution, the contribution of radiofrequency EMF-induced surface heating above 6 GHz to the fetus' temperature elevation would be expected to be smaller than that below 6 GHz. However, as this has not been addressed quantitatively, it is reasonable to take a conservative approach and assume that body core temperature elevation in the fetus above 6 GHz will be similar to that below 6 GHz.

It follows that an EMF-induced body core temperature rise within the mother will result in a similar rise within the fetus, and thus an exposure at the occupational whole body average SAR basic restriction would result in a similar body core temperature rise in mother and fetus. Therefore, to maintain fetal temperature to the level required by the general public whole body average SAR basic restriction, a pregnant woman is considered a member of the general public in terms of the whole body average SAR limit.

ICNIRP's decision on the occupational whole body average SAR for pregnant women can be significantly conservative compared with the established teratogenic fetal temperature threshold (2°C; Edwards et al, 2003; Ziskin & Morrissey, 2011). However, ICNIRP also

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recognizes that the body core temperature of the fetus, especially during early stage one or embryonic development, is not clearly defined, and that there is no direct evidence that occupation whole body exposure of the pregnant worker will harm the fetus. It is thus acknowledged that the decision to treat a pregnant worker as a member of the general public is conservative. ICNIRP also notes that there are some mitigating techniques that can be considered in order to allow pregnant workers to enter areas where radiofrequency EMFs are at occupational exposure levels, without exceeding the general public restrictions. For example, reducing the time that a pregnant worker is within an area with occupational exposure, by a factor of 5, will keep the pregnant worker within the general public restrictions (assuming an even temporal distribution of field over the 30 minute averaging window). However, restrictions concerning local exposure are also important to a pregnant worker, and are described in Sections 3.2.5 and 3.3.5.

3.2. LOCAL EXPOSURE UP TO 6 GHZ (≥ 6 MINUTES)

3.2.1. Relevant quantity

For cases of localized exposure to radiofrequency EMF, temperature can rise in part of the body without altering body core temperature. Local temperature rise must therefore be limited. The maximum local temperature rise generally appears on the surface of the body, and local SAR is a useful surrogate of the local temperature rise due to localized radiofrequency EMF exposure. However, other factors, such as clothing, sweating and environmental conditions, can have more impact on local temperature than SAR itself.

3.2.2. Spatial averaging considerations

Different averaging schemes (e.g. cubic, spherical, contiguous single tissue) and masses have been assessed in terms of their ability to predict local temperature rise (Hirata and Fujiwara, 2009; McIntosh and Anderson, 2011). These suggest that the effect of averaging mass is more crucial than the shape of averaging volume, and that SAR varies with different averaging schemes by a factor of approximately 2 (Hirata, Fujimoto et al., 2006). It has also been shown that SAR averaged over a single tissue provides somewhat worse correlation with local temperature than that for multiple tissues, because the heat generated in biological tissue can diffuse up to a few centimeters (across multiple tissue types). Consequently, a cubic averaging mass of 10 g, including all tissues, is used as an appropriate spatial averaging regime for frequencies up to 6 GHz. This metric has been shown to be applicable even for plane wave exposures, in that local temperature elevation in the Head and Trunk, and Limbs, are correlated with this averaging mass (Razmadze et al., 2009; Bakker et al., 2011; Hirata et al., 2013).

3.2.3. Temporal averaging considerations

Time to reach the steady-state temperature, given the balance between rate of radiofrequency power deposition on one hand, and heat diffusion and conduction on the other, is characterized by the time constant of temperature elevation. The time constant primarily depends on heat convection due to blood flow and thermal conduction. Van Leeuwen et al (1999), Wang and Fujiwara (1999) and Bernardi et al. (2000) report that the time needed for 80-90% of the steady-state temperature rise, at 800 MHz to 1.9 GHz, is 12–16 minutes. These guidelines take 6 minutes as a suitable, conservative averaging time for steady-state temperature elevation up to 6 GHz.

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3.2.4. Local SAR required to increase local Type-1 and Type-2 tissue temperature by 5 and 2 °C respectively

Although early research provided useful rabbit data concerning the relation between 2.45 GHz exposure and local temperature elevation (e.g. Guy et al., 1975; Emery et al., 1975), more recent research with more accurate techniques has demonstrated that the rabbit is an inaccurate model for the human eye (Oizumi, et al., 2013). However, given the concern about potential radiofrequency harm to the eye, there are now several studies that provide information about radiofrequency-induced heating of the human eye. Expressed as heating factors (the °C elevation over a 1 kg mass, per W of absorbed power), the computed heating factors of a human eye have been relatively consistent (0.11–0.16 °C kg W^{-1}; Hirata et al., 2005; Hirata, Watanabe et al., 2007; Wainwright, 2007; Buccella, De Santis & Feliziani, 2007; Buccella, 2007; Laakso 2009; Diao et al., 2016). In most studies, the heating factor was derived for the SAR averaged over the eyeball (contiguous tissue). The SAR averaged over the cubic volume (which includes other tissues) is higher than that value (Diao et al, 2016), resulting in lower heating factors. Based on these heating factors, the operational adverse health effect thresholds for the eye will not be exceeded for local exposures of 20 W kg^{-1}.

There are also a considerable number of studies on the temperature elevation in the head exposed to mobile phone handset antennas (Bernardi et al., 2000/2001; Gandhi, Li & Kang, 2001; Hirata & Shiozawa, 2003; Hirata, Fujiwara et al., 2006a; Ibrahim et al., 2005; van Leeuwen et al., 1999; Wainwright, 2000; Wang & Fujiwara, 1999). Hirata and Shiozawa (2003) reported that heating factors are 0.24 or 0.14 °C kg W^{-1} for the local SAR averaged over 10 gram contiguous volume with and without the pinna respectively. Other studies considering the local SAR averaged over a 10 g cubic volume including the pinna reported heating factors in the range of 0.2-0.25 °C kg W^{-1} (Bernardi et al., 2000; Hirata & Shiozawa, 2003; Razmadze et al., 2009; Wainwright, 2000). Fujimoto et al. (2006) studied the temperature elevation in a child head exposed to a dipole antenna and found that it is comparable to that in the adult when the same thermal parameters were used. In most of the studies, the temperature elevation in the brain is also computed. The heating factor in the brain (the ratio of the temperature elevation in the brain to peak SAR in the head) is 0.1 °C kg W^{-1} or smaller (Morimoto et al, 2016). Uncertainty factors associated with the heating factors are attributable to the energy absorbed in the pinna and its surrounding structures (see, e.g., Foster et al., 2018).

Those studies are consistent with recent research showing that, within the 100 kHz – 6 GHz range, numerical estimations converge to show that the maximum heating factor is lower than 0.25 °C kg W^{-1} in the skin and 0.1 °C kg W^{-1} in the brain, for exposures of at least approximately 30 minutes. The result of this is that the operational health effect thresholds will not be exceeded for exposures of 20 W kg^{-1}.

3.2.5. Considerations for fetus exposure

The primary thermoregulatory mechanism for a fetus is body core heat exchange with the mother via blood flow through the umbilical cord, making it difficult to increase fetal temperature without also increasing the body core temperature of the mother. Heating factors for the fetus, as a function of gestation stage and fetal posture and position, have been determined that take such heat exchange into account (Akimoto et al., 2010, Tateno et al., 2014, and Takei et al., in press). This research used numerical models of 13-week, 18-week and 26-week pregnant women. The heating factors of the fetus are several times lower than those of the mother in most cases. However, the worst case has been found where the fetal

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body position is very close to the surface of the abdomen (i.e. middle and later stages of gestation). These provide 0.1 °C kg W^{-1} as a conservative heating factor for the fetus.

Based on these findings, a fetal exposure at the occupational limit of 10 W kg^{-1} will result in an increase of approximately 1 °C, which is higher than that allowable for the Head and Torso of the general public (i.e. 0.1 [°C kg W-1] x 2 [W] = 0.2 [°C]). It follows that a local occupational radiofrequency EMF exposure of the mother would cause temperature to rise in the fetus to a level higher than that deemed acceptable for the general public. Therefore, to maintain fetal temperature to the level required by the general public local SAR restrictions, a pregnant woman is considered a member of the general public in terms of the local SAR limit, which means that the fetal temperature rise will be restricted to within 0.2°C.

It is noted that the worst case appears only in the middle and late pregnancy stages (or 18-week and 26-week gestation, pregnant woman models), while the heating factor of the fetus in the early pregnancy stage (12-week gestation, pregnant woman model) is at most 0.02 °C kg W^{-1} (Tateno et al., 2014, and Takei et al., 2018). This 12-week gestation fetal temperature rise is 100 times lower than the threshold (2°C) for teratogenic effects in animals (Edwards et al, 2003; Ziskin & Morrissey, 2011).

3.3. LOCAL EXPOSURE FROM 6 GHZ TO 300 GHZ

3.3.1. Relevant quantity

In a human body exposed to radiofrequency EMF, an electromagnetic wave exponentially decays from the surface to deeper regions. This phenomenon is characterized according to penetration depth, as described below;

$$S_{\mathrm{tr}}(x) = S_0 e^{-\frac{2x}{\delta}} \qquad \text{(Eq. 3.2),}$$

where $S_{\mathrm{tr}}(x)$ is the transmitted power density propagating in the direction of the x axis, S_0 is the transmitted power density at the surface boundary ($x = 0$), and δ is the penetration depth. This equation shows that 86% of the radiofrequency power is absorbed within the penetration depth.

The penetration depth depends on the electrical properties of the medium, as well as frequency. As frequency increases, the penetration depth decreases, and is limited within the surface tissues at frequencies higher than 6 GHz. The following table lists the penetration depth based on the dielectric properties of skin tissue (dermis) measured by Sasaki et al., (2017).

Table 3.1. Penetration depth of human skin tissue (dermis), for frequencies 6 to 300 GHz.

Frequency (GHz)	Relative permittivity	Conductivity (S/m)	Penetration depth (mm)
6	36.	4.0	8.1
10	33.	7.9	3.9
30	18.	27.	0.92
60	10.	40.	0.49
100	7.3	46.	0.35

300	5.0	55.	0.23

As a result, the local SAR averaged over a 10 gram mass with side length of 2.15 mm is no longer a good proxy for the local temperature elevation; that is, the power deposition is limited to within a few millimeters of the surface tissues. Conversely, the power density transmitted into the skin provides a better approximation of the superficial temperature rise from 6 GHz to 300 GHz (Foster et al., 2016; Hashimoto et al., 2017).

3.3.2 Spatial averaging considerations

At frequencies over 6 GHz, a focused beam can be radiated. This makes the averaging area of the transmitted power density an important consideration in the basic restrictions of the transmitted power density. Because the focal area is limited by wavelength, the averaging area of the transmitted power density relevant to the temperature elevation depends on frequency; smaller averaging areas are necessary as frequency increases.

Recent thermal modeling (Hashimoto et al., 2017; Foster et al., 2017) and analytical solutions suggest that an averaging area of 4 cm² (2 cm × 2 cm) or smaller provides a close approximation to local maximum temperature elevation due to radiofrequency exposure greater than 6 GHz. This is supported by computations for realistic exposure scenarios (He et al., 2018). An important advantage of the 4 cm² averaging area is the consistency at 6 GHz between local SAR and transmitted power density. However, a smaller averaging area is sometimes necessary for extremely focused beams at higher frequencies, with a 10 mm x 10 mm area more appropriate at 300 GHz. Although an ideal averaging area would decrease from 4 cm² to 1 cm² across this range, a step function has been applied to simplify compliance, resulting in averaging areas for transmitted power density basic restrictions, of 4 cm² and 1 cm² for 6-30 GHz and 30-300 GHz respectively.

3.3.3 Temporal averaging considerations

As well as the cases of localized exposure at frequencies lower than 6 GHz, the temperature rise due to localized exposure to radiofrequency EMF over 6 GHz also achieves an equilibrium state with a particular time constant. Morimoto et al., (2017) demonstrated that the same averaging time as the local SAR (6 minutes) is appropriate for localized exposure from 6 GHz to 300 GHz. The time needed for steady-state local temperature elevation decreases gradually as frequency increases, but no notable change is observed at frequencies higher than 15 GHz (Morimoto et al, 2017). The time needed to reach 80-90% of the maximum temperature elevation is approximately 5-10 min at 6 GHz and 3-6 min at 30 GHz. It is however noted that the time constant becomes shorter if brief or irregular exposure is considered, which is discussed in A.3.5.

3.3.4 Transmitted power density required to increase local Type-1 tissue temperature by 5 °C

Above 6 GHz, exposure is too superficial to produce significant heating of Type-2 tissue. Therefore, exposure level must be chosen to ensure that temperature rise in the more superficial Type-1 tissue does not exceed 5 °C.

Tissue heating, as a function of transmitted power density over 6 GHz, is dependent on a variety of factors, as it is for lower frequencies. A comprehensive investigation of the heating factors (in degrees C over a square meter, per watt) has been conducted in the case of a plane wave incident to a multi-layered slab model, as the worst or uniform exposure condition (Sasaki et al, 2017). In that study, Monte-Carlo statistical estimation of the heating factor was

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conducted, where it was shown that the maximum heating factor is 2.5×10^{-2} °C m² W^{-1}. This value is consistent with results from other studies (Foster et al., 2016; Hashimoto et al., 2017). Thus to increase temperature by 5 °C requires a transmitted power density of 200 W m^{-2}.

3.3.5 Considerations for the fetus

As discussed in Section 3.2.5 in relation to the frequency characteristics of the SAR distribution, the contribution of surface heating due to radiofrequency EMF exposure above 6 GHz to fetal temperature elevation is likely very small (and smaller than that from below 6 GHz). This suggests that the fetus will not receive appreciable exposure from local exposure above 6 GHz. However, there is currently no study that has assessed this. ICNIRP thus takes a conservative approach and requires that the pregnant worker is treated as a member of the general public in order to ensure that the fetus will not be exposed above the general public basic restrictions.

3.4 REQUIREMENTS FOR LOCAL EXPOSURE UP TO 6 GHZ (< 6 MINUTES)

The 6 minute averaging scheme for localized exposure allows greater strength of the local SAR if the exposure duration is shorter than the averaging time. However, if the exposure duration is significantly shorter, heat diffusion mechanisms are inadequate to restrict temperature rise. This means that the 6 minute averaged basic restriction can temporarily cause higher temperature elevation than the operational adverse health effect thresholds if the exposure period is shorter than 6 minutes.

If the exposure duration is extremely short, adiabatic temperature elevation ($\Delta T_{adiabatic}$) can occur as described in the following equation;

$$\Delta T_{adiabatic} = {}^{SAR \cdot t}/_{C} = {}^{SA}/_{C} \quad \text{(Eqn. 3.3)},$$

where C is heat capacitance and t is the exposure duration. This implies that the SA corresponding to the operational adverse health effect threshold, or $\Delta T_{\mathrm{OAHET}}$, is constant and derived as follows;

$$SA_{\mathrm{adiabatic}} = C \cdot \Delta T_{\mathrm{OAHET}} \quad \text{(Eqn. 3.4)}.$$

It is noted that the adiabatic heating assumption is extremely conservative. Therefore, for cases where the exposure duration is longer than the time scale of the adiabatic heating, the SA corresponding to $\Delta T_{\mathrm{OAHET}}$ is higher than $SA_{\mathrm{adiabatic}}$ and depends on the exposure duration t.

A recent numerical modelling investigation for brief exposure to radiofrequency EMF from 100 MHz to 6 GHz, using a multi-layer model and a Japanese head model, found that the SA corresponding to the allowable temperature elevation is greatly dispersive depending on various factors (Kodera et al., unpublished). Based on that study and empirical equations of the SA corresponding to the operational health effect threshold for the skin (5 °C), the exposure corresponding to this temperature rise is derived from the following equations;

$$SA(\mathrm{t}) = 500 \text{ [J/kg] for } t \leq 1 \text{ [sec]} \quad \text{(Eqn. 3.5)},$$

$$SA(t) = 500 + 354\sqrt{t-1} \text{ [J kg}^{-1}\text{] for } 1 \text{ [sec]} < t \leq 360 \text{ [sec]} \quad \text{(Eqn. 3.6)},$$

where $SA(t)$ is spatially averaged over any 10 gram cubic tissue.

It is noted that the above logic results in slightly different time functions for brief exposure above 6 GHz. However, as the resultant time functions above 6 GHz are more conservative

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than for below 6 GHz, Eqns. 3.5 and 3.6 include an adjustment that incorporates the more conservative nature of the derivations for exposures above 6 GHz (i.e. Eqns. 3.7 and 3.8).

The recent numerical modelling study by Kodera et al. (unpublished) also show that the temperature elevation in Type-2 tissue (i.e. the brain) is also protected by the SA restriction for the skin defined in the above equations. They furthermore reported that the SA corresponding to the allowable temperature rise increases as frequency decreases. At 400 MHz or lower, the cumulative SA derived from the local 6 minute SAR (10 [W kg^{-1}] x 360 [s] = 3.6 [kJ/kg]) does not reach the temperature rise corresponding to the OAHET for the Head and Trunk. Accordingly, this SA limit is only required for exposures above 400 MHz.

It should be noted that Eqns. 3.5-3.6 must be met for all intervals up to 6 minutes, regardless of the particular pulse patterns. That is, exposure from any pulse, group of pulses, or subgroup of pulses in a train, delivered in t seconds, must not exceed Eqns. 3.5-3.6, as exposure to a part of the pulse pattern can be more critical than exposure to a single pulse or the exposure averaged over t. For example, if two, 1-second pulses are separated by 1 second, the limits provided by Eqns. 3.5-3.6 must be satisfied for each of the pulses, as well as for the total 3-second pulse-pattern interval.

Temperature elevation due to brief exposure is limited to surface tissues because the effect of heat diffusion into deeper regions is not significant. This suggests that the temperature elevation in the fetus will be lower than that assumed for the steady state (6 minute) exposure. However, there is no study available that has considered the effect of brief exposure of the pregnant worker. ICNIRP thus maintains the same policy for < 6 minute exposure as for > 6 minute exposure (Section 3.2.4), and requires the pregnant worker to be subject to the general public restrictions.

3.5 REQUIREMENTS FOR LOCAL EXPOSURE ABOVE 6 GHZ (< 6-MINUTES)

Similar to the situation for frequencies lower than 6 GHz, temperature elevation can be enhanced for intense short pulses or discontinuous exposures above 6 GHz, even at the same transmitted power density that is allowed in a 6 minute average. This becomes significant at frequencies higher than 30 GHz (Foster et al 2016). Considering the robustness and consistency of simple multi-layer models, the basic restrictions for the brief exposures are derived based on investigations using simple models (Foster et al., 2016; Morimoto et al., 2017). Unlike continuous wave exposure, the effect of diffraction, or interference of waves reflected from protruding parts of the body back to the skin, may be apparent for brief pulses. Although the effect of diffraction to the transmitted power density is yet to be fully determined, the resultant temperature elevation is estimated to be up to 3 times higher if pulsed than that due to the same transmitted power density spread evenly over a 6 minute interval (Laakso et al., 2017).

Considering these factors, transmitted energy density (H_{tr}) has been set as a function of the square root of the time interval, to account for heterogeneity of temperature elevation (Foster et al 2016). As is the case for frequencies lower than 6 GHz, a constant H_{tr} has been set for time intervals shorter than 1 second, with intervals between 1 and 360 seconds adjusted (as a function of time-interval) to match the OAHET for Type 1 tissue, as well as to match the cumulative transmitted energy density derived from the transmitted power density at 360 seconds. As per the brief interval exposure limits for frequencies less than 6 GHz, the superficial nature of the resultant temperature rise will not result in temperatures that exceed Type-2 tissue OAHETs, and so only the 5 °C OAHET needs to be considered here.

Consequently, the brief exposure levels corresponding to the 5 °C OAHET is as follows;

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$$H_{\mathrm{tr}}(\mathrm{t}) = 5\ [\mathrm{kJ\ m^{-2}}]\ \text{ for } t \leq 1\ [\mathrm{sec}] \qquad \text{(Eqn. 3.7),}$$

$$H_{\mathrm{tr}}(t) = 5 + 3.54\sqrt{t-1}\ [\mathrm{kJ\ m^{-2}}]\ \text{ for } 1\ [\mathrm{sec}] < t \leq 360\ [\mathrm{sec}] \qquad \text{(Eqn. 3.8),}$$

where t is the time interval.

As a basic principle, any exposure (or set of exposures) must satisfy the above equations for all potential time intervals, regardless of the characteristics of the particular set of exposures. That is, exposure from any pulse, group of pulses, or subgroup of pulses in a train, delivered in *t* seconds, must not exceed Eqns. 3.7-3.8, as exposure to a part of the pulse pattern can be more critical than exposure to a single pulse or the exposure averaged over *t*. For example, if two, 1 second pulses are separated by 1 second, the limits provided by Eqns. 3.7-3.8 must be satisfied for each of the pulses, as well as for the total 3 second pulse-pattern interval.

As discussed above in relation to the frequency characteristics of the SAR distribution, the contribution of the surface heating due to radiofrequency EMF above 6 GHz to fetal temperature elevation is likely smaller than that below 6 GHz. This is the same for cases of brief exposure. However, as there is no study on fetal exposure to radiofrequency EMF above 6 GHz, ICNIRP adopts a conservative approach and treats a pregnant worker as a member of the general public to ensure that the fetal exposure will not exceed that of the general public.

4. DERIVATION OF THE REFERENCE LEVELS

4.1. GENERAL CONSIDERATIONS FOR REFERENCE LEVELS

As described in the main guidelines document, the reference levels have been derived as a practical means of assessing compliance with these guidelines, that will provide an equivalent level of protection to the basic restrictions. The reference levels **E**-field strength, **H**-field strength and incident power density are derived from dosimetric studies assuming whole-body exposure to uniform field distribution. This is generally considered the worst-case scenario regarding radiofrequency power absorption because the whole of the human body is assumed to be exposed to the homogeneous electromagnetic field. Due to the strongly conservative nature of the reference levels in most exposure scenarios, reference levels may be exceeded without exceeding the corresponding basic restriction. Where reference levels are exceeded, the exposure will be compliant with the guidelines if it is compliant with the basic restrictions.

From 30 MHz to 6 GHz, the reference levels are set in terms of the **E**-field, **H**-field and incident power density. The relationship between **E**-field and **H**-field follows the characteristics of the plane wave where the characteristic impedance (i.e. E/H), is equal to 377 Ohm in free space. ICNIRP recognizes that high-strength radiofrequency EMF comparable to or higher than the reference levels frequently appears in the near region of radiofrequency sources. The characteristics of fields close to a radiofrequency source is not the same as the plane wave, and is referred to as the reactive near-field. In the reactive near-field, ICNIRP therefore requires evaluation of both the **E**-field and **H**-field and confirmation that both fields do not exceed the reference levels.

If the radiofrequency EMF has the same characteristics as the plane wave, which generally appear far away from radiation sources, and if there is no reflection object to cause standing waves, being within either the **E**-field, **H**-field or incident power density reference level is sufficient to demonstrate compliance with these guidelines. The criterion for requiring adherence to a single reference level (i.e., demonstrating compliance with either the **E**-field or **H**-field, as opposed to both) depends on various factors, such as the frequency, distance from the antenna and the dimension of the antenna. This makes it difficult to specify without

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consideration of a range of factors that cannot be easily specified in advance. A guide to potential definition of near- and far-field exposure conditions is provided in the main document, but it is expected that determination of such conditions for the application of reference levels would need to be guided by compliance standards organizations.

Below 30 MHz, the relationship between the **E**-field and **H**-field reference levels is not the same as that of the plane wave, and thus power density reference levels are not set (see Section 4.2). Consequently, both the **E**-field and **H**-field reference levels must be met. However, where the **E**-field is more dominant than the **H**-field (i.e. where E/H is larger than 377 Ω), only the **E**-field needs to be measured because this is more conservative than the **H**-field reference level.

Reference levels have been derived to match the various basic restrictions of the guidelines. As the basic restrictions vary in terms of a range of parameters, including spatial and temporal averaging, it follows that adherence to particular reference levels will not necessarily be relevant to compliance (or safety) associated with other reference levels. In order to be compliant with the reference levels, all relevant reference levels must be complied with simultaneously.

For some special cases where the standing wave appears due to interference between the incident and reflected plane waves, the spatial averaging of either **E**-field or **H**-field is enough to demonstrate compliance to these guidelines.

It is also important to note that the local SAR resulting from whole body exposure to a plane wave at the reference level will not result in exposure that exceeds the local basic restrictions (Uusitupa et al., 2010). Therefore, if the spatial peaks of a non-uniform field are lower than the local reference levels, the exposure is deemed to be compliant with both the whole body average SAR and local SAR basic restrictions.

As described above in relation to exposure of a pregnant worker, to maintain the fetal exposure to within the general public basic restrictions, a pregnant worker must be treated as a member of the general public. This rule also applies to reference levels.

4.2. E, H-FIELD REFERENCE LEVELS < 30 MHZ

In the ICNIRP 1998 guidelines, the reference levels in this frequency region were derived from the whole body averaged SAR for whole body exposure to the plane wave. However, a recent study showed that whole body exposure to the decoupled **H**-field results in a whole body average SAR significantly lower than that calculated for the whole body exposure to the plane-wave with the same **H**-field strength (Kashiwa et al., 2018). The whole body exposure to the decoupled **E**-field was also calculated and it was found that the whole body average SARs are almost the same as those for the plane wave with the same direction and strength as the **E**-field (Kashiwa et al., 2018). The reference levels relevant to the whole body averaged SAR basic restrictions below 30 MHz in these guidelines are therefore based on the numerical calculations of the whole body average SAR for the whole body exposure to the decoupled uniform **E**-field and **H**-field, separately. The study also concluded that local SAR basic restrictions will also be satisfied, when the whole body SAR basic restrictions are satisfied. This means that compliance with the reference levels in this frequency region will result in exposures that do not exceed either the whole body average or local SAR basic restrictions.

The reference levels in this frequency region are based on numerical computation. In the low frequency guidelines (ICNIRP, 2010) where reference levels are set to protect against

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stimulation effects up to 10 MHz, a reduction factor of 3 was applied to account for uncertainty associated with the numerical simulation.

In these guidelines, however, the uncertainty of the numerical simulation is not remarkable because the spatial averaging procedure applied in evaluating the whole body average and local SAR significantly decreases the uncertainty of the computational artifact. The situation is different for the low frequency guidelines (ICNIRP 2010), where non-averaged values defined for a calculation cell or lattice (in the numerical calculation space) are evaluated in the low frequency guidelines and are significantly affected by the computational artifact. Therefore, the reduction factor due to computational uncertainty does not need to be considered in deriving the reference levels relevant to the whole body average SAR basic restrictions below 30 MHz in these guidelines.

4.3. E, H-FIELDS AND S REFERENCE LEVELS FROM 30 MHZ TO 6 GHZ

The whole body average SAR for exposure at the field strength of reference level (ICNIRP 1998) becomes close to the basic restrictions around the whole-body resonant frequency (45-170 MHz) and post resonant frequency region (1400-4000 MHz).

The resonance frequency appears at a frequency where half of the wavelength in free space is close to the height (vertical dimension of a person standing) of the human body in free space, or a quarter of the wavelength in free space is close to the height of a human body standing on the ground plane (Durney et al., 1986), resulting in higher whole body averaged SARs. Whole body resonance appears only for the case of **E**-polarization plane wave incidence. If different polarizations are assumed, the resultant whole body average SAR is significantly (a few orders of magnitude) lower than that of the case of the **E**-polarization around the whole body resonant frequency (Durney et al., 1986). Whole body resonance has been confirmed by recent numerical computations (Conil et al., 2008; Dimbylow, 2005; Dimbylow, 1997; Hirata et al., 2010/2012; Kühn et al., 2009; Nagaoka et al., 2004).

Above the whole-body resonant frequency, especially above a few GHz, the differences in the whole body average SARs due to polarization are not significant compared with those at the whole body resonant frequency. Hirata et al., (2009) reported that the whole body average SAR in child models from 9 months to 7 years old exposed to **H**-polarized plane waves, is only slightly higher (up to 20%) than the **E**-polarized plane wave at frequencies from 2 GHz to 6 GHz. A similar tendency has been reported in other studies (Kühn et al., 2009; Vermeeren et al., 2008).

ICNIRP has concluded that, given the same external field, the child whole body average SAR can be 40% higher than those of adults (ICNIRP Statement, 2009). After this ICNIRP statement, Bakker et al., (2010) reported similar (but slightly higher) enhancements (45%) of the child whole body average SAR. The effects of age dependence of electrical properties of the tissues and organs have also been investigated, but no significant effect relevant to whole body average SAR has been found (Gabriel, 2005; Lee and Choi, 2012). It is noted that the increased whole body average SARs have been reported from calculations using very thin child models, which were homogeneously scaled down from adult or very young (infant) models, and require the child or infant to maintain their posture for a substantial time interval so as to match the worst condition, in order for their whole body SAR to exceed the basic restriction. The most recent study using child models which have used the standard dimensions specified by ICRP showed that the increases of the whole body average SARs in the standard child models are not significant (at most 15%; Nagaoka et al., 2007). Similarly, the relationship between whole body average SAR and whole body weight has been investigated and it was found that the whole body average SAR in light-weight adults can

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increase in a similar manner to the case of the child (Lee and Choi, 2012; Hirata et al., 2010/2012).

As discussed in Section 3.1.5, the temperature of the fetus is almost the same as the body core temperature of his/her mother. The whole body averaged SAR, which is used to restrict temperature rise, is defined as the power absorption in the whole body divided by the whole body weight. Therefore, the whole body averaged SARs of the pregnant women whose weight is heavier are generally lower than those of the non-pregnant women in this frequency region. Nagaoka et al., (2007) reported that the whole body average SAR of a 26-week pregnant woman model exposed to the vertically polarized plane wave from 10 MHz to 2 GHz was almost the same as or lower than the non-pregnant woman model for the same exposure condition.

Dimbylow (2007) reported that, using a simplified pregnant women model, the whole body average SAR in the fetus becomes maximal at 70 MHz for the isolated condition, which is the same as the mother. A similar tendency was found for anatomical fetus models of second and third trimester and the whole body average SARs in the fetus of 20 week, 26 week, and 29 week gestation period are approximately 80%, 70% and 60% of those in the mother, respectively (Nagaoka et al., 2014). The whole body average SARs of the fetus, while still embryonic, are comparable to or lower than the whole body averaged SARs in the mother, because the embryo is located deep within the abdomen of the mother (Kawai et al., 2010). The fetus is therefore not considered independently from the mother in terms of reference levels.

As described above, there are numerous databases relevant to whole body average SAR for whole body exposure in this frequency region. These include a considerable number reported since the ICNIRP (1998) radiofrequency guidelines, which are generally consistent with the database used as the basis for the ICNIRP (1998) guidelines. ICNIRP uses a combination of the older and newer databases to derive the reference levels, taking into account some inconsistencies discussed below.

Considering the need to cover the local SAR basic restrictions, the averaging time to be applied to the reference levels is set the same as for the local SAR basic restrictions, which is 6 minutes for local SAR, and 30 minutes for whole body average SAR basic restrictions.

The most significant inconsistency found since the publications of the ICNIRP (1998) guidelines is the exceeding of the whole body average SARs in children or small stature people even if the exposure level is at the reference level. As reviewed above, the exceeding of the whole body average SAR basic restriction is at most 40%. However, the maximum exceeding is limited to specific child models. Conversely, the only study using the internationally standardized child models shows only a modest increase of 15 % at most (Nagaoka et al., 2008). This deviation is comparable with the uncertainty expected in the numerical calculations. For example, Dimbylow et al. (2008), reported that differences in the procedure or algorithm used for the whole body averaging results in 15% variation of the whole body average SARs at 3 GHz, and that the differences in the dielectric properties between the dry skin and the dry skin reported in the de-fact database (Gabriel, 1996) also results in 10% variation in the whole body average SARs at 1.8 GHz.

As reviewed in Section 3.1.4, the heating factor of children is generally lower than that of adults. For example, Hirata et al. (2008) and Hirata et al. (2013) numerically evaluated the body core temperature elevation in a 3 year old child model and found that the heating factor of the child is 35% smaller than in an adult female model for the same whole body average SAR. It follows that the increased SAR will not result in a larger temperature rise than is

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allowed for adults, and so will not affect health. Given the magnitude of uncertainty and the lack of health benefit in reducing the reference levels to account for small stature people, this has not resulted in ICNIRP altering the reference levels.

It is also noted that the whole body average reference levels can result in whole body average SARs that exceed the basic restrictions by up to 35%. This occurs in human models with unusual postures that would be difficult to maintain for a sufficient duration in order to cause the elevated SAR (Findlay et al., 2005/2009). On the other hand, Uusitupa et al., (2010) reported a larger increase (2 dB) for a normal posture (sitting). This relates to the whole body average SAR of adults at 300-400 MHz, where the ratio of whole body average SAR to the whole body exposure at the reference level is lower than other frequencies. Thus the elevated SAR in this frequency range is small, particularly compared with the associated uncertainties, and does not provide sufficient evidence to alter the reference levels.

4.4. S REFERENCE LEVELS FROM 6 GHZ TO 300 GHZ FOR WHOLE BODY EXPOSURE

Above 6 GHz, the radiofrequency EMFs generally follow the characteristics of the plane wave or far-field exposure conditions. Therefore, only incident power density is used as the reference level in this frequency region. The reactive near-field exists very close to a radiofrequency source in this frequency region. The typical boundary of the reactive near-field and the radiative near-field is defined as $\lambda/2\pi$ (e.g., 8 mm at 6 GHz). Because the equivalent power density usually exceeds the reference level in the reactive near-field region, compliance with the basic restrictions needs to be assessed for such cases.

The radiofrequency power absorbed in the body exponentially decays in the direction from the surface to deeper regions. Therefore, the absorbed power is confined within the body surface above 6 GHz, where the total absorbed power or the whole body average SAR is approximately proportional to the exposed area of the body surface (Hirata, Asano et al., 2007; Gosselin et al., 2009). Kuhn et al. (2009) and Uusitupa et al. (2010) verified this dependence not only for normal conditions, such as standing posture on the ground plane, but also for various postures, incident angles and polarizations. Furthermore, a recent experimental study using a reverberation chamber found a strong correlation between the whole body average SAR and the surface area of a human body from 1 GHz to 12 GHz (Flintoft et al., 2014).

Since the whole body average SAR is approximately proportional to the incident power density and body surface (and is not dependent on EMF frequency), ICNIRP has extended the whole body reference levels from below 6 GHz, up to 300 GHz. ICNIRP (1998) set whole body reference levels within this range at 50 W m^{-2} and 10 W m^{-2} (for occupational and general public exposure respectively). As there is no evidence that these levels will result in exposures that exceed the whole body basic restrictions, or that they will cause harm, these guidelines retain the ICNIRP (1998) reference levels for whole body exposure conditions.

The same time and spatial average for the whole body average SAR basic restrictions are applied to these corresponding reference levels. Therefore, the incident power density is to be temporally averaged over 30 minutes and spatially averaged over the space to be occupied by a human body.

4.5. S REFERENCE LEVELS FROM 6 GHZ TO 300 GHZ FOR LOCALIZED EXPOSURE

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The reference levels above 6 GHz (incident power density) for the localized exposure can be derived from the basic restrictions in terms of the transmitted power density divided by the transmittance. Transmittance is defined as follows:

$$\text{Transmittance} = 1 - |\text{reflection coefficient}|^2 \qquad \text{(Eqn. 4.1).}$$

The reflection coefficient is derived from the electrical properties of the surface tissues, shape of the body surface, incident angle and polarization. The angle corresponding to the maximum transmittance is usually the angle normal to the body surface, and is referred to as the Brewster angle for a specific polarization of TM-wave incidence. Recent research has shown that the normal angle results in the maximum transmitted power density (greatest absorption) and is used for calculating the reference levels (Li et al., 2018).

The variation and uncertainty of the transmittance for the normal-angle incident condition have been investigated (Sasaki et al., 2017). The transmittance asymptotically increases from 0.4 to 0.8 as the frequency increases from 10 GHz to 300 GHz. Similar tendencies have also been reported elsewhere (Kanezaki et al., 2009; Foster et al 2016; Hashimoto et al., 2017).

Considering the frequency characteristics of the transmittance, the reference levels for the localized exposure have been derived as exponential functions of the frequency linking 200 W m^{-2} at 6 GHz to 100 W m^{-2} at 300 GHz (for occupational exposure). The same method is applied for the derivation of reference levels for the general public.

The temporal and spatial characteristics are almost the same for incident power density and transmitted power density at the body surface for the scale considered in the basic restrictions, i.e., 6 minutes and 4 cm^2 (below 30 GHz) or 1 cm^2 (above 30 GHz). Therefore, the same averaging conditions are applied to the incident power density reference levels, as for the transmitted power density basic restrictions.

4.6. LIMB CURRENT REFERENCE LEVELS

Limb current is defined as the current flowing through the limbs, such as through an ankle or wrist. Because the current focuses into high conductivity tissues such as muscle, and the ratio of the high conductivity tissues is small in the ankle and wrist, high local SAR can appear in these parts of the body. This phenomenon is particularly pronounced for cases of a human body standing on the ground plane in a whole body resonant condition.

The local SAR in limbs (ankle and wrist) is strongly correlated with the current flowing through the limbs. Although the local SAR is generally difficult to measure directly, the limb SAR can be derived from the limb current (I), which can be relatively easily measured, as follows:

$$SAR = \frac{\sigma E^2}{\rho} = \frac{J^2}{\sigma\rho} = \frac{I^2}{\sigma\rho A^2} \qquad \text{(Eqn. 4.2),}$$

where σ, ρ, and A are the conductivity, density and effective section area (in m^2) respectively.

The limb current reference levels are therefore set in order to evaluate the local SAR in the ankle and wrist, especially around the ankle in a grounded human body for the whole body resonant condition. Above the whole body resonant frequency for the grounded condition, the maximum local SAR does not always appear around limbs, and is thus not relevant.

Dimbylow (2002) showed that a limb current of 1 A causes 531 W kg^{-1} to 973 W kg^{-1} of local SAR averaged over 10 g in the ankles of an adult male model standing on a grounded plane from 10 MHz to 80 MHz. It is noted that the shape of the averaging region of the 10 g tissue was not cubic, but contiguous, which results in higher SAR values than those of a cube.

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Based on that study, ICNIRP sets the limb current reference levels at 100 mA and 20 mA, for occupational and general public exposures respectively, to conservatively protect against the local SAR basic restrictions in the limbs (e.g. the maximum local SAR in the limbs for a 100 mA current would only be 10 W kg^{-1}). Similarly, Dimbylow (2001) computed the 10 g local SAR (with contiguous tissue) for a 100 mA wrist current, resulting in 26.90 W kg^{-1} at 100 kHz, decreasing to 12.50 W kg^{-1} at 10 MHz. Considering the reduction of the cubic compared to contiguous shape, the 100 mA limb current at the wrist will also protect against the local SAR basic restrictions at the wrist.

As shown in Eqn. 4.2, the local SAR is proportional to the squared value of the limb current. In Eqn. 4.2, however, the effective area is a constant to relate the limb current to the 10 g averaged local SAR and depends on not only the actual section area but also tissue distribution/ratio and conductivity. Because the conductivity asymptotically increases as the frequency increases from 100 kHz to 110 MHz, the relationship between local SAR and limb current is not constant across this frequency range. For example, Dimbylow (2002) demonstrated that the local SAR due to a constant limb current halved as frequency of current reduced from 80 MHz to 10 MHz. This suggests that the upper limit frequency for limb current reference levels could potentially be lowered, relative to the 100 kHz – 110 MHz range of ICNIRP (1998). However, due to the lack of research addressing this issue, ICNIRP has decided to keep the same frequency range as in ICNIRP (1998).

Because the limb current reference levels are relevant to the local SAR basic restrictions, the same temporal averaging is applied (i.e. 6 minutes). It is noted that as the squared value of the limb current is proportional to the local SAR, the squared value of the limb current must be used for time averaging (as described in Section 2).

4.7. REFERENCE LEVELS FOR BRIEF EXPOSURE (< 6 MINUTES)

The reference levels for brief exposure are derived to match the brief exposure basic restrictions, which have been set in terms of SA and transmitted energy density, below and above 6 GHz respectively.

The reference levels have been derived from numerical computations with the multi-layered human model exposed to a plane wave, or to typical sources used close to the body such as a dipole antenna (e.g. Hashimoto et al., 2017).

The reference levels vary as a function of time interval to match the transmitted energy density basic restrictions (above 6 GHz), with a similar function used below 6 GHz to match the SA basic restrictions. It is noted that the time function of the reference levels and the transmitted energy density basic restrictions are more conservative than those for the SA reference levels and basic restrictions. This means that the reference levels are more conservative above than below 6 GHz. As with the other reference levels, exposure will be compliant with the guidelines if the basic restrictions are complied with, even if the reference levels are exceeded.

Because the reference levels are based on the multi-layered model, the uncertainty included in the dosimetry is not significant. Conversely, this simple modeling is likely overly conservative for a realistic human body shape and structure. This overestimation decreases as the frequency increases because the penetration depth is short relative to the body-part dimensions. Morphological variations are also not significant.

5. REFERENCES

DRAFT

Adair ER, Black DR. Thermoregulatory responses to RF energy absorption, Bioelectromagnetics, 2003, Supplement 6:17-38.

Adair ER, Mylacraine KS, Cobb BL. Human Exposure to 2450MHz CW Energy at Levels Outside the IEEEC95.1Standard does not increase core temperature. Bioelectromagnetics, 2001, 22:429-39.

Adair ER, Mylacraine KS, Allen SJ. Thermophysiological consequences of whole-body resonant RF exposure (100 MHz) in human volunteers. Bioelectromagnetics, 2003, 24:489-501

Adair ER, Blick DW, Allen SJ, Mylacraine KS, Ziriax JM, Scholl DM, Thermophysiological Responses of Human Volunteers to Whole Body RF Exposure at 220MHz, Bioelectromagnetics, 2005, 26:448-61.

Akimoto S, Kikuchi S, Nagaoka T, Saito K, Watanabe S, Takahashi M, Ito K. Evaluation of Specific Absorption Rate for a Fetus by Portable Radio Terminal Close to the Abdomen of a Pregnant Woman. IEEE Transactions on Microwave Theory and Techniques, 2010, 58(12):3859-65.

Asakura H. Fetal and neonatal thermoregulation. J Nippon Med Sch. 2004, 71(6):360-70.

Bakker JF, Paulides MM, Christ A, Kuster N, van Rhoon GC, Assessment of induced SAR in children exposed to electromagnetic plane waves between 10 MHz and 5.6 GHz. Physics in Medicine and Biology, 2010, 55:3115-30.

Bakker JF, Paulides MM, Neufeld E, Christ A, Kuster N, van Rhoon GC, Children and adults exposed to electromagnetic fields at the ICNIRP reference levels: theoretical assessment of the induced peak temperature increase. Physics in Medicine and Biology, 2011, 65:4967-89.

Bernardi P, Cavagnaro M, Pisa S, Piuzzi E, Human Exposure to Radio Base-Station Antennas in Urban Environment, IEEE Transactions on Microwave Theory and Techniques, 2000, 48:1996-2002.

Bernardi P, Cavagnaro M, Pisa S, Piuzzi E. Power absorption and temperature elevations induced in the human head by a dual-band monopole-helix antenna phone. IEEE Trans Microwave Theory and Techniques, 2001, 49(12):2539-46.

Brockow T, Wagner A, Franke A, Offenbächer M, Resch KL. A randomized controlled trial on the effectiveness of mild water-filtered near infrared whole-body hyperthermia as an adjunct to a standard multimodal rehabilitation in the treatment of fibromyalgia. Clinical Journal of Pain, 2007, 23(1):67-75.

Buccella C, De Santis V, Feliziani M. Prediction of temperature increase in human eyes due to RF sources. IEEE Transactions on Electromagnetic Compatibility, 2007, 49:825–33.

Conil E, Hadjem A, Lacroux F, Wong MF, Wiart J. Variability analysis of SAR from 20 MHz to 2.4 GHz for different adult and child models using finite-difference time-domain. Physics in Medicine and Biology, 2008, 53:1511-25.

Diao Y, Leung SW, He Y, Sun W, Chan KH, Siu YM, Kong R, Detailed modeling of palpebral fissure and its influence on SAR and temperature rise in human eye under GHz exposures. Bioelectromagnetics, 2016, 37:256-63.

Dimbylow PJ. FDTD calculations of the whole-body averaged SAR in an anatomically realistic voxel model of the human body from 1 MHz to 1 GHz. Physics in Medicine and Biology, 1997, 42:479-90.

DRAFT

Dimbylow PJ. The relationship between localized SAR in the arm and wrist current. Radiation Protection Dosimetry, 2001, 95:177-79.

Dimbylow PJ. Fine resolution calculations of SAR in the human body for frequencies up to 3 GHz. Physics in Medicine and Biology, 2002, 47:2835-46.

Dimbylow PJ. Development of the female voxel phantom, NAOMI, and its application to calculations of induced current densities and electric field from applied low frequency magnetic and electric fields. Physics in Medicine and Biology, 2005, 50:1047-70.

Dimbylow PJ. SAR in the mother and foetus for RF plane wave irradiation. Physics in Medicine and Biology, 2007, 52:3791-3802.

Dimbylow PJ, Bolch WE. Whole-body averaged SAR from 50 MHz to 4 GHz in the University of Florida child voxel phantoms. Physics in Medicine and Biology, 2007, 52:6639-49.

Dimbylow PJ, Hirata A, Nagaoka T. Intercomparison of whole-body averaged SAR in European and Japanese voxel phantoms. Physics in Medicine and Biology, 2008, 53:5883-97.

Durney CH, Massoudi H, Iskander MF. Radiofrequency radiation dosimetry handbook (Fourth Edition), USAFSAM-TR-85-73, USAF School of Aerospace Medicine, Brooks Air Force Base, TX 78235; 1986.

Edwards MJ, Saunders RD, Shiota K. Effects of heat on embryos and fetuses. International Journal of Hyperthermia, 2003, 19(3):295-324.

Emery AF, Kramar P, Guy AW, Lin JC. Microwave induced temperature rises in rabbit eyes in cataract research. Journal of Heat Transfer, 1975, 97:123-28.

Findlay RP, Dimbylow PJ. Effects of posture on FDTD calculations of specific absorption rate in a voxel model of the human body. Physics in Medicine and Biology, 2005, 50:3825-35.

Findlay RP, Lee AK, Dimbylow PJ, FDTD calculations of SAR for child voxel models in different postures between 10 MHz and 3 GHz. Radiation Protection Dosimetry, 2009, 135(4): 226–31.

Flintoft M, Robinson MP, Melia GCR, Marvin AC, Dawson JF. Average absorption cross-section of the human body measured at 1–12 GHz in a reverberant chamber: results of a human volunteer study. Physics in Medicine & Biology, 2014, 59(13):3297-317.

Foster KR, Ziskin MC, Balzano Q. Thermal Response of Human Skin to Microwave Energy: A Critical Review. Health Physics, 2016, 111(6):528-41.

Foster, KR, Ziskin MC, Balzano Q. Thermal Modeling for the Next Generation of Radiofrequency Exposure Limits: Commentary. Health Physics, 2017, 113(1):41–53.

Foster, KR, Ziskin MC, Balzano Q, Bit-Babik G. Modeling Tissue Heating From Exposure to Radiofrequency Energy and Relevance of Tissue Heating to Exposure Limits: Heating Factor. Health Physics, 2018, 115(2):295-307.

Fujimoto M, Hirata A, Wang J, Fujiwara O, Shiozawa T. FDTD-derived correlation of maximum temperature increase and peak SAR in child and adult head models due to dipole antenna. IEEE Transactions on Electromagnetic Compatibility, 2006, 48(1):240-47.

Gandhi OP, Li Q-X, Kang G. Temperature rise for the human head for cellular telephones and for peak SARs prescribed in safety guidelines. IEEE Transactions on Microwave Theory and Techniques, 2001, 49(9):1607-13.

DRAFT

Gabriel C. Compilation of the dielectric properties of body tissues at RF and microwave frequencies. Brooks Air Force Technical Report AL/OE-TR-1996-0037; 1996.

Gabriel C, Dielectric Properties of Biological Tissue: Variation With Age, Bioelectromagnetics, 2005, Supplement 7:S12-S18.

Gosselin MC, Christ A, Kuhn S, Kuster N, Dependence of the Occupational Exposure to Mobile Phone Base Stations on the Properties of the Antenna and the Human Body, IEEE Transactions on Electromagnetic Compatibility, 2009, 51:227-35.

Guy AW, Lin JC, Kramar PO, Emery A. Effect of 2450-MHz radiation on the rabbit eye. IEEE Transactions on Microwave Theory and Techniques, 1975, 23:492-98.

Hashimoto Y, Hirata A, Morimoto R, Aonuma S, Laakso I, Jokela, K Foster KR. On the averaging area for incident power density for human exposure limits at frequencies over 6 GHz. Physics in Medicine & Biology, 2017, 62(8):3124-38.

He W, Xu B, Gustafsson M, Ying Z, He S RF Compliance Study of Temperature Elevation in Human Head Model Around 28 GHz for 5G User Equipment Application: Simulation Analysis. IEEE Access, 2018, 6: 830-8.

Hirata A, Shiozawa T. Correlation of maximum temperature increase and peak SAR in the human head due to handset antennas. IEEE Transactions on Microwave Theory & Techniques, 2003, 51(7):1834-41.

Hirata A, Temperature Increase in Human Eyes Due to Near-Field and Far-Field Exposures at 900 MHz, 1.5 GHz, and 1.9 GHz, IEEE Transaction on Electromagnetic Compatibility, 2005, 47:68-76.

Hirata A, Fujimoto M, Asano T, Wang J, Fujiwara O, Shiozawa T, Correlation Between Maximum Temperature Increase and Peak SAR with Different Average Schemes and Masses, IEEE Transactions on Electromagnetic Compatibility, 2006a, 48:569-78.

Hirata A, Fujiwara O, Shiozawa T. Correlation between peak spatial-average SAR and temperature increase due to antennas attached to human trunk. IEEE Transactions on Biomediccal Engineering, 2006b, 53:1658-64.

Hirata A, Watanabe S, Fujiwara O, Kojima M, Sasaki K, Shiozawa T. Temperature elevation in the eye of anatomically based human models for plane-wave exposure. Physics in Medicine and Biology, 2007a, 52:6389-99.

Hirata A, Asano T, Fujiwara O, FDTD analysis of human body-core temperature elevation due to RF far-field energy prescribed in the ICNIRP guidelines, Physics in Medicine and Biology, 2007b, 52:5013–23.

Hirata A, Shirai K, Fujiwara O. On averaging mass of SAR correlating with temperature elevation due to a dipole antenna. Progress in Electromagnetic Research, 2008a, 84:221-37.

Hirata A, Ito N, Fujiwara O, Nagaoka T, Watanabe S, Conservative estimation of whole-body-averaged SARs in infants with a homogeneous and simple-shaped phantom in the GHz region. Physics in Medicine and Biology, 2008b, 53: 7215-23.

Hirata A, Sugiyama H, Fujiwara O. Estimation of core temperature elevation in humans and animals for whole-body averaged SAR. Progress in Electromagnetics Research, 2009a, 99:53-70.

DRAFT

Hirata A, Ito N, Fujiwara O, Influence of electromagnetic polarization on the whole-body averaged SAR in children for plane-wave exposures. Physics in Medicine and Biology, 2009b, 54:N59–N65.

Hirata A, Fujiwara O. The correlation between mass-averaged SAR and temperature elevation in the human head model exposed to radiofrequency near-fields from 1 to 6 GHz. Physics in Medicine and Biology, 2009c, 54(23):7171-82.

Hirata A, Fujiwara O, Nagaoka T, Watanabe S, Estimation of Whole-Body Average SAR in Human Models Due to Plane-Wave Exposure at Resonance Frequency, IEEE Transactions on Electromagnetic Compatibility, 2010, 52:41-8.

Hirata A, Yanase K, Laakso I, Chan KH, Fujiwara O, Nagaoka T, Watanabe S, Conil E, Wiart J, Estimation of the whole-body averaged SAR of grounded human models for plane wave exposure at respective resonance frequencies. Physics in Medicine and Biology, 2012, 57:8427–42.

Hirata A. Laakso I, Oizumi T, Hanatani R, Chan KH, Wiart J, The relationship between specific absorption rate and temperature elevation in anatomically based human body models for plane wave exposure from 30 MHz to 6 GHz. Physics in Medicine & Biology, 2013, 58(4):903-21.

Hirata A, Laakso I, Ishii Y, Nomura T, Chan KH, Computation of Temperature Elevation in a Fetus Exposed to Ambient Heat and Radio Frequency Fields, Numerical Heat Transfer, Part A: Applications, 2014, 65:1176-87.

Ibrahim A, Dale C, Tabbara W, Wiart J. Analysis of the temperature increase linked to the power induced by RF source. Progress in Electromagnetic Research, 2005, 52:23-46.

ICNIRP - International Commission on Non-ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Physics, 1998, 74(4):494-522.

ICNIRP - International Commission on Non-ionizing Radiation Protection. ICNIRP statement on the “Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)”. Health Physics, 2009, 97(3):257-58.

ICNIRP - International Commission on Non-ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz). Health Physics, 2010, 99(6):818-36.

Kanezaki A, Hirata A, Watanabe S, Shirai H, Effects of dielectric permittivities on skin heating due to millimeter wave exposure, BioMedical Engineering OnLine, 2009, 8:20 doi:10.1186/1475-925X-8-20.

Kashiwa et al. (2018). Unpublished observations.

Kawai H, Nagaoka T, Watanabe S, Saito K, Takahashi M, Ito K, Computational dosimetry in embryos exposed to electromagnetic plane waves over the frequency range of 10 MHz–1.5 GHz. Physics in Medicine and Biolog, 2010, 55:N1–N11.

Kodera et al., (2018). Unpubished observations.

Kühn S, Jennings W, Christ A, Kuster N, Assessment of induced radio-frequency electromagnetic fields in various anatomical human body models. Physics in Medicine and Biology, 2009, 54:875–90.

DRAFT

Laakso I, Hirata A. Dominant factors affecting temperature rise in simulations of human thermoregulation during RF exposure. Physics in Medicine and Biology, 2011, 56: 7449-21.

Laakso I, Morimoto R, Heinonen J, Jokela K, Hirata A. Human exposure to pulsed fields in the frequency range from 6 to 100 GHz. Physics in Medicine and Biology, 2017, 62(17):6980-92.

Lee AK, Choi HD, Determining the influence of Korean population variation on whole-body average SAR. Physics in Medicine and Biology, 2012, 57:2709-25.

Li K, Sasaki K, Watanabe S. Evaluation of heating effects due to millimeter wave exposure in oblique incidence. Conference Proceedings, BioEM, June 2018.

McIntosh RL, Anderson V, SAR Versus VAR, and the Size and Shape That Provide the Most Appropriate RF Exposure Metric in the Range of 0.5-6 GHz, Bioelectromagnetics, 2011, 32:312-21.

R Morimoto, I Laakso, V De Santis, A Hirata. Relationship between peak spatial-averaged specific absorption rate and peak temperature elevation in human head in frequency range of 1–30 GHz. Physics in Medicine and Biology, 2016, 61:5406-25.

Morimoto R., Hirata A., Laakso I, Ziskin M, Foster R. Time constants for elevation in human models exposed to dipole antenna and beams in the frequency range from 1 to 30 GHz. Physics in Medicine and Biology, 2017, 62:1676-99.

Nagaoka T, Watanabe S, Saurai K, Kunieda E, Watanabe S, Taki M, Yamanaka Y. Development of realistic high-resolution whole- body voxel models of Japanese adult males and females of average height and weight, and application of models to radio-frequency electromagnetic-field dosimetry. Physics in Medicine and Biology, 2004, 49:1-15.

Nagaoka T, Togashi T, Saito K, Takahashi M, Ito K, Watanabe S, An anatomically realistic whole-body pregnant-woman model and specific absorption rates for pregnant-woman exposure to electromagnetic plane waves from 10 MHz to 2 GHz. Physics in Medicine and Biology, 2007, 52: 6731-45.

Nagaoka T, Kunieda E, Watanabe S. Proportion-corrected scaled voxel models for Japanese children and their application to the numerical dosimetry of specific absorption rate for frequencies from 30 MHz to 3 GHz. Physics in Medicine and Biology, 2008, 53:6695-711.

Nagaoka T, Niwa T, Watanabe S, Specific Absorption Rate in Mothers and Fetuses in the Second and Third Trimesters of Pregnancy. International Journal of Microwave and optical Technology, 2014, 9(1):34-38.

Nelson DA, Curran AR, Nyberg HA, Marttila EA, Mason PA, Ziriax JM, High-resolution simulations of the thermophysiological effects of human exposure to 100 MHz RF energy. Physics in Medicine and Biology, 2013, 58:1947-68.

Neubauer G, Preiner P, Cecil S, Mitrevski N, Gonter J, Garn H, The relation between the specific absorption rate and electromagnetic field intensity for heterogeneous exposure conditions at mobile communications frequencies. Bioelectromagnetics, 2009, (30):651-62.

Nomura T, Laakso I, Hirata A, FDTD computation of temperature elevation in the elderly for far-field RF exposures. Radiation Protection Dosimetry, 2014, 158(4): 497–500.

Oizumi T, Laakso I, Hirata A, Fujiwara O, Watanabe S, Taki M, Kojima M, Sasaki H, Sasaki K, FDTD analysis of temperature elevation in the lens of human and rabbit models due to near-field and far-field exposures at 2.45 GHz. Radiation Protection Dosimetry, 2013, 155(3):284-91.

DRAFT

Razmadze A, Shoshiashvili L, Kakulia D, Zaridze R, Bit-Babik G, Faraone A, Influence of Specific Absorption Rate Averaging Schemes on Correlation between Mass-Averaged Specific Absorption Rate and Temperature Rise. Electromagnetics, 2009, (29):77-90.

Sasaki K, Mizuno M, Wake K, Watanabe S. Monte Carlo simulations of skin exposure to electromagnetic field from 10 GHz to 1 THz. Physics in Medicine and Biology, 2017, 62(17):6993-7010.

Kashiwa T, Taguchi K, Laakso I, Aga K., Hirata A. Exposure reference level for intermediate frequency exposures. Presented at IEEE International Committee on Electromagnetic Safety Meeting (January, 2018).

Takei R, Nagaoka T, Nishino K, Saito K, Watanabe S, Takahashi M. Specific absorption rate and temperature increase in pregnant women at 13, 18, and 26 weeks of gestation due to electromagnetic wave radiation from a smartphone. IEICE Communications Express, in press (https://doi.org/10.1587/comex.2018XBL0026).

Tateno A, Akimoto S, Nagaoka T, Saito K, Watanabe S, Takahashi M, Ito K. Specific Absorption Rates and Temperature Elevations due to Wireless Radio Terminals in Proximity to a Fetus at Gestational Ages of 13, 18, and 26 Weeks. IEICE Transactions on Communications, 2014, E97-B(10):2175-83.

Uusitupa T, Laakso I, Ilvonen S, Nikoskinen K, SAR variation study from 300 to 5000 MHz for 15 voxel models including different postures. Physics in Medicine and Biology, 2010, 55: 1157-76.

Van Leeuwen GMJ, Lagendijk JJW, Van Leersum BJAM, Zwamborn APM, Hornsleth SN, Kotte ANTJ. Calculation of change in brain temperatures due to exposure to a mobile phone. Physics in Medicine and Biology, 1999, 44:2367-23.

Vermeeren G, Joseph W, Martens L, Whole-body SAR in spheroidal adult and child phantoms in realistic exposure environment. Electronics Letters, 2008, 44(13):790-91.

Wainwright P. Thermal effects of radiation from cellular telephones. Physics in Medicine and Biology, 2000, 45:2363-72.

Wainwright PR. Computational modelling of temperature rise in the eye in the near field of radiofrequency sources at 380,900 and 1800 MHz. Physics in Medicine and Biology, 2007, 52:3335-50.

Wang J, Fujiwara O. FDTD computation of temperature rise in the human head for portable telephones. IEEE Transactions on Microwave Theory and Techniques, 1999, 47:1528-34.

Ziskin MC, Morrissey J. Thermal thresholds for teratogenicity, reproduction, and development. International Journal of Hyperthermia, 2011, 27(4):373-87.

DRAFT