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ICNIRP Guidelines

GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC AND ELECTROMAGNETIC FIELDS (100 kHz TO 300 GHz)

International Commission on Non-Ionizing Radiation Protection

1. INTRODUCTION

The guidelines described here are for the protection of humans exposed to radiofrequency electromagnetic fields (EMFs) in the range 100 kHz to 300 GHz (hereafter 'radiofrequency'). This publication replaces the radiofrequency part of the 1998 guidelines (ICNIRP 1998); ICNIRP has already published updated guidelines for the low-frequency part (ICNIRP 2010). Although these guidelines are based on the best science currently available, it is recognized that there may be limitations to this knowledge which could impact on the exposure restrictions. Accordingly, the guidelines will be periodically revised and updated as advances are made in the relevant scientific knowledge.

2. PURPOSE AND SCOPE

The main objective of this publication is to establish guidelines for limiting exposure to EMFs that will provide a high level of protection for all people against known adverse health effects from direct, non-medical exposures to both short- and long-term, continuous and discontinuous radiofrequency EMFs. Within this context, 'direct' refers to effects of radiofrequency EMF directly on tissue, rather than via an intermediate object. Medical procedures may utilize or alter EMF fields and result in direct effects on the body (e.g. radiofrequency ablation, hyperthermia). As medical procedures require potential harm to be weighed against intended benefits, ICNIRP treats exposure related to medical procedures (i.e. to patients, carers and comforters) as beyond the scope of these guidelines (for further information, see UNEP/WHO/IRPA, 1993). Similarly, volunteer research participants are deemed to be outside the scope of these guidelines, providing that an institutional ethics committee approves such participation following consideration of potential harms and benefits. Cosmetic procedures may also utilize radiofrequency EMFs. ICNIRP treats people exposed to radiofrequency EMF as a result of cosmetic treatments as subject to these guidelines, with any decisions as to potential exemptions the role of national regulatory bodies, which are better suited to weigh potential benefits and harms within the context of cultural norms. Radiofrequency EMF may also interfere with electrical equipment, which can affect health indirectly by causing equipment to malfunction. This is referred to as electromagnetic compatibility, and is outside the scope of these guidelines (for further information, see ISO14117 and IEC 60601-1-2).

3. PRINCIPLES FOR LIMITING RADIOFREQUENCY EXPOSURE

These guidelines specify quantitative EMF levels for safe personal exposure. Adherence to these levels is intended to protect people from all known harmful effects of radiofrequency EMF exposure. To determine these levels, ICNIRP first identified published scientific literature concerning effects of radiofrequency EMF exposure on biological systems, and established which of these were both harmful to human health [1], and scientifically substantiated. This latter point is important because ICNIRP considers that, in general, reported effects need to be independently replicated, be of sufficient scientific quality and explicable more generally within the context of the scientific literature, in order to be taken as 'evidence' and used for setting exposure restrictions. Within the guidelines, 'evidence' will be used within this context, and 'substantiated effect' used to describe reported effects that satisfy this definition of evidence.

For each substantiated effect, ICNIRP then identified the 'adverse health effect threshold'; the lowest exposure level known to cause the health effect. These thresholds were derived to be strongly conservative for typical exposure situations and populations. Where no such threshold could be explicitly obtained from the radiofrequency health literature, or where evidence that is independent from the radiofrequency health literature has (indirectly) shown that harm can occur at levels lower than the 'EMF-derived threshold', ICNIRP set an 'operational threshold'. These are based on more-general knowledge of the relation between the primary effect of exposure (e.g. heating) and health effect (e.g. pain), to provide an operational level with which to derive restriction values in order to attain an appropriate level of protection. Consistent with previous guidelines from ICNIRP, reduction factors were then applied to the resultant thresholds (or operational thresholds) to provide exposure limit values. Reduction factors account for biological variability in the population, variance in baseline conditions (e.g. tissue temperature), variance in environmental factors (e.g. air temperature, clothing), dosimetric uncertainty associated with deriving exposure values, uncertainty associated with the health science, and as a conservative measure more generally.

The exposure limit values are referred to as 'basic restrictions', and relate to physical quantities inside an exposed body that are closely related to radiofrequency-induced adverse health effects. These quantities cannot be easily measured, and so quantities that are more easily evaluated, termed 'reference levels', have been derived from the basic restrictions to provide a more-practical means of demonstrating compliance with the guidelines. Reference levels have been derived to provide an equivalent degree of protection to the basic restrictions, and thus an exposure is taken to be compliant with the guidelines if it is shown to be below either the relevant basic restrictions or relevant reference levels. Note that the relative concordance between exposures resulting from basic restrictions and reference levels may vary depending on a range of factors. As a conservative step, reference levels have been derived such that under worst-case exposure conditions (which are highly unlikely to occur in practice), they will result in similar exposures to those specified by the basic restrictions. It follows that in the vast majority of cases the reference levels will result in substantially lower exposures than the corresponding basic restrictions allow. See Section 5.2 for further details.

The guidelines differentiate between occupationally-exposed individuals and members of the general public. Occupationally-exposed individuals are defined as healthy adults who are exposed under controlled conditions associated with their occupational duties, trained to be aware of potential radiofrequency EMF risks and to employ appropriate harm-mitigation

[1] Note that the World Health Organization (2006) definition of 'health' is used here. Specifically, "health is a state of complete physical, mental and social well-being, and not merely the absence of disease or infirmity".

measures, and who have the capacity for such awareness and harm-mitigation response; it is not sufficient for a person to merely be a worker. The general public is defined as individuals of all ages and of differing health statuses, which may include particularly vulnerable groups or individuals, and who may have no knowledge of or control over their exposure to EMF. These differences suggest the need to include more stringent restrictions for the general public, as members of the general public would not be suitably trained to mitigate harm, or may not have the capacity to do so. Occupationally-exposed individuals are not deemed to be at greater risk than the general public, providing that appropriate screening and training is provided to account for all known risks. Note that a fetus is here defined as a member of the general public, regardless of exposure scenario, and is subject to the general public restrictions.

As can be seen above, there are a number of steps involved in deriving ICNIRP's guidelines. ICNIRP adopts a conservative approach to each of these steps in order to ensure that its limits would remain protective even if exceeded by a substantial margin. For example the choice of adverse health effects, presumed exposure scenarios, application of reduction factors and derivation of reference levels are all conducted conservatively. The degree of precaution in the exposure levels is thus greater than may be suggested by considering only the reduction factors, which represent only one conservative element of the guidelines. ICNIRP considers that the derivation of limits is sufficiently conservative to make additional precautionary measures unnecessary.

4. SCIENTIFIC BASIS FOR LIMITING HIGH FREQUENCY EXPOSURE

4.1. QUANTITIES, UNITS AND INTERACTION MECHANISMS

A brief overview of the electromagnetic quantities and units employed in this document, as well as the mechanisms of interaction of these with the body, is provided here. A more detailed description of the dosimetry relevant to the guidelines is provided in Appendix A.

Radiofrequency EMFs consist of rapidly oscillating electric and magnetic fields; the number of oscillations per second is referred to as 'frequency', and is described in units of hertz (Hz). As the field propagates away from a source, it transfers power from its source, described in units of watts (W), which is equivalent to joules (J, a measure of energy) per second. When the field impacts upon material, it interacts with the atoms and molecules in that material. When radiofrequency EMF reaches a biological body, some of its power is reflected away from the body, and some is transmitted into it. This results in complex patterns of fields inside the body that are heavily dependent on the EMF source and frequency, as well as on the physical properties and dimensions of the body. These internal fields are referred to as induced electric fields (**E**, measured in volts per meter; V m^{-1}), and they can affect the body in different ways that are potentially relevant to health.

Firstly, the induced electric field in the body exerts force on both polarized molecules (mainly water molecules) and on free moving charged particles such as electrons and ions. In both cases the EMF energy is converted to movement energy, forcing the polarized molecules to rotate and charged particles to move as a current. As the polarized molecules rotate and charged particles move, they typically interact with other polarized molecules and charged particles, causing the movement energy to be converted to heat. This heat can affect health in a range of ways. Secondly, if the induced electric field is strong and brief enough, it can exert electrical forces that are sufficient to stimulate nerves, or to cause dialectric breakdown of biological membranes, as occurs during direct current (DC) electroporation (Mir, 2008).

From a health risk perspective we are generally interested in how much EMF power is absorbed by biological tissue, as this is responsible for the heating effects described above.

This is typically described as a function of a relevant dosimetric quantity. For example, below 6 GHz, where EMF penetrates deep into tissue (and thus requires depth to be considered), it is useful to describe this in terms of 'specific absorption rate' (SAR), which is the power absorbed per unit mass (W kg^{-1}). Conversely, above 6 GHz, where EMF is absorbed more superficially (making depth less relevant), it is useful to describe exposure in terms of transmitted power density ($\mathbf{S}_{tr}$), which is the power absorbed per unit area (W m^{-2}). In these guidelines SAR is specified over different masses to better match particular adverse health effects; SAR_{10g} represents the power absorbed (per kg) over a 10-g cubical mass, and whole body average SAR represents power absorbed (per kg) over the entire body. Similarly, transmitted power density is specified over different areas due to such factors as exposure duration and EMF frequency. In some situations the rate of energy deposition (power) is less relevant than the total energy deposition. This may be the case for brief exposures where there is not sufficient time for heat diffusion to occur. In such situations, specific absorption (SA, in J kg^{-1}) and transmitted energy density ($\mathbf{H}_{tr}$, in J m^{-2}) are used, for EMF below and above 6 GHz respectively. SAR, $\mathbf{S}_{tr}$, SA and $\mathbf{H}_{tr}$ are the quantities used in these guidelines to specify the basic restrictions.

As the quantities used to specify basic restrictions can be difficult to measure, quantities that are more easily evaluated, termed reference levels, are also specified. The reference level quantities relevant to these guidelines are electric field (**E**) and magnetic field (**H**), as described above, as well as incident power density ($\mathbf{S}_{inc}$) and equivalent incident power density ($\mathbf{S}_{eq}$), both measured outside the body and described in units of watts per square-meter (W m^{-2}), and electric current inside the body, *I*, described in units of ampere (A).

Table 1. Quantities and corresponding SI units used in these guidelines

Quantity	**Symbol**	**Unit**
Current	*I*	ampere (A)
Electric field strength	**E**	volt per meter (V m^{-1})
Equivalent incident power density	$\mathbf{S}_{eq}$	watt per square meter (W m^{-2})
Frequency	*f*	hertz (Hz)
Incident power density	$\mathbf{S}_{inc}$	watt per square meter (W m^{-2})
Magnetic field strength	**H**	ampere per meter (A m^{-1})
Specific energy absorption	*SA*	joule per kilogram (J kg^{-1})
Specific energy absorption rate	*SAR*	watt per kilogram (W kg^{-1})
Transmitted energy density	$\mathbf{H}_{tr}$	radiant exposure (J m^{-2})
Transmitted power density	$\mathbf{S}_{tr}$	watt per square meter (W m^{-2})
Time	*t*	second (s)

RADIOFREQUENCY EMF HEALTH RESEARCH

In order to set safe limits, ICNIRP first determined whether there was evidence that radiofrequency EMF impaired health, and for each adverse effect that was substantiated, determined (where available) both the mechanism of interaction and the minimum exposure required to cause harm. This information was obtained primarily from major international reviews of the literature on radiofrequency EMF and health, including an in-depth review from the WHO on radiofrequency EMF exposure and health that will be released as a Technical Document in the near future (World Health Organization, 2014), and SCENIHR (2015). These reports have reviewed an extensive body of literature, ranging from experimental research to epidemiology. To complement those reports, ICNIRP also considered research published since those reviews. A brief summary of this literature is provided in Appendix B.

As described in Appendix B, radiofrequency EMF can affect the body via three primary biological effects: nerve stimulation, membrane permeabilization, and temperature elevation. In addition to these, knowledge concerning relations between these primary biological effects and health, independent of the radiofrequency EMF literature, was also evaluated. ICNIRP considers this appropriate given that the vast majority of radiofrequency EMF health research has been conducted using exposures substantially lower than those shown to produce adverse health effects, with relatively little research addressing adverse health effect thresholds themselves. Thus it is possible that the radiofrequency health literature may not be sufficiently comprehensive to ascertain thresholds. Conversely, where a more-extensive literature is available that clarifies the relation between health and the primary biological effects, this can be useful for setting guidelines. For example, if the thermal physiology literature demonstrated that local temperature elevations of a particular magnitude caused harm, but radiofrequency exposure known to produce a similar temperature elevation had not been evaluated for harm, then it would be reasonable to also consider this additional thermal physiology literature. ICNIRP refers to thresholds derived from such additional literature as *operational* adverse health effect thresholds.

It is important to note that ICNIRP only uses operational thresholds to set restrictions where they are lower (more conservative) than those demonstrated to affect health in the radiofrequency literature, or where the radiofrequency literature does not provide sufficient evidence to deduce an adverse health effect threshold. For the purpose of determining thresholds, evidence of adverse health effects arising from all exposures is considered, including those referred to as ‘low-level’ and ‘non-thermal’, and including those where mechanisms have not yet been elucidated.

4.3. THRESHOLDS FOR RADIOFREQUENCY EMF-INDUCED HEALTH EFFECTS

4.3.1. NERVE STIMULATION

Exposure to EMF can induce electric fields within the body, which for frequencies up to 10 MHz can stimulate nerves (Saunders and Jeffreys, 2007); this is not known to occur *in vivo* at frequencies higher than approximately 10 MHz. The effect of this stimulation varies as a function of frequency, and is typically reported as a ‘tingling’ sensation for frequencies around 100 kHz (where peak field is most relevant). As frequency increases, heating effects predominate and the likelihood of nerve stimulation decreases; at 10 MHz the electric field is typically described as ‘warmth’. Nerve stimulation by induced electric fields is protected by the ICNIRP low frequency guidelines (2010), and is not discussed further here.

4.3.2. MEMBRANE PERMEABILIZATION

When (low frequency) EMF is pulsed, the power is distributed across a range of frequencies, which can include radiofrequency EMF (Joshi and Schoenbach, 2010). If the pulse is sufficiently intense and brief, exposure to the resultant EMF may cause cell membranes to become permeable, which in turn can lead to other cellular changes. However, there is no evidence that the radiofrequency spectral component from an EMF pulse (without the low-frequency component) is sufficient to cause this permeability. The restrictions on nerve stimulation in the ICNIRP (2010) guidelines provide adequate protection against the low frequency components, so additional protection from the resultant radiofrequency EMF is not necessary. Membrane permeability has also been shown to occur with 18 GHz continuous wave exposure (e.g. Nguyen et al., 2015). This has only been demonstrated *in vitro*, and requires very high exposure levels (circa 5 kW kg^{-1}) that far exceed those required to cause thermally-induced harm (see Section 4.3.3). Therefore there is also no need to specifically protect against this effect, as restrictions designed to protect against smaller temperature elevations will also protect against this.

4.3.3. TEMPERATURE ELEVATION

Radiofrequency EMFs can generate heat in the body. As heat can affect health, it is important that heat generated by EMF is kept to a safe level. However, as can be seen from Appendix B, there is a dearth of radiofrequency exposure research using sufficient power to cause heat-induced health effects. Of particular note is that although exposures (and resultant temperature rises) have occasionally been shown to cause severe harm, the literature lacks concomitant evidence of the highest exposures that do not cause harm. For very low exposure levels (such as within the ICNIRP (1998) basic restrictions) there is extensive evidence that the amount of heat generated is not sufficient to cause harm, but for exposure levels above those of the ICNIRP (1998) basic restriction levels, yet below those shown to produce harm, there is still uncertainty. Where there is good reason to expect health impairment at temperatures lower than those shown to impair health via radiofrequency EMF exposure, ICNIRP uses those lower temperatures to base limits on.

It is important to note that these guidelines restrict radiofrequency EMF exposure to limit temperature increase (ΔT) rather than absolute temperature, whereas health effects are primarily related to absolute temperature. This strategy is used because it is not feasible to limit absolute temperature, which is dependent on many factors that are outside the scope of these guidelines, such as environmental temperature, clothing and work rate. This means that if exposure caused a given temperature increase, this could improve, not affect, or impair health depending on the prevailing conditions. For example, mild heating can be pleasant if a person is cold, but unpleasant if they are already very hot. The restrictions are therefore set to avoid significant increase in temperature, where ‘significant’ is considered in light of both potential harm and normal physiological temperature variation. These guidelines differentiate between steady-state temperature elevations (where temperature increases slowly, allowing time for temperature to dissipate over a larger tissue mass and for thermoregulatory processes to counter temperature rise), and brief temperature elevations (where there may not be sufficient time for temperature to dissipate, which can cause larger temperature elevations in small regions given the same absorbed radiofrequency power). This distinction suggests the need to account for steady-state and brief exposure durations separately.

4.3.3.1. STEADY-STATE TEMPERATURE RISE

4.3.3.1.1. BODY CORE TEMPERATURE

Body core temperature refers to the temperature deep within the body, such as in the abdomen and brain, and varies substantially as a function of such factors as gender, age, time of day, work rate, environmental conditions and thermoregulation. For example, although the mean body core temperature is approximately 37 °C (and within the 'normothermic' range[2]), this typically varies over a 24-hour period to meet physiological needs, with the magnitude of the variation as large as 1 °C (Reilly et al., 2007). As thermal load increases, thermoregulatory functions such as vasodilation and sweating can be engaged to restrict body core temperature elevation. This is important because a variety of health effects can occur beyond this range (>38 °C, termed 'hyperthermia'). Although most health effects induced by mild hyperthermia resolve readily and have no lasting effects, risk of accident increases with hyperthermia (Ramsey et al, 1983), and at body core temperatures > 40 °C it can lead to heat stroke, which can be fatal (Cheshire, 2016).

Detailed guidelines are available for minimising risk associated with hyperthermia within the occupational setting (ACGIH, 2017). These aim to modify work environments so as to keep body core temperature within +1 °C of normothermia, and require substantial knowledge of each particular situation due to the range of variables that can affect it. As described in Appendix B, body core temperature rise due to radiofrequency EMF that results in harm is only seen where temperature greatly exceeds +1 °C (e.g. > +5 °C in rats; Jauchem and Frei, 1997), with no clear evidence of the adverse health effect threshold. Due to the limited literature available ICNIRP has adopted a conservative temperature rise value as the operational adverse health effect threshold (the 1 °C rise of ACGIH, 2017). It is important to note that even though body core temperature increases at the operational adverse health effect threshold (+ 1°C) can result in significant physiological changes, this can be part of the body's normal thermoregulatory response and within the normal physiological range, and thus does not *in itself* represent an adverse health effect.

Recent theoretical modelling and generalization from experimental research across a range of species predicts that exposures resulting in a whole body average SAR of approximately 6 W kg^{-1}, within the 100 kHz – 6 GHz range, over at least a 1-hour interval at moderate ambient temperature (28 °C), is required to induce a 1 °C body core temperature rise in human adults; a substantially higher SAR is required to reach this temperature rise in children due to their more-efficient heat dissipation (Hirata et al., 2013). However, given the limited measurement data available, ICNIRP has adopted a conservative position and uses 4 W kg^{-1}, averaged over 30 minutes, as the radiofrequency EMF exposure level corresponding to a body core temperature rise of 1 °C. As a comparison, a human adult generates a total of approximately 1 W kg^{-1} at rest (Weyand et al., 2009), nearly 2 W kg^{-1} standing, and 12 W kg^{-1} running (Teunissen et al., 2007).

As EMF frequency increases, exposure of the body and the resultant heating becomes more superficial, and above about 6 GHz this heating occurs predominantly within the skin. For example, 86% of the power at 6 and 300 GHz is absorbed within 8 and 0.2 mm of the surface respectively (Sasaki, 2017). Heat is more easily removed from the body when superficial than deep in the body because it is easier for the heat energy to transfer to the environment through convection; this is why basic restrictions to protect against body core temperature elevation

[2] 'Normothermia' refers to the thermal state within the body whereby active thermoregulatory processes are not engaged to either increase or decrease body core temperature.

have traditionally been limited to frequencies below 10 GHz (e.g. ICNIRP 1998). However, recent research has shown that EMF frequencies beyond 300 GHz (e.g. infrared) can increase body core temperature beyond the 1 °C operational adverse health effect threshold described above (Brockow et al., 2007). This is because infrared, as well as lower frequencies within the scope of the present guidelines, cause heating within the dermis, and the extensive vascular network within the dermis can transport this heat deep within the body. It is therefore appropriate to also protect against body core temperature elevation above 6 GHz.

ICNIRP is not aware of research that has assessed the effect of 6 – 300 GHz EMF on body core temperature, nor of research that has demonstrated that it is harmful. However, as a conservative measure, ICNIRP uses the 4 W kg^{-1} corresponding to the operational adverse health effect threshold for frequencies up to 6 GHz, for the >6 – 300 GHz range as well. In support of this being a conservative value, it has been shown that 1257 W m^{-2} (incident power density) infrared exposure to one side of the body results in a 1 °C body core temperature rise (Brockow et al, 2007). If we related this to the exposure of a 70 kg adult with an exposed surface area of 1 m^2 and no skin reflectance, this would result in a whole body exposure of approximately 18 W kg^{-1}, which is far higher than the 4 W kg^{-1} taken here for EMF below 6 GHz to represent the exposure corresponding to a 1 °C body core temperature rise. This is viewed as additionally conservative given that the Brockow et al. study reduced heat dissipation via a thermal blanket, which underestimates the exposure required to increase body core temperature under typical conditions.

4.3.3.1.2. LOCAL TEMPERATURE

In addition to body core temperature, excessive localised heating can cause pain and thermal damage. There is an extensive literature showing that skin contact with temperatures below 42 °C for extended periods will not cause pain or damage cells (e.g. Defrin et al., 2006). As described in Appendix B, this is consistent with the limited data available for radiofrequency EMF heating of the skin (e.g. Walters et al., 2000 reported a pain threshold of 43 °C using 94 GHz exposure), but fewer data are available for heat sources that penetrate beyond the protective epidermis and to the heat-sensitive epidermis/dermis interface. However, there is also a substantial body of literature assessing thresholds for tissue damage which shows that damage can occur at tissue temperatures > 41-43 °C, with damage likelihood and severity increasing as a function of time at such temperatures (e.g. Dewhirst et al. 2003, Yarmolenko et al. 2011, van Rhoon et al. 2013).

The current guidelines treat radiofrequency EMF exposure that results in local temperatures of 41 °C or greater as potentially harmful. As body temperature varies as a function of body region, ICNIRP treats exposure to different regions separately. Corresponding to these regions, these guidelines define two sets of tissue types which, based on their temperature under normothermal conditions, are assigned different operational health effect thresholds; 'Type-1' tissue, which typically has a lower thermo-normal temperature (all tissues in the upper arm, forearm, hand, thigh, leg, foot, pinna and the cornea, anterior chamber and iris of the eye, epidermal, dermal, fat, muscle and bone tissue), and 'Type-2' tissue, which typically has a higher normothermal temperature (all tissues in the head, eye, abdomen, back, thorax and pelvis, excluding those defined as Type-1 tissue). The normothermal temperature of Type 1 tissue is typically < 33-36 °C, and that of Type-2 tissue < 38-38.5 °C (DuBois 1941; Aschoff & Wever, 1958; Arens and Zhang, 2006; Shafahi & Vafai, 2011). These values were used to define operational thresholds for local heat-induced health effects; adopting 41 °C as potentially harmful, these guidelines take a conservative approach and treat radiofrequency EMF-induced temperature rises of 5 °C and 2 °C, within Type-1 and Type-2 tissue respectively, as operational adverse health effect thresholds for local exposure. It is difficult to set exposure limits as a function of the above tissue-type classification. ICNIRP thus defines two regions, and sets separate exposure limits, where relevant, for these regions; ‘Head and Torso’, comprising the head, eye, abdomen, back, thorax and pelvis, and the ‘Limbs’, comprising the upper arm, forearm, hand, thigh, leg and foot. Operational adverse health effect thresholds for each of these regions are set such that they do not result in temperature elevations of more than 5 °C and 2 °C, in Type-1 and Type-2 tissue respectively. As the limbs, by definition, do not contain any Type-2 tissue, the operational adverse health effect threshold for the limbs is always 5 °C.

The testes can be viewed as representing a special case, whereby reversible, graded, functional change can occur within normal physiological temperature variation if maintained over extended periods, with no apparent threshold. For example, spermatogenesis is reversibly reduced as a result of the 2 °C increase caused by normal activities such as sitting (relative to standing; Mieusset and Bujan, 1995). Thus it is possible that the operational threshold for Type-2 tissue may result in reversible changes to sperm function. However, there is currently no evidence that such effects are sufficient to impair health. Accordingly, ICNIRP views the operational threshold of 2 °C for Type-2 tissue, which is within the normal physiological range for the testes, as appropriate for the testes also. Note that the operational threshold for Type-2 tissue, which includes the abdomen and thus potentially the fetus, is also consistent with protecting against the fetal temperature threshold of 2 °C for teratogenic effects in animals (Edwards et al, 2003; Ziskin & Morrissey, 2011).

Within the 100 kHz – 6 GHz EMF range, average SAR over 10 g provides an appropriate measure of the radiofrequency EMF-induced steady-state temperature rise within tissue. A 10 g mass is used because, although there can initially be EMF-induced temperature heterogeneity within that mass, heat diffusion rapidly distributes the thermal energy to a much larger volume that is well-represented by a 10 g cubic mass (Hirata and Fujiwara, 2009). In specifying exposures that correspond to the operational adverse health effect thresholds, ICNIRP thus specifies an average exposure over a 10 g cubic mass, such that the exposure will keep the Type-1 and Type-2 tissue temperature elevations, to below 5 and 2 °C respectively. Further, ICNIRP assumes realistic exposures (such as from radio-communications sources). This method provides for higher exposures in the limbs than in the head and torso. A SAR_{10g} of at least 20 W kg^{-1} is required to exceed the operational adverse health effect thresholds in the Head and Torso, and 40 W kg^{-1} in the Limbs, over an interval sufficient to produce a steady state temperature (from a few minutes to 30 minutes). This time interval is operationalized as a 6-minute average as it closely matches the thermal time constant for local exposure.

Within the >6 – 300 GHz range, EMF energy is deposited predominantly in superficial tissues; this makes SAR_{10g}, which includes deeper tissues, less relevant to this frequency range. Conversely, transmitted power density ($\mathbf{S}_{tr}$) provides a measure of the power absorbed in tissue that closely approximates the superficial temperature rise (Hashimoto et al., 2017). From 6 to 10 GHz there may still be significant absorption in the subcutaneous tissue. However, as the maximum and thus worst-case temperature elevation from >6 to 300 GHz is close to the skin, exposure that will restrict temperature elevation to below the operational adverse health effect threshold for Type-1 tissue (5 °C) will also restrict temperature elevation to below the Type-2 tissue threshold (2 °C). Note that there is uncertainty with regard to the precise frequency for the change from SAR to transmitted power density. 6 GHz was chosen because at that frequency, most of the absorbed power is within the cutaneous tissue, which is within the upper half of a 10 g SAR cubic volume (that is, it can be represented by the 2.15 x 2.15 cm surface of the cube). Indeed recent thermal modeling and analytical solutions suggest that the averaging area of 4 cm^2 (2 cm × 2 cm) provides a good estimate of local maximum temperature elevation due to radiofrequency exposure between 6 and 30 GHz (Hashimoto et al., 2017; Foster et al., 2017). As frequency increases further, the averaging area needs to be reduced to account for the possibility of smaller beam diameters, such that it is 1 cm^2 from approximately 30 GHz to 300 GHz. Although the ideal averaging area would therefore gradually change from 4 to 1 cm^2 as frequency increases from 6 to 300 GHz, ICNIRP uses a step function (4 cm^2 for >6-30 GHz, and 1 cm^2 above 30 GHz) because this is sufficiently similar to the ideal averaging area across frequency. Further, as 6 minutes is an appropriate averaging interval (Morimoto et al., 2017) and as approximately 200 W m^{-2} is required to produce the Type-1 tissue operational adverse health effect threshold of a 5 °C local temperature rise (Sasaki et al., 2017), ICNIRP has set the transmitted power density value for local heating, averaged over 6 minutes and either 4 cm^2 (>6-30 GHz) or 1 cm^2 (>30 GHz), at 200 W m^{-2}.

4.3.3.2. RAPID TEMPERATURE RISE

For some types of exposure, rapid temperature elevation can result in 'hot spots', heterogeneous temperature distribution over tissue mass (Foster et al 2016; Morimoto et al 2017; Laakso et al., 2017). This suggests the need to consider averaging over smaller time-intervals for certain types of exposure. Hot spots can occur for short duration exposures because there is not sufficient time for heat to dissipate (or average out) over tissue. This effect is more pronounced as frequency increases, due to the smaller penetration depth.

To account for such heterogeneous temperature distributions, an adjustment to the steady-state exposure level is required. This can be achieved by specifying the maximum exposure level allowed, as a function of time, in order to restrict temperature elevation to below the operational adverse health effect thresholds. Note that for this specification, exposure from any pulse, group of pulses, or subgroup of pulses in a train, delivered in *t* seconds, must not exceed the below formulae (in order to ensure that the temperature thresholds are not exceeded). From 400 MHz to 6 GHz, ICNIRP specifies the limit in terms of specific absorption (SA) of any 10 g cubic mass, where SA is restricted to $500+354(t-1)^{0.5}$ J $kg^{-1}$for both Head and Torso, and Limb exposure, where *t* is exposure interval (in seconds); for intervals less than 1 second, SA is set at 500 J kg^{-1}. No distinction is made between Head and Torso, and Limb exposure for this operational adverse health effect threshold, because recent modelling shows that the operational health effect thresholds for both tissue types will be met simultaneously. There is no brief-interval exposure level specified below 400 MHz because, due to the large thermal diffusion length below 400 MHz, the total SA resulting from the 6 minute local SAR average (corresponding to the operational adverse health effect threshold) cannot increase temperature by more than the operational adverse health effect threshold (regardless of the particular pattern of pulses or brief exposures). Above 6 GHz, ICNIRP specifies the limit in terms of transmitted energy density ($\mathbf{H}_{tr}$) over any 4 cm^2 or 1 cm^2 area (for >6-30 GHz, and >30 GHz respectively), where $\mathbf{H}_{tr}$ is specified as $5+3.54(t-1)^{0.5}$ kJ m^{-2} for intervals between 1 and 360 seconds, where 't' is interval in seconds (Foster et al., 2016); for intervals less than a second, the value is set at 5 kJ m^{-2}. The SA and $\mathbf{H}_{tr}$ values are conservative in that, under worst-case (adiabatic) conditions, they are not sufficient to raise temperature by 5 °C.

5. GUIDELINES FOR LIMITING RADIOFREQUENCY EMF EXPOSURE

As described in Section 4, radiofrequency EMF thresholds for a number of operational adverse health effects were identified (increased body core or local tissue temperature due to absorption of EMF power). Exposure limits have been derived from these and are described below.

To be compliant with the present guidelines, exposure cannot exceed any of the restrictions described below, nor those for the 100 kHz – 10 MHz range of the ICNIRP (2010) low frequency guidelines, which includes protection against nerve stimulation. The present guidelines restrict radiofrequency EMF to levels that *do not cause any known health effect*, using relationships between exposure and tissue heating, as well as exposure and health more generally, to do so. Although the guidelines protect against significant temperature rise due to EMF power deposition within tissue, they do not limit other sources of heat (i.e. that are not due to radiofrequency EMF). For information concerning the relation between workers' health and *total* thermal load, see ACGIH 2017.

5.1. BASIC RESTRICTIONS

Basic restriction values are provided in Table 2-3, with an overview of their derivation described below. A more detailed description of issues pertinent to the basic restrictions is provided in Appendix A. Note that for the basic restrictions described below, a pregnant woman is treated as a member of the general public. This is because recent modelling suggests that for both whole body and local exposure scenarios, exposure of the mother at the occupational basic restrictions can lead to fetal exposures that exceed the general public basic restrictions.

5.1.1. WHOLE BODY AVERAGE SAR (100 kHz – 300 GHz)

As described in Section 4.3.3.1.1, the guidelines take a whole body average SAR of 4 W kg^{-1}, averaged over the entire body mass and a 30-minute interval, as the exposure level corresponding to the operational adverse threshold of an increase in body core temperature of 1 °C. A reduction factor of 10 was applied to this threshold for occupational exposure to account for scientific uncertainty, as well as differences in thermal baselines, thermoregulation ability and body core temperature health threshold across the population. Variability in an individual's ability to regulate their body core temperature is particularly important as it is dependent on a range of factors that the guidelines cannot control, such as central and peripherally-mediated modification to blood perfusion and sweat rate (which are in turn affected by a range of other factors, including age and certain medical conditions), as well as behavior and environmental conditions.

The reduction factor of 10 makes the basic restriction for occupational exposure a whole body average SAR of 0.4 W kg^{-1}, averaged over 30 minutes. Although this means that SAR can be larger for smaller time intervals, this will not affect body core temperature rise appreciably because the temperature will be 'averaged-out' within the body over the 30 minute interval, and it is this time-averaged temperature elevation that is relevant to body core temperature-related health effects. Further, as both whole body and local restrictions must be met simultaneously, exposures sufficiently high to be hazardous locally will be protected against by the local limits described below.

As the general public cannot be expected to be aware of exposures and thus to mitigate risk, a reduction factor of 50 was applied for the general public, reducing the general public restriction to 0.08 W kg^{-1}. It is noteworthy that the scientific uncertainty pertaining to both dosimetry and potential health consequences of whole body radiofrequency exposure have reduced substantially since the ICNIRP 1998 Guidelines. This would justify less conservative reduction factors, but as ICNIRP considers that the benefits of maintaining stable basic restrictions outweighs any benefits that subtle changes to the basic restrictions would provide, ICNIRP has retained the conservative reduction factors and the ICNIRP 1998 whole body average basic restrictions. Similarly, although temperature rise is more superficial as frequency increases (and thus it is easier for the heat to be lost to the environment), the whole body average SAR limits above 6 GHz have been conservatively set the same as those below 6 GHz.

5.1.2 Local SAR (100 kHz – 6 GHz)

Head and torso

As described in Section 4.3.3.1.2, the guidelines take a SAR of 20 W kg^{-1}, averaged over a 10 g cubic mass and 6 minute interval, within the 100 kHz to 6 GHz range, as the local exposure corresponding to the operational adverse health effect threshold for the Head and Torso (5 °C in Type-1 tissue and 2 °C in Type-2 tissue). A reduction factor of 2 was applied to this threshold for occupational exposure to account for scientific uncertainty, as well as differences in both thermal baselines and thermoregulation ability across the population. Reduction factors for local exposure are smaller than for whole body exposure because the associated health effect threshold is less dependent on the highly variable centrally-mediated thermoregulatory processes, and because the associated health effect is less serious medically.

The reduction factor of 2 makes the basic restriction for occupational exposure a SAR_{10g} of 10 W kg^{-1}, averaged over a 6 minute interval. As the general public cannot be expected to be aware of exposures and thus to mitigate risk, a reduction factor of 10 was applied for the general public, reducing the general public restriction to 2 W kg^{-1}.

Limbs

As described in Section 4.3.3.1.2, the guidelines take a SAR of 40 W kg^{-1}, averaged over a 10 g cubic mass and 6 minute interval, within the 100 kHz to 6 GHz range, as the local exposure corresponding to the operational adverse health effect threshold for the limbs of 5 °C local temperature elevation. As per the Head and Torso restrictions, a reduction factor of 2 was applied to this threshold for occupational exposure to account for scientific uncertainty, as well as differences in both thermal baselines and thermoregulation ability across the population, resulting in a basic restriction for occupational exposure a SAR_{10g} of 20 W kg^{-1}. As the general public cannot be expected to be aware of exposures and thus to mitigate risk, a reduction factor of 10 was applied for the general public, reducing the general public restriction to 4 W kg^{-1}.

5.1.3. LOCAL SA (400 MHz – 6 GHz)

As described in 4.3.3.2, an additional constraint is required within this frequency range to ensure that the cumulative energy permitted by the 6 minute average SAR_{10g} basic restriction is not absorbed by tissue too rapidly. Accordingly, for both the Head and Torso, and Limbs, ICNIRP set an SA level for exposure intervals of less than 6 minutes, as a function of time, to limit temperature elevation to below the operational adverse health effect thresholds. This SA level, averaged over a 10 g cubic mass, is given by $500+354(t-1)^{0.5}$ J kg^{-1} for exposure durations of at least 1 second, where ‘t’ is exposure duration in seconds for a single pulse, and 500 J kg^{-1} for exposure durations less than 1 second. The exposure from any group of pulses, or subgroup of pulses in a train, delivered in t seconds should not exceed this threshold. This threshold is for both the Head and Torso, and Limbs, because in both cases energy absorption is larger in superficial tissues, with the result being that operational adverse health effect thresholds will not be exceeded for either Type-1 or Type-2 tissue.

As per the SAR_{10g} basic restrictions, a reduction factor of 2 was applied to this threshold for occupational exposure to account for scientific uncertainty, as well as differences in both thermal baselines and thermoregulation ability across the population, resulting in a basic restriction for occupational exposure of $250+177(t-1)^{0.5}$ J kg^{-1}. As the general public cannot be expected to be aware of exposures and thus to mitigate risk, a reduction factor of 10 was applied for the general public, reducing the general public restriction to $50+35.4(t-1)^{0.5}$ J kg^{-1}.

5.1.4. LOCAL TRANSMITTED POWER DENSITY (>6 GHz – 300 GHz)

As described in Section 4.3.3.1.2, the guidelines take a transmitted power density of 200 W m^{-2}, averaged over 6 minutes and either 4 cm^2 (>6 to 30 GHz) or 1 cm^2 (>30 to 300 GHz) surface area of the body, within the >6 to 300 GHz range, as the local exposure corresponding to the operational adverse health effect threshold for both the Head and Torso, and Limb regions (5 and 2 °C local temperature elevation in Type-1 and Type-2 tissue respectively). As per the local SAR restrictions, a reduction factor of 2 was applied to this threshold for occupational exposure to account for scientific uncertainty, as well as differences in both thermal baselines and thermoregulation ability across the population. This results in a basic restriction for occupational exposure of 100 W m^{-2}. As the general public cannot be expected to be aware of these exposures and thus to mitigate risk, a reduction factor of 10 was applied, which reduces the general public basic restriction to 20 W m^{-2}.

5.1.5. LOCAL TRANSMITTED ENERGY DENSITY (>6 GHz – 300 GHz)

As described in 4.3.3.2, an additional constraint is required within this frequency range to ensure that the cumulative energy permitted by the 6 minute average transmitted power density basic restriction is not absorbed by tissue too rapidly. Accordingly, for both the Head and Torso, and Limbs, ICNIRP set a transmitted energy density level for exposure intervals of less than 6 minutes, as a function of time, to limit temperature elevation to below the operational adverse health effect thresholds for both Type-1 and Type-2 tissue. This transmitted energy density level, averaged over 4 cm^2 (from >6 to 30 GHz) or 1 cm^2 (from >30 to 300 GHz), is given by $5+3.54(t-1)^{0.5}$ kJ m^{-2} for exposure durations of at least 1 second, where 't' is exposure duration in seconds, and 5 kJ m^{-2} for exposure durations less than 1 second. The exposure from any group of pulses, or subgroup of pulses in a train, delivered in t seconds, should not exceed this threshold.

As per the transmitted power density basic restrictions, a reduction factor of 2 was applied to this threshold for occupational exposure to account for scientific uncertainty, as well as differences in both thermal baselines and thermoregulation ability across the population, resulting in a basic restriction for occupational exposure of $2.5+1.77(t-1)^{0.5}$ kJ m^{-2} for exposure durations of at least 1 second, and 2.5 kJ m^{-2} for exposure durations less than 1 second. As the general public cannot be expected to be aware of exposures and thus to mitigate risk, a reduction factor of 10 was applied for the general public, reducing the general public restriction to $0.5+0.354(t-1)^{0.5}$ kJ m^{-2} for exposure durations of at least 1 second, and 0.5 kJ m^{-2} for exposure durations less than 1 second.

5.1.6. RISK MITIGATION CONSIDERATIONS FOR OCCUPATIONAL EXPOSURE

The relevant health effects that the whole body SAR restrictions protect against are increased cardiovascular load (due to the work that the cardiovascular system must perform in order to restrict body core temperature rise), and where temperature rise is not restricted to a safe level, a cascade of functional changes that may lead to both reversible and irreversible damage to tissue (including brain, heart and kidney). These effects typically require body core temperatures of greater than 40 °C (or an increase of approximately 3 °C relative to normothermia). Large reduction factors have thus been used to make it extremely unlikely that radiofrequency-induced temperature rise would exceed 1 °C (occupational limits have been set that would, under normothermic conditions, lead to body core temperature rises of < 0.1 °C), but care must be exercised when a worker is subject to other heat sources that may add to that of the radiofrequency exposure, such as high environmental temperatures, high work rates, or impediments to normal thermoregulation (such as thermally insulating clothing or certain medical conditions). Where significant heat is expected from other sources, it is advised that workers have a suitable means of verifying their body core temperature (see ACGIH 2018b for further guidance).

The relevant health effects that the local basic restrictions protect against are pain and thermally-induced tissue damage. Within superficial (Type-1) tissue, pain (due to stimulation of nociceptors) and tissue damage (due to denaturation of tissue) typically require temperatures above approximately 41 °C. Occupational exposure of the limbs is unlikely to increase local temperature by more than 2.5 °C, and given that superficial temperatures are normally below 31-36 °C, it is unlikely that radiofrequency exposure of superficial tissue, in itself, would result in either pain or tissue damage. Within Type-2 tissue of the Head and Torso (which excludes superficial tissue), harm is also unlikely to occur at temperatures below 41 °C. As occupational exposure of the Head and Torso tissue is unlikely to increase temperature by more than 1 °C, and given that body core temperature is normally around 37 °C, it is unlikely that radiofrequency EMF exposure would lead to temperature elevations sufficient to harm Type-2 tissue or tissue function.

However, care must be exercised when a worker is subject to other heat sources that may add to that of the radiofrequency exposure, such as high environmental temperatures, high work rates, or impediments to normal thermoregulation (such as thermally insulating clothing or certain medical conditions). For superficial exposure scenarios, local thermal discomfort or pain are important indicators of potential thermal tissue damage. It is thus important, particularly in situations where other thermal stressors are present, that the worker understands about the effect that radiofrequency exposure can contribute to their thermal load.

Table 2. Basic restrictions for electric, magnetic and electromagnetic field exposure (≥ 6 minutes).[a]

Exposure Scenario	Frequency Range	Whole body average SAR ($W\ kg^{-1}$)	Local head/torso SAR ($W\ kg^{-1}$)	Local limb SAR ($W\ kg^{-1}$)	Local $\mathbf{S}_{tr}$ ($W\ m^{-2}$)
Occupational	100 kHz – 6 GHz	0.4	10	20	---
	>6 GHz – 300 GHz	0.4	---	---	100
General Public	100 kHz – 6 GHz	0.08	2	4	---
	>6 GHz – 300 GHz	0.08	---	---	20

[a] Note:
1. Whole body average SAR is to be averaged over 30 minutes.
2. Local SAR and $\mathbf{S}_{tr}$ exposures are to be averaged over 6 minutes.
3. Local SAR is to be averaged over a 10 g cubic mass.
4. Local $\mathbf{S}_{tr}$ is to be averaged over a 4 cm^2 (>6-30 GHz) or 1 cm^2 (>30 GHz) square.
5. Where relevant, equivalent incident plane wave power density can be used in place of incident plane wave power density.
6. "---" indicates that this cell is not relevant to the basic restrictions.

Table 3. Basic restrictions for electric, magnetic and electromagnetic field exposure (< 6 minutes).[a]

Exposure Scenario	Frequency Range	Local SA ($J\ kg^{-1}$)	Local $\mathbf{H}_{tr}$ ($kJ\ m^{-2}$)

Occupational	400 MHz – 6 GHz	$250+177(t-1)^{0.5}$	---
	>6 GHz – 300 GHz	---	$2.5+1.770(t-1)^{0.5}$
General Public	400 MHz – 6 GHz	$50+35.4(t-1)^{0.5}$	---
	>6 GHz – 300 GHz	---	$0.5+0.354(t-1)^{0.5}$

[a] Note:

1. SA is to be averaged over a 10-g cubic mass.
2. $\mathbf{H}_{tr}$ is to be averaged over a 4 cm^2 (>6-30 GHz) or 1 cm^2 (>30 GHz) square.
3. ‘t’ is time interval, in seconds; for t < 1, ‘t = 1’ must be used.
4. Limits must be met for all values of t < 360 seconds, regardless of the temporal characteristics of the brief exposure itself.
5. “---” indicates that this cell is not relevant to the basic restrictions.

5.2. REFERENCE LEVELS

Reference levels have been derived from a combination of computation and measurement studies to provide a means of demonstrating compliance using quantities that are more-easily assessed than basic restrictions, but that provide an equivalent level of protection to the basic restrictions for worst-case exposure scenarios. However, as the derivations rely on conservative assumptions, in most exposure scenarios the reference levels will be more conservative than the corresponding basic restrictions. For the purpose of these guidelines, compliance is demonstrated if either the relevant reference levels or basic restrictions are complied with; both are not required. Further detail regarding the reference levels is provided in Appendix A.

Separate **E**-field, **H**-field and incident power density far-field reference levels (depending on frequency) have been set for occupational and general public exposure separately, to protect against effects associated with whole body exposure (averaged over 30 minutes; Table 4), local exposure (averaged over 6 minutes; Table 5), and brief local exposure (averaged over less than 6 minutes; Table 6). Although these reference levels will be more conservative than the corresponding basic restrictions in most exposure scenarios, effects of grounding near human body resonance frequencies can potentially increase exposures beyond the basic restrictions. An additional (limb current) reference level has been set to account for this (averaged over 6 minutes; Table 7). Reference level values are provided in Tables 4-7, with application details given as ‘notes’ in the corresponding table legends; ‘numbered’ notes represent detail pertinent to exposure in the far-field, whereas notes prefixed with ‘symbols’ represent detail pertinent to near-field exposure.

Below 30 MHz, compliance with the present guidelines will typically be evaluated in the zone of the reactive and radiative near-field. In such cases it is rare for there to be a plane wave incident to a human body. The whole body average **E**-field and **H**-field reference levels within this range (Table 4) have therefore been derived separately from calculations assuming whole body exposure to capacitive near-field (only **E**-field) or inductive near-field (only **H**-field). Above 30 MHz it is difficult to set reference levels for exposure within the reactive and radiative near-field due to a range of factors. Where suitable dosimetry was not available to set reference levels in the near-field, ICNIRP applied additional constraints to the far-field reference levels to provide conservative reference levels that can be used for near-field exposure. However, this was not possible for some exposure scenarios; in such cases, compliance with the basic restrictions is required. Reference level values above 30 MHz in Tables 4-6 refer to far-field exposure conditions, with any accommodation for near-field exposures specified in the notes provided in the tables. As a rough guide, < $\lambda/2\pi$ m, between $\lambda/2\pi$ and $2D^2/\lambda$ m, and > $2D^2/\lambda$ m from the antenna correspond approximately to the reactive near-field, radiative near-field and far-field respectively, where D and **λ** refer to antenna diameter and wavelength respectively, in meters. However, due to a range of factors that impact on the degree to which these definitions are appropriate for application to the reference levels, input from the compliance community is required to determine which of these field types is most appropriate for a given exposure.

ICNIRP is aware that for some exposure scenarios, EMFs at the reference levels described below could potentially result in exposure that exceeds basic restrictions. Where such scenarios were identified, ICNIRP determined whether the reference levels needed to be reduced by considering the magnitude of the difference between the resultant tissue exposure and basic restriction (including comparison with the associated dosimetric uncertainty), and whether the violation was likely to affect health (including consideration of the degree of conservativeness in the associated basic restriction). Where the difference was small, and where it would not impact on health, reference levels were set that can potentially result in exposures that exceed the basic restrictions. This reduces unnecessary changes and maintains the stability of the guidelines (relative to ICNIRP 1998), which ICNIRP views as beneficial to the whole community.

This situation has been shown to occur in terms of the reference levels corresponding to whole body average SAR basic restrictions, which, in the frequency range of body resonance (up to 100 MHz) and from 1 to 4 GHz, can potentially lead to whole body average SARs that exceed the basic restrictions. The exposure scenario where this can potentially occur is very specific, requiring a small stature person (such as a 3-year old child) to be extended (e.g. standing) for at least 30 minutes, while being subject to a plane wave exposure within the above frequency ranges, incident to the child from the front to back. The resultant SAR elevation is small relative to the basic restriction (circa 40%, which is similar to the *in vivo* whole body average SAR measurement uncertainty; Flintoft et al., 2014), there are many levels of conservativeness built into the basic restriction derivation itself, and importantly, this will not impact on health. This latter point is important because the basic restriction that this relates to was set to protect against body core temperature elevations of greater than 1 °C, and being of small stature, the individual in this hypothetical exposure scenario would more-easily dissipate heat to the environment than a larger person due to their increased body ‘surface area to mass ratio’ ((Hirata et al., 2013). Within a small stature person the net effect of this ‘increased whole body SAR’ and ‘increased heat loss’ would be a smaller temperature rise than would occur in a person of larger stature. ICNIRP has thus not altered the reference levels to account for this situation, because to do so would reduce the continuity of its guidelines (with those of ICNIRP 1998) without any benefit to health and safety.

Table 4. Reference levels for whole body exposure to time-varying far-field electric, magnetic and electromagnetic fields, from 100 kHz to 300 GHz (unperturbed rms values).[a]

Exposure Scenario	Frequency Range	**E**-field strength ($V\ m^{-1}$)	**H**-field strength ($A\ m^{-1}$)	Incident plane wave power density (**S**$_{inc}$) ($W\ m^{-2}$)
Occupational	0.1-20 MHz[#]	1220/f	4.9/f	----
	>20-30 MHz[#]	61	4.9/f	----
	>30-400 MHz[#]	61	0.16	10
	>400-2,000 MHz[*]	$3f^{0.5}$	$0.008f^{0.5}$	f/40
	>2-300 GHz[*]	----	----	50

General Public	0.1-20 MHz[#]	560/f	2.2/f	----
	>20-30 MHz[#]	28	2.2/f	----
	>30-400 MHz[#]	28	0.073	2
	>400-2,000 MHz[*]	$1.375f^{0.5}$	$0.0037f^{0.5}$	f/200
	>2-300 GHz[*]	----	----	10

[a] Note:
1. *f* is frequency in MHz.
2. $\mathbf{S}_{inc}$, $\mathbf{E}^2$ and $\mathbf{H}^2$ are to be averaged over 30 minutes, over the whole body space. **E**- and **H**-field values are to be derived from these averaged values.
3. For frequencies up to 2 GHz, compliance is demonstrated if either the **E**-field, **H**-field or $\mathbf{S}_{inc}$ value is within the reference levels; only one is required.
4. "---" indicates that this cell is not relevant to the reference levels.
#. For frequencies up to 400 MHz: For reactive and radiative near-field exposure conditions, exposure is compliant with the reference levels if both **E**- and **H**-field levels are within the relevant far-field reference levels.
*. For frequencies above 400 MHz: Far-field reference levels are also applicable to radiative near-field exposure conditions; no reference level is provided for reactive near-field exposure conditions.

Table 5. Reference levels for local exposure to time varying far-field electric, magnetic and electromagnetic fields, from 100 kHz to 300 GHz, for time intervals ≥ 6 minutes (unperturbed rms values).[a]

Exposure Scenario	Frequency Range	Incident plane wave power density ($\mathbf{S}_{inc}$) (W m^{-2})
Occupational	100 kHz – 400 MHz[#]	See note 2
	>400 MHz – 6 GHz[#]	See note 3
	>6 – 300 GHz[*]	$275f^{-0.177}$
	300 GHz[*]	100
General Public	100 kHz – 400 MHz[#]	See note 2
	>400 MHz – 6 GHz[#]	See note 3
	>6 – 300 GHz[*]	$55f^{-0.177}$
	300 GHz[*]	20

[a] Note:
1. *f* is frequency in GHz.
2. For frequencies up to 400 MHz, exposure is compliant with the reference levels if the spatial peak value, averaged over 6 minutes, is less than the corresponding whole body average far-field reference levels (from Table 4). Where relevant, equivalent incident plane wave power density can be used in place of incident plane wave power density.
3. For frequencies >400 MHz to 6 GHz, Table 6 reference levels averaged over 6 minutes are to be used (i.e. t = 360 seconds).
4. $\mathbf{S}_{inc}$ is to be averaged over 6-minutes, over a 4-cm^2 (66-30 GHz) or 1-cm^2 (>30-300 GHz) square region in space, approximating the body surface.
5. "---" indicates that this cell is not relevant to the reference levels.

#. For frequencies up to 6 GHz, far-field reference levels are also applicable to radiative and reactive near-field exposure conditions.
*. For frequencies above 6 GHz, far-field reference levels are also applicable to radiative near-field exposure conditions; no reference levels are provided for reactive near-field exposure conditions within this frequency range.

Table 6. Reference levels for local exposure to time varying far-field electric, magnetic and electromagnetic fields, from 100 kHz to 300 GHz, for time intervals ≤ 6 minutes (unperturbed rms values).[a]

Exposure Scenario	Frequency Range	Incident plane wave energy density ($\mathbf{H}_{inc}$) (kJ m^{-2})
Occupational	100 kHz – 400 MHz	See note 2
	>400 MHz – 6 GHz#	$0.8f^{0.51}[2.5+1.77(t-1)^{0.5}]$
	>6 – 300 GHz*	$2.75f^{-0.177}2.5+1.77(t-1)^{0.5}]$
General Public	100 kHz – 400 MHz	See note 2
	>400 MHz – 6 GHz#	$0.8f^{0.51}[0.5+0.354(t-1)^{0.5}]$
	>6 – 300 GHz*	$2.75f^{-0.177}[0.5+0.354(t-1)^{0.5}]$

[a] Note:
1. *f* is frequency in GHz; *t* is time interval in seconds.
2. For frequencies 100 kHz – 400 MHz, no additional constraint is imposed for brief intervals (the 6 minute average reference levels described in Table 5 are to be used). Where relevant, equivalent incident plane wave energy density can be used in place of incident plane wave energy density.
3. Peak spatial $\mathbf{H}_{inc}$ is to be used for frequencies >400 MHz – 6 GHz; $\mathbf{H}_{inc}$ is to be averaged over a 4 cm^2 (6 – 30 GHz) or 1 cm^2 (>30 – 300 GHz) square region in space, representative of body surface.
4. The exposure from any group of pulses, or subgroup of pulses in a train, delivered in t seconds, should not exceed the limits in this table.
#. For frequencies 400 MHz to 6 GHz, for reactive and radiative near-field exposure conditions, exposure is compliant with the reference levels if both the spatial peaks of the equivalent incident plane wave energy density, based on **E**- and **H**-field, are less than the corresponding $\mathbf{H}_{inc}$ reference level.
*. For frequencies above 6 GHz, far-field reference levels are also applicable to radiative near-field exposure conditions; no reference level is provided for reactive near-field exposure conditions within this frequency range.

Table 7. Reference levels for current induced in any limb at frequencies between 100 kHz and 110 MHz. [a]

Exposure Scenario	Frequency Range	Current I_L (mA)
Occupational	100 kHz – 110 MHz	100
General Public	100 kHz – 110 MHz	45

[a] Note
1. I_L^2 values are averaged over 6 minutes. Current values are to be derived from these averaged values.

2. Limb current reference levels are not provided for any other frequency range.

5.3. GUIDANCE

5.3.1. CONTACT CURRENTS

Within approximately the 100 kHz - 110 MHz range, contact currents can occur when a person touches a conducting object that is within an electric or magnetic field, causing current flow between object and person. At high levels these can result in nerve stimulation or pain (and potentially tissue damage), depending on EMF frequency (Kavet et al. 2014, Tell and Tell 2018). This can be a particular concern around large radiofrequency transmitters, such as are found near high power antennas used for broadcasting below 30 MHz, where there have been sporadic reports of pain and burn-related accidents. Contact currents occur at the region of contact, with smaller contact regions producing larger biological effects (given the same current). This is due to the larger current density (**A** m^{-2}), and consequently the higher localized SAR and **E**-field in the body.

Exposure due to contact currents is indirect, in that it requires an intermediate conducting object to conduct the field. This makes contact current exposure unpredictable, due to both behavioral (e.g. grasping versus finger contact) and environmental (e.g. configuration of conductive objects) conditions, and reduces ICNIRP's ability to protect against them. Of particular importance is the heterogeneity of the current density passing to and being absorbed by the person, which is due not only to the contact area, but also to the tissue conductivity, density and heat capacity of the tissue through which the current passes, and most importantly the resistance between conducting object and contacting tissue (Tell and Tell 2018).

Accordingly, these guidelines do not provide strict limits for contact currents, and instead provide 'guidance' to assist those responsible for transmitting high-power radiofrequency fields to understand contact currents, the potential hazards, and how to mitigate such hazards. For the purpose of specification, ICNIRP here defines high-power radiofrequency fields as those emitting greater than 100 V m^{-1} at their source.

There is limited research available on the relation between contact currents and health. In terms of pain, the health effect arising from the lowest contact current level, the main data comes from Chatterjee et al. (1986). In that study sensation and pain were assessed in a large adult cohort as a function of contact current frequency and contact type (point versus grasp contact). Reversible, painful heat sensations were found to occur with average (point) contact current thresholds of 46 mA within the 100 kHz to 10 MHz range tested, and these required at least 10 seconds of exposure to occur. Thresholds were frequency-independent within that range, and thresholds for grasping contact were substantially higher than those for point contact.

However, given that the threshold value was an average across the participants, and given the standard deviation of the thresholds reported, ICNIRP considers that the lowest threshold across the cohort would have been approximately 20 mA. Further, modelling from that data suggests that children would have lower thresholds; extrapolating from Chatterjee et al. (1986) and Chan et al. (2015), we would expect the lowest threshold in children to be within the range of 10 mA. The upper frequency of contact current capable of causing harm is also not known. Although the ICNIRP 1998 guidelines specified that contact currents should be protected against from 100 kHz to 110 MHz, Chatterjee et al. (1986) only tested up to 10 MHz, and Tell and Tell (2018) reported strong reductions in contact current magnitude from about 1 MHz to 28 MHz (and did not assess higher frequencies). Thus it is not clear that contact currents will remain a health hazard across the entire 100 kHz to 110 MHz range.

In determining the likelihood and nature of hazard due to potential contact current scenarios, ICNIRP views the following as important for the responsible person in managing risk associated with contact currents within the 100 kHz to 110 MHz EMF region. This may also be useful for assisting the responsible person in conducting a risk-benefit analysis associated with allowing a person into a radiofrequency EMF environment that may result in contact currents.

- Available data suggest that contact current thresholds for reversible, mild pain, for adults and children, are likely to be approximately 20 mA and 10 mA respectively;
- Contact current thresholds for tissue damage, which can be irreversible, have not been determined, making it difficult to differentiate between contact current levels capable of causing pain versus tissue damage;
- There is currently no evidence that hazards associated with contact currents occur for radiofrequency radiation above about 30 MHz, but it may be a useful conservative approach to assume that they can occur up to 110 MHz;
- Contact current magnitude will increase as a function of field strength and is affected by conducting-object configuration;
- Risk of contact current hazards can be minimized by training workers to avoid contact with conducting objects, but where contact is required
    - Large metallic objects should be connected to ground (grounding)
    - Workers should make contact via insulating materials (e.g. radiofrequency protective gloves).
    - Workers should be made aware of the risks, including the possibility of 'surprise', which may impact on safety in ways other than the direct impact of the current on tissue (for example, by causing accidents).

5.4. SIMULTANEOUS EXPOSURE TO MULTIPLE FREQUENCY FIELDS

It is important to determine whether, in situations of simultaneous exposure to fields of different frequencies, these exposures are additive in their effects. Additivity should be examined separately for the effects of thermal and electrical stimulation, and restrictions met after accounting for such additivity. The formulae below apply to relevant frequencies under practical exposure situations. The below reference level summation formulae assume worst-case conditions among the fields from multiple sources. As a result, typical exposure situations may in practice require less restrictive exposure levels than indicated by the formulae for the reference levels (but would require compliance to be demonstrated with basic restrictions to demonstrate this).

5.4.1 Basic restrictions ≥ 6 minutes

Above 100 kHz, whole body averaged SAR should be added according to;

$$\sum_{i=100\ \text{kHz}}^{300\ \text{GHz}} \frac{SAR_i}{SAR_L} \le 1 \qquad \text{(Eqn. 1)},$$

and local SAR and transmitted power density values added according to;

$$\sum_{i=100\text{ kHz}}^{6\text{ GHz}} \frac{SAR_i}{SAR_L} + \sum_{i>6\text{ GHz}}^{300\text{ GHz}} \frac{S_{\text{tr},i}}{S_{\text{tr},L}} \leq 1, \qquad \text{(Eqn. 2),}$$

where, SAR_i is the SAR caused by exposure at frequency i; SAR_L is the SAR limit given in Table 2; $S_{\text{tr},\,i}$ is the transmitted power density at frequency i, and $S_{\text{tr},\,L}$ is the transmitted power density limit given in Table 2.

5.4.2 Reference levels ≥ 6 minutes

For practical application of the basic restrictions, the following criteria regarding reference levels of field strengths should be applied to the field levels;

$$\sum_{i=100\text{ kHz}}^{2\text{ GHz}} \left(\frac{E_i}{E_{L,i}}\right)^2 \leq 1 \qquad \text{(Eqn. 3),}$$

$$\sum_{i=100\text{ kHz}}^{2\text{ GHz}} \left(\frac{H_i}{H_{L,i}}\right)^2 \leq 1 \qquad \text{(Eqn. 4),}$$

and,

$$\sum_{i=30\text{ MHz}}^{300\text{ GHz}} \frac{S_{\text{inc},i}}{S_{\text{inc},L,i}} \leq 1 \qquad \text{(Eqn. 5),}$$

where E_i is the electric field strength at frequency i; $E_{L,\,i}$ is the electric field reference level at frequency i from Table 4; H_i is the magnetic field strength at frequency i; $H_{L,\,i}$ is the magnetic field reference level at frequency i from Table 4; $S_{\text{inc},\,i}$ is the incident power density at frequency i; and $S_{\text{inc},\,L,\,i}$ is the incident power density reference level at frequency i from Tables 4 and 5.

For practical application of the basic restrictions, the following criteria regarding limb current reference levels should be applied;

$$\sum_{i=100\text{ kHz}}^{110\text{ MHz}} \left(\frac{I_i}{I_{L,i}}\right)^2 \leq 1 \qquad \text{(Eqn. 6),}$$

where I_i is the limb current component at frequency i; and $I_{L,\,i}$ is the limb current reference level (see Table 7).

5.4.3 Basic restrictions < 6 minutes

For time intervals < 6 minutes above 400 MHz, SA and transmitted energy density values should be added according to:

$$\sum_{i=400\ \mathrm{MHz}}^{6\ \mathrm{GHz}} \frac{SA_i}{SA_L} + \sum_{i>6\ \mathrm{GHz}}^{300\ \mathrm{GHz}} \frac{H_{\mathrm{tr},i}}{H_{\mathrm{tr},L}} \leq 1 \qquad \text{(Eqn. 7)},$$

where SA_i is the SA caused by exposure at frequency i; SA_L is the SA limit given in Table 3; $H_{\mathrm{tr},\,i}$ is the transmitted energy density at frequency i; and $H_{\mathrm{tr},\,L}$ is the transmitted energy density limit given in Table 3.

5.4.4 Reference levels < 6 minutes

For practical application of the basic restrictions, the following criteria regarding reference levels of field strengths should be applied.

$$\sum_{i=400\ \mathrm{MHz}}^{300\ \mathrm{GHz}} \frac{H_{\mathrm{inc},i}}{H_{\mathrm{inc},L,i}} \leq 1 \qquad \text{(Eqn. 8)},$$

where $H_{\mathrm{inc},\,i}$ is the incident energy density at frequency i; and $H_{\mathrm{inc},\,L,\,i}$ is the incident energy density reference level at frequency i from Table 6.

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