

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., E , H , 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 E , 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 E over a volume V ;

$$E_{spatial_average} = \sqrt{\frac{1}{V} \int_V |E(r)|^2 dr} \quad (\text{Eqn. 2.1}),$$

where r is the location in the volume of the integration ($V = \int_V dr$).

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

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

$$43 \quad SAR = \frac{\delta}{\delta t} \left(\frac{\delta W}{\delta m} \right) = \frac{\delta}{\delta t} \left(\frac{\delta W}{\rho \delta V} \right) \quad (\text{Eqn. 2.2}).$$

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

$$47 \quad SAR = \frac{\sigma |E|^2}{\rho} \quad (\text{Eqn. 2.3}),$$

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

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

$$53 \quad SAR = C \frac{dT}{dt} \quad (\text{Eqn. 2.4}),$$

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

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

$$59 \quad SA = \int_{t_1}^{t_2} SAR(t) dt \quad (\text{Eqn. 2.5}).$$

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

$$61 \quad \Delta T = SA/C \quad (\text{Eqn. 2.6}).$$

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

$$66 \quad \text{Whole body average SAR} = \frac{(\text{Total power})_{WB}}{(\text{Total weight})_{WB}} = \frac{\int_{WB} \sigma |E|^2 dv}{\int_{WB} \rho dv} \quad (\text{Eqn. 2.7}).$$

67 SAR_{10g} is defined as the total power absorbed in a 10 g cubic volume divided by 10 grams:

$$68 \quad SAR_{10g} = \frac{(\text{Total power})_{V_{10g}}}{(\text{Total weight})_{V_{10g}}} = \frac{\int_{V_{10g}} \sigma |E|^2 dv}{\int_{V_{10g}} \rho dv} \quad (\text{Eqn. 2.8}).$$

69 A 10 g volume (V_{10g}) is generally defined as a $2.15[\text{cm}] \times 2.15[\text{cm}] \times 2.15[\text{cm}]$ cube,
 70 based on the assumption that the tissue has the same mass density as water, or 1000 kg m^{-3} .

71 **2.2. TRANSMITTED POWER DENSITY (S_{TR}) AND TRANSMITTED ENERGY** 72 **DENSITY (H_{TR})**

73 The transmitted power and energy densities are newly introduced in the guidelines for basic
 74 restrictions above 6 GHz, where the radiofrequency power or energy absorption is confined
 75 within very superficial regions of the body; e.g., the penetration depths are approximately 1

76 cm and 0.4 mm at 6 GHz and 300 GHz, respectively; SAR_{10g} is no longer an appropriate
77 surrogate for local temperature elevation at such frequencies.

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

$$80 \quad S_{tr} = \iint_A dx dy \int_0^{\infty} \rho(x, y, z) \cdot SAR(x, y, z) dz / A \quad (\text{Eqn. 2.9}),$$

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

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

$$85 \quad S_{tr} = \iint_A \text{Re}[\mathbf{S}] \cdot \mathbf{ds} / A = \iint_A \text{Re}[\mathbf{E} \times \mathbf{H}^*] \cdot \mathbf{ds} / A \quad (\text{Eqn. 2.10}),$$

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

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

$$90 \quad H_{tr} = \int_{t_1}^{t_2} S_{tr}(t) dt \quad (\text{Eqn. 2.11}).$$

91 **2.3. INCIDENT POWER DENSITY (S_{INC}) AND INCIDENT ENERGY DENSITY** 92 **(H_{INC})**

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

$$95 \quad S_{inc} = |\mathbf{E} \times \mathbf{H}^*| \quad (\text{Eqn. 2.12}).$$

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

$$98 \quad S_{inc} = EH = \frac{E^2}{Z_0} = Z_0 H^2 \quad (\text{Eqn. 2.13}).$$

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

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

$$102 \quad S_{tr} = (1 - |R|^2) \cdot S_{inc} \quad (\text{Eqn. 2.14}).$$

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

$$105 \quad H_{inc} = \int_{t_1}^{t_2} S_{inc}(t) dt \quad (\text{Eqn. 2.15}).$$

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

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

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

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

120 **3. RELEVANT BIOPHYSICAL MECHANISMS**

121 **3.1. WHOLE BODY EXPOSURE**

122 **3.1.1. Relevant quantity**

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

126 Body core temperature depends on the whole body thermal energy balance. Radiofrequency
127 energy absorbed by the body is transferred to the body core via blood flow, which can
128 activate thermoregulatory responses to maintain the body core temperature (Adair & Black,
129 2003). This means that the time rate of the energy balance is essential for the body core
130 temperature dynamics. Whole body average SAR is used as the physical quantity relating to
131 body core temperature elevation.

132 The relationship between the total energy absorption and the body core temperature is in
133 general independent of frequency. However, at frequencies higher than a few GHz, core
134 temperature does not elevate as much as with the same level of whole body average SAR at
135 lower frequencies because of heat transfer from the body surface to air, including the effect of
136 vasodilation in the skin (Hirata et al 2013). The power absorption is confined within skin
137 surface tissues where localized temperature elevation is more significant than the body core
138 temperature elevation (Laakso and Hirata, 2011). It has also been reported that infrared
139 radiation (IR) exposure can cause significant body core temperature elevation (Brockow et al.,
140 2007). Infrared radiation refers to electromagnetic waves with frequencies between those of
141 radiofrequency EMF and visible light. This means that the penetration depth of IR is very
142 small or comparable to the high GHz radiofrequency EMFs (or millimeter waves). For
143 conservative reasons, therefore, ICNIRP set equal whole body average limits for frequencies
144 both above and below 6 GHz. This is especially important for cases of multiple-frequency
145 exposure of both higher and lower frequencies. Thus, the applicable frequency is the entire
146 frequency range considered in the guidelines.

147 **3.1.2. Temporal averaging considerations**

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

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

$$155 \quad T(t) = T_0 + (T_\infty - T_0) \left(1 - e^{-\frac{t}{\tau}}\right) \quad (\text{Eqn. 3.1}),$$

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

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

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

177 **3.1.3. Whole body average SAR needed to raise body core temperature by 1°C**

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

181 Adair and colleagues have experimentally investigated body core temperature (via
182 esophageal temperature measurements) during whole body exposure. They have reported no
183 or minor increases of the esophageal temperature (<0.1°C) during the whole body exposure at
184 100 MHz, 220 MHz, and 2450 MHz, with whole body average SAR ranging from 0.54 to 1
185 W kg⁻¹ in normal ambient temperature conditions, from 24°C to 28°C (Adair et al., 2001;
186 Adair et al., 2003; Adair et al., 2005).

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

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

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

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

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

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

222 **3.1.4. Considerations for fetus exposure**

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

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

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

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

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

260 **3.2. LOCAL EXPOSURE UP TO 6 GHZ (\geq 6 MINUTES)**

261 **3.2.1. Relevant quantity**

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

268 **3.2.2. Spatial averaging considerations**

269 Different averaging schemes (e.g. cubic, spherical, contiguous single tissue) and masses have
270 been assessed in terms of their ability to predict local temperature rise (Hirata and Fujiwara,
271 2009; McIntosh and Anderson, 2011). These suggest that the effect of averaging mass is
272 more crucial than the shape of averaging volume, and that SAR varies with different
273 averaging schemes by a factor of approximately 2 (Hirata, Fujimoto et al., 2006). It has also
274 been shown that SAR averaged over a single tissue provides somewhat worse correlation
275 with local temperature than that for multiple tissues, because the heat generated in biological
276 tissue can diffuse up to a few centimeters (across multiple tissue types). Consequently, a
277 cubic averaging mass of 10 g, including all tissues, is used as an appropriate spatial averaging
278 regime for frequencies up to 6 GHz. This metric has been shown to be applicable even for
279 plane wave exposures, in that local temperature elevation in the Head and Trunk, and Limbs,
280 are correlated with this averaging mass (Razmadze et al., 2009; Bakker et al., 2011; Hirata et
281 al., 2013).

282 **3.2.3. Temporal averaging considerations**

283 Time to reach the steady-state temperature, given the balance between rate of radiofrequency
284 power deposition on one hand, and heat diffusion and conduction on the other, is
285 characterized by the time constant of temperature elevation. The time constant primarily
286 depends on heat convection due to blood flow and thermal conduction. Van Leeuwen et al
287 (1999), Wang and Fujiwara (1999) and Bernardi et al. (2000) report that the time needed for
288 80-90% of the steady-state temperature rise, at 800 MHz to 1.9 GHz, is 12–16 minutes. These
289 guidelines take 6 minutes as a suitable, conservative averaging time for steady-state
290 temperature elevation up to 6 GHz.

291 **3.2.4. Local SAR required to increase local Type-1 and Type-2 tissue temperature by 5**
292 **and 2 °C respectively**

293 Although early research provided useful rabbit data concerning the relation between 2.45
294 GHz exposure and local temperature elevation (e.g. Guy et al., 1975; Emery et al., 1975),
295 more recent research with more accurate techniques has demonstrated that the rabbit is an
296 inaccurate model for the human eye (Oizumi, et al., 2013). However, given the concern about
297 potential radiofrequency harm to the eye, there are now several studies that provide
298 information about radiofrequency-induced heating of the human eye. Expressed as heating
299 factors (the °C elevation over a 1 kg mass, per W of absorbed power), the computed heating
300 factors of a human eye have been relatively consistent (0.11–0.16 °C kg W⁻¹; Hirata et al.,
301 2005; Hirata, Watanabe et al., 2007; Wainwright, 2007; Buccella, De Santis & Feliziani,
302 2007; Buccella, 2007; Laakso 2009; Diao et al., 2016). In most studies, the heating factor was
303 derived for the SAR averaged over the eyeball (contiguous tissue). The SAR averaged over
304 the cubic volume (which includes other tissues) is higher than that value (Diao et al, 2016),
305 resulting in lower heating factors. Based on these heating factors, the operational adverse
306 health effect thresholds for the eye will not be exceeded for local exposures of 20 W kg⁻¹.

307 There are also a considerable number of studies on the temperature elevation in the head
308 exposed to mobile phone handset antennas (Bernardi et al., 2000/2001; Gandhi, Li & Kang,
309 2001; Hirata & Shiozawa, 2003; Hirata, Fujiwara et al., 2006a; Ibrahim et al., 2005; van
310 Leeuwen et al., 1999; Wainwright, 2000; Wang & Fujiwara, 1999). Hirata and Shiozawa
311 (2003) reported that heating factors are 0.24 or 0.14 °C kg W⁻¹ for the local SAR averaged
312 over 10 gram contiguous volume with and without the pinna respectively. Other studies
313 considering the local SAR averaged over a 10 g cubic volume including the pinna reported
314 heating factors in the range of 0.2-0.25 °C kg W⁻¹ (Bernardi et al., 2000; Hirata & Shiozawa,
315 2003; Razmadze et al., 2009; Wainwright, 2000). Fujimoto et al. (2006) studied the
316 temperature elevation in a child head exposed to a dipole antenna and found that it is
317 comparable to that in the adult when the same thermal parameters were used. In most of the
318 studies, the temperature elevation in the brain is also computed. The heating factor in the
319 brain (the ratio of the temperature elevation in the brain to peak SAR in the head) is 0.1 °C kg
320 W⁻¹ or smaller (Morimoto et al, 2016). Uncertainty factors associated with the heating factors
321 are attributable to the energy absorbed in the pinna and its surrounding structures (see, e.g.,
322 Foster et al., 2018).

323 Those studies are consistent with recent research showing that, within the 100 kHz – 6 GHz
324 range, numerical estimations converge to show that the maximum heating factor is lower than
325 0.25 °C kg W⁻¹ in the skin and 0.1 °C kg W⁻¹ in the brain, for exposures of at least
326 approximately 30 minutes. The result of this is that the operational health effect thresholds
327 will not be exceeded for exposures of 20 W kg⁻¹.

328 **3.2.5. Considerations for fetus exposure**

329 The primary thermoregulatory mechanism for a fetus is body core heat exchange with the
330 mother via blood flow through the umbilical cord, making it difficult to increase fetal
331 temperature without also increasing the body core temperature of the mother. Heating factors
332 for the fetus, as a function of gestation stage and fetal posture and position, have been
333 determined that take such heat exchange into account (Akimoto et al., 2010, Tateno et al.,
334 2014, and Takei et al., in press). This research used numerical models of 13-week, 18-week
335 and 26-week pregnant women. The heating factors of the fetus are several times lower than
336 those of the mother in most cases. However, the worst case has been found where the fetal

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

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

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

353

354 3.3. LOCAL EXPOSURE FROM 6 GHZ TO 300 GHZ

355 3.3.1. Relevant quantity

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

$$359 S_{tr}(x) = S_0 e^{-\frac{2x}{\delta}} \quad (\text{Eq. 3.2}),$$

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

364 The penetration depth depends on the electrical properties of the medium, as well as
365 frequency. As frequency increases, the penetration depth decreases, and is limited within the
366 surface tissues at frequencies higher than 6 GHz. The following table lists the penetration
367 depth based on the dielectric properties of skin tissue (dermis) measured by Sasaki et al.,
368 (2017).

369 **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
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370 As a result, the local SAR averaged over a 10 gram mass with side length of 2.15 mm is no
371 longer a good proxy for the local temperature elevation; that is, the power deposition is
372 limited to within a few millimeters of the surface tissues. Conversely, the power density
373 transmitted into the skin provides a better approximation of the superficial temperature rise
374 from 6 GHz to 300 GHz (Foster et al., 2016; Hashimoto et al., 2017).

375 **3.3.2 Spatial averaging considerations**

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

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

392 **3.3.3 Temporal averaging considerations**

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

403 **3.3.4 Transmitted power density required to increase local Type-1 tissue temperature 404 by 5 °C**

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

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

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

416 3.3.5 Considerations for the fetus

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

425 3.4 REQUIREMENTS FOR LOCAL EXPOSURE UP TO 6 GHZ (< 6 MINUTES)

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

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

$$434 \Delta T_{adiabatic} = SAR \cdot t / C = SA / C \quad (\text{Eqn. 3.3}),$$

435 where C is heat capacitance and t is the exposure duration. This implies that the SA
 436 corresponding to the operational adverse health effect threshold, or ΔT_{OAHE} , is constant and
 437 derived as follows;

$$438 SA_{adiabatic} = C \cdot \Delta T_{OAHE} \quad (\text{Eqn. 3.4}).$$

439 It is noted that the adiabatic heating assumption is extremely conservative. Therefore, for
 440 cases where the exposure duration is longer than the time scale of the adiabatic heating, the
 441 SA corresponding to ΔT_{OAHE} is higher than $SA_{adiabatic}$ and depends on the exposure duration
 442 t .

443 A recent numerical modelling investigation for brief exposure to radiofrequency EMF from
 444 100 MHz to 6 GHz, using a multi-layer model and a Japanese head model, found that the SA
 445 corresponding to the allowable temperature elevation is greatly dispersive depending on
 446 various factors (Kodera et al., unpublished). Based on that study and empirical equations of
 447 the SA corresponding to the operational health effect threshold for the skin ($5 \text{ }^\circ\text{C}$), the
 448 exposure corresponding to this temperature rise is derived from the following equations;

$$449 SA(t) = 500 \text{ [J/kg]} \text{ for } t \leq 1 \text{ [sec]} \quad (\text{Eqn. 3.5}),$$

$$450 SA(t) = 500 + 354\sqrt{t - 1} \text{ [J kg}^{-1}] \text{ for } 1 \text{ [sec]} < t \leq 360 \text{ [sec]} \quad (\text{Eqn. 3.6}),$$

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

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

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

456 The recent numerical modelling study by Kodera et al. (unpublished) also show that the
457 temperature elevation in Type-2 tissue (i.e. the brain) is also protected by the SA restriction
458 for the skin defined in the above equations. They furthermore reported that the SA
459 corresponding to the allowable temperature rise increases as frequency decreases. At 400
460 MHz or lower, the cumulative SA derived from the local 6 minute SAR ($10 \text{ [W kg}^{-1}] \times 360$
461 $[\text{s}] = 3.6 \text{ [kJ/kg]}$) does not reach the temperature rise corresponding to the OAHET for the
462 Head and Trunk. Accordingly, this SA limit is only required for exposures above 400 MHz.

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

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

477 **3.5 REQUIREMENTS FOR LOCAL EXPOSURE ABOVE 6 GHz (< 6-MINUTES)**

478 Similar to the situation for frequencies lower than 6 GHz, temperature elevation can be
479 enhanced for intense short pulses or discontinuous exposures above 6 GHz, even at the same
480 transmitted power density that is allowed in a 6 minute average. This becomes significant at
481 frequencies higher than 30 GHz (Foster et al 2016). Considering the robustness and
482 consistency of simple multi-layer models, the basic restrictions for the brief exposures are
483 derived based on investigations using simple models (Foster et al., 2016; Morimoto et al.,
484 2017). Unlike continuous wave exposure, the effect of diffraction, or interference of waves
485 reflected from protruding parts of the body back to the skin, may be apparent for brief pulses.
486 Although the effect of diffraction to the transmitted power density is yet to be fully
487 determined, the resultant temperature elevation is estimated to be up to 3 times higher if
488 pulsed than that due to the same transmitted power density spread evenly over a 6 minute
489 interval (Laakso et al., 2017).

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

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

500 $H_{tr}(t) = 5 \text{ [kJ m}^{-2}\text{]} \text{ for } t \leq 1 \text{ [sec]}$ (Eqn. 3.7),

501 $H_{tr}(t) = 5 + 3.54\sqrt{t-1} \text{ [kJ m}^{-2}\text{]} \text{ for } 1 \text{ [sec]} < t \leq 360 \text{ [sec]}$ (Eqn. 3.8),

502 where t is the time interval.

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

510 As discussed above in relation to the frequency characteristics of the SAR distribution, the
511 contribution of the surface heating due to radiofrequency EMF above 6 GHz to fetal
512 temperature elevation is likely smaller than that below 6 GHz. This is the same for cases of
513 brief exposure. However, as there is no study on fetal exposure to radiofrequency EMF above
514 6 GHz, ICNIRP adopts a conservative approach and treats a pregnant worker as a member of
515 the general public to ensure that the fetal exposure will not exceed that of the general public.

516 **4. DERIVATION OF THE REFERENCE LEVELS**

517 **4.1. GENERAL CONSIDERATIONS FOR REFERENCE LEVELS**

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

529 From 30 MHz to 6 GHz, the reference levels are set in terms of the **E**-field, **H**-field and
530 incident power density. The relationship between **E**-field and **H**-field follows the
531 characteristics of the plane wave where the characteristic impedance (i.e. E/H), is equal to
532 377 Ohm in free space. ICNIRP recognizes that high-strength radiofrequency EMF
533 comparable to or higher than the reference levels frequently appears in the near region of
534 radiofrequency sources. The characteristics of fields close to a radiofrequency source is not
535 the same as the plane wave, and is referred to as the reactive near-field. In the reactive near-
536 field, ICNIRP therefore requires evaluation of both the **E**-field and **H**-field and confirmation
537 that both fields do not exceed the reference levels.

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

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

549 Below 30 MHz, the relationship between the **E**-field and **H**-field reference levels is not the
550 same as that of the plane wave, and thus power density reference levels are not set (see
551 Section 4.2). Consequently, both the **E**-field and **H**-field reference levels must be met.
552 However, where the **E**-field is more dominant than the **H**-field (i.e. where E/H is larger than
553 377Ω), only the **E**-field needs to be measured because this is more conservative than the **H**-
554 field reference level.

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

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

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

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

572 **4.2. E, H-FIELD REFERENCE LEVELS < 30 MHZ**

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

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

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

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

601 **4.3. E, H-FIELDS AND S REFERENCE LEVELS FROM 30 MHZ TO 6 GHZ**

602 The whole body average SAR for exposure at the field strength of reference level (ICNIRP
603 1998) becomes close to the basic restrictions around the whole-body resonant frequency (45-
604 170 MHz) and post resonant frequency region (1400-4000 MHz).

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

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

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

637 increase in a similar manner to the case of the child (Lee and Choi, 2012; Hirata et al.,
638 2010/2012).

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

648 Dimbylow (2007) reported that, using a simplified pregnant women model, the whole body
649 average SAR in the fetus becomes maximal at 70 MHz for the isolated condition, which is
650 the same as the mother. A similar tendency was found for anatomical fetus models of second
651 and third trimester and the whole body average SARs in the fetus of 20 week, 26 week, and
652 29 week gestation period are approximately 80%, 70% and 60% of those in the mother,
653 respectively (Nagaoka et al., 2014). The whole body average SARs of the fetus, while still
654 embryonic, are comparable to or lower than the whole body averaged SARs in the mother,
655 because the embryo is located deep within the abdomen of the mother (Kawai et al., 2010).
656 The fetus is therefore not considered independently from the mother in terms of reference
657 levels.

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

664 Considering the need to cover the local SAR basic restrictions, the averaging time to be
665 applied to the reference levels is set the same as for the local SAR basic restrictions, which is
666 6 minutes for local SAR, and 30 minutes for whole body average SAR basic restrictions.

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

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

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

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

696 **4.4. S REFERENCE LEVELS FROM 6 GHZ TO 300 GHZ FOR WHOLE BODY** 697 **EXPOSURE**

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

705 The radiofrequency power absorbed in the body exponentially decays in the direction from
706 the surface to deeper regions. Therefore, the absorbed power is confined within the body
707 surface above 6 GHz, where the total absorbed power or the whole body average SAR is
708 approximately proportional to the exposed area of the body surface (Hirata, Asano et al.,
709 2007; Gosselin et al., 2009). Kuhn et al. (2009) and Uusitupa et al. (2010) verified this
710 dependence not only for normal conditions, such as standing posture on the ground plane, but
711 also for various postures, incident angles and polarizations. Furthermore, a recent
712 experimental study using a reverberation chamber found a strong correlation between the
713 whole body average SAR and the surface area of a human body from 1 GHz to 12 GHz
714 (Flintoft et al., 2014).

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

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

726 **4.5. S REFERENCE LEVELS FROM 6 GHZ TO 300 GHZ FOR LOCALIZED** 727 **EXPOSURE**

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

$$731 \text{ Transmittance} = 1 - |\text{reflection coefficient}|^2 \quad (\text{Eqn. 4.1}).$$

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

738 The variation and uncertainty of the transmittance for the normal-angle incident condition
739 have been investigated (Sasaki et al., 2017). The transmittance asymptotically increases from
740 0.4 to 0.8 as the frequency increases from 10 GHz to 300 GHz. Similar tendencies have also
741 been reported elsewhere (Kanezaki et al., 2009; Foster et al 2016; Hashimoto et al., 2017).

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

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

751 **4.6. LIMB CURRENT REFERENCE LEVELS**

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

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

$$761 \text{ SAR} = \frac{\sigma E^2}{\rho} = \frac{J^2}{\sigma \rho} = \frac{I^2}{\sigma \rho A^2} \quad (\text{Eqn. 4.2}),$$

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

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

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

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

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

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

794 **4.7. REFERENCE LEVELS FOR BRIEF EXPOSURE (< 6 MINUTES)**

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

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

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

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

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