Safety Code 6 (2013) –Rationale

This document provides an overview of the rationale for the proposed basic restrictions and derived reference levels within the revised version of Safety Code 6 (SC6, 2013). This document is not intended as an authoritative scientific review of the relevant literature, as that would entail a much more thorough discussion of the relevant scientific literature. Where appropriate, references are provided to authoritative reviews of the scientific literature or to some individual studies which form the scientific basis on specific issues. Since SC6 provides guidance for maximum human exposure to electromagnetic radiation across a wide frequency spectrum and the thresholds for adverse health effects are based upon different biological phenomena at different regions within this frequency range, this document has been subdivided into four (4) sections, namely:

1. Electric and Magnetic Fields (3 kHz – 10 MHz)
2. Induced and Contact Current (3 kHz – 110 MHz)
3. Electric-fields, Magnetic-fields and Power Density (10 MHz – 6 GHz)
4. Electric-fields, Magnetic-fields and Power Density (6 GHz – 300 GHz)

In the 3 – 100 kHz band, the threshold for adverse health effects is based upon the avoidance of peripheral nerve stimulation (PNS) by induced fields within the body from external electric and magnetic fields. Basic restrictions in this frequency band are proposed for internal electric field strength within the body. In the 100 kHz – 10 MHz frequency range, the threshold for adverse health effects are based upon the avoidance of both PNS and thermal effects. As such, basic restrictions are proposed for both internal electric field strength and specific absorption rate (SAR; whole body average and peak spatially-averaged SAR). In the frequency range 10 MHz – 6 GHz, the threshold for adverse effects is based upon the avoidance of tissue heating and basic restrictions are proposed for whole-body average SAR and spatially-averaged peak SAR. In the frequency range from 6 - 300 GHz, since measurements of whole-body SAR and peak spatially-averaged SAR are not readily achievable or appropriate due to the superficial nature of tissue heating within the body, reference levels for electric- and magnetic-fields and power density form the basis of the human exposure limits in this frequency range.

The basic restrictions outlined in SC6 (2013) are intended to protect against all known adverse health hazards from electromagnetic radiation in the frequency range 3 kHz – 300 GHz. In the WHO Framework for the Development of EMF Standards (2006), adverse health hazards are defined as “a biological effect that has health consequences outside the compensation mechanisms of the human body and is detrimental to health or well-being”. It is important to note that the WHO endorses international guidelines that are based upon a weight-of-evidence risk assessment of the scientific literature, such as those established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE), and it encourages member states to adopt these international guidelines or to base national exposure limits on similar risk assessment principles. Where practical, revisions to SC6 (2013) have adopted portions of the ICNIRP guidelines (ICNIRP 2010, for frequencies below 100 kHz; ICNIRP 1998, for frequencies from 100 kHz – 300 GHz) in an effort to harmonize with international standards.

Section 1 Electric and Magnetic Fields (3 kHz – 10 MHz)

Basic Restrictions

In the frequency range 3 kHz – 10 MHz, the threshold for adverse health effects in SC6 (2009) and other science-based human exposure limits have been based upon the avoidance of both PNS and thermal effects from externally applied electric and/or magnetic fields (ICNIRP 1998, 2010; IEEE C95.1, 2005; Lin, 2007). PNS predominates at the lower end of this frequency range, while tissue temperature elevation due to energy absorption (SAR) generally predominates at higher frequencies. In the 100 kHz – 10 MHz range, low-duty cycle electromagnetic fields may elicit PNS before thermal effects arise, while continuous-wave exposures may elicit thermal effects before PNS occurs, therefore basic restrictions for both biological endpoints are required in the revised version of SC6, and both must be respected for compliance with SC6. While central nervous system (CNS) tissue and cardiac tissue can also be stimulated by induced internal electric fields, the thresholds for these effects occur at higher exposure levels than that for PNS in this frequency range. Since the last version of SC6 (2009), no newly identified adverse health effects have been established in this frequency range. Therefore, the avoidance of PNS and thermal effects remains the basis for the basic restrictions in this frequency range.

Peripheral Nerve Stimulation (PNS)

In unperturbed conditions, voltage-gated ion channels maintain the “resting” membrane potential of neurons at approximately -60 to -75 mV. Externally applied electric or magnetic fields can induce internal electric fields that can perturb the “resting” membrane potential on neurons and can stimulate action potentials in peripheral nerve axons if the induced membrane depolarization is above a threshold value sufficient for the opening of voltage-gated sodium channels to become self-sustaining (WHO, 2007). Numerous studies have estimated that the minimum threshold for PNS is in the range of 4 - 6 Vm^{-1} using theoretical calculations of nerve stimulation thresholds (Reilly 1998, 2002) and empirical data from volunteers exposed to switched gradient magnetic resonance (Nyenhuis et al., 2001, So et al., 2004).

In recent years, several studies have refined dosimetric calculations for induced electric fields and currents within anatomically-derived heterogeneous models of various sizes of the human body (including those of children), using voxel sizes below 4 mm (Dimbylow 2005, 2006; Bahr 2007; Hirata 2009; Nagaoka 2004). This approach is advantageous over previous modelling methodologies that have employed homogeneous ellipsoidal human models. These studies have indicated that maximum induced electric fields from externally applied electric and magnetic fields, relevant to PNS, occur in the skin and associated fatty tissue in the peripheral region of the body near the waist region. As such, induced electric fields within skin tissue, represents the worst-case scenario upon which to establish basic restrictions for the avoidance of PNS in the 3 kHz - 10 MHz frequency range for all parts of the body (ICNIRP, 2010).

Based upon this information, the ICNIRP have recently issued updated safety recommendations for human exposure to low frequency electric and magnetic fields entitled "Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz to 100 kHz). As there remains uncertainty about the precise thresholds for PNS and the accuracy of current dosimetry models, the guidelines established by ICNIRP in the 3 kHz – 10 MHz frequency range provide a conservative approach for the avoidance of PNS since exposure uncertainties have been factored into the derivation of the basic restrictions within ICNIRP (2010). According to ICNIRP (2010), these basic restrictions provide a 5-fold safety margin for exposure in the Controlled Environment, and a 10-fold safety margin for exposures in the Uncontrolled Environment, against PNS.

In the previous version of SC6 (2009), reference levels were provided that would prevent the occurrence of PNS in this frequency range, but basic restrictions were not specified. It is recommended that the revised version of SC6 (2013) should specify separate basic restrictions for the avoidance of PNS and that of thermal effects. Since the ICNIRP (2010) guidelines are based upon the most updated dosimetric information and approaches, it is recommended that the basic restrictions in SC6 (2013) for the avoidance of PNS should be harmonized with those of ICNIRP (2010) in the 3 kHz – 10 MHz frequency range.

The basic restrictions for the avoidance of PNS proposed for SC6 (2013) are:

Exposure Group	**Frequency range**	**Internal E-field (Vm^{-1}) (for any part of the body)**
Controlled Environment	3 kHz – 10 MHz	$2.70e^{-4}f$
Uncontrolled Environment	3 kHz – 10 MHz	$1.35e^{-4}f$

- *f* denotes frequency in Hz

Thermal effects

In the 100 kHz – 10 MHz frequency range, SC6 (2009) specified basic restrictions for the avoidance of thermal effects. These basic restrictions specified limits on whole-body average (WBA) specific absorption rate (SAR; a measure of energy deposition rate within the body), and peak spatially-averaged SAR (maximum energy deposition rate within a discrete tissue volume). These basic restrictions are based upon scientific consensus of a threshold value of approximately 4 W/kg for thermally-related (~1^{o}C colonic temperature rise) behavioural changes in rodents, non-human primates and in human volunteers (reviewed in IEEE C95.1, 2005; Foster and Adair, 2004; Adair and Black, 2003; Foster and Glaser, 2007). Existing international (ICNIRP 1998; IEEE C95.1, 2005) and national (SC6, 2009; FCC, 2006) science-based exposure standards have incorporated safety margins of 10 and 50 in the derivation of basic restrictions for the avoidance of thermal effects for exposures in Controlled and Uncontrolled Environments, respectively. These safety factors ensure that worst-case human exposures to RF fields incurred in uncontrolled- and controlled-environments, within the prescribed exposure limits, do not result in alterations in core body temperature of the individual of more than a few tenths of 1^{o}C (reviewed in IEEE C95.1, 2005).

The basic restrictions for WBA-SAR in SC6 (2009) are identical to those in ICNIRP (1998) and IEEE C95.1 (2005). It is recommended that these basic restrictions remain unchanged in the revised version of SC6 (2013) since no new adverse health effects have been identified at exposures below these levels since the last version of SC6 (2009).

The basic restrictions proposed for WBA-SAR in SC6 (2013) are:

Exposure Group	Frequency range	WBA-SAR limit (W/kg)*
Controlled Environment	100 kHz – 10 MHz	0.40
Uncontrolled Environment	100 kHz – 10 MHz	0.08

* - averaged over any 6 minute reference period.

In addition to basic restrictions on WBA-SAR, SC6 (2009) also includes basic restrictions for peak spatially-averaged SAR within discrete volumes of tissue. The original derivation of peak spatially-averaged SAR limits in SC6 and other international standards were based upon dosimetric estimates of a 20:1 variation in peak spatially-averaged SAR to WBA-SAR within the human body, whereby a 1.6 W/kg peak spatially-averaged SAR limit for the uncontrolled environment was based upon a WBA-SAR limit of 0.08 W/kg. With refinements in dosimetry, it was later determined that the actual variation among peak spatially-averaged SAR to WBA-SAR was more approximately a 100:1 ratio (Bernardi et al., 2003). If a similar approach were used, based upon a WBA-SAR limit of 0.08 W/kg, this would translate to a peak spatially-averaged SAR limit of 8 W/kg.

On the other hand, numerous studies have demonstrated cataract formation in experimental animals at peak spatially-averaged SARs of ~100-150 W/kg (Elder, 2003), presumably due to thermal effects in the eye (tissue volume ~ 10 g). However, recently Hirata et al. (2008) used modern computational approaches to re-examine some of the early work on cataract formation in rabbit eyes conducted by Guy et al. (1975). They found that the threshold for the occurrence of cataracts in rabbit eyes observed by Guy et al. (1975) may actually have occurred at a lower SAR (~67 W/kg) than previously estimated, although the use of anaesthesia in the Guy et al. (1975) study predisposed the animals to thermal effects in the lens. Additional work is required to study the effect of localized RF exposure in the near-field on temperature responses in the eye. Based upon a considerable breadth of historical information on cataract induction in animals, ICNIRP (1998) and IEEE C95.1 (2005) have established Uncontrolled Environment peak spatially-averaged SAR limits of 2 W/kg averaged over 10 g tissue, based upon an estimated 50-fold reduction below the threshold for cataract formation in animals (~100 W/kg).

Studies modelling the thermal response to RF fields in discrete volumes of human tissue have indicated that temperature changes in the eye from exposures at the ICNIRP (1998) Controlled Environment peak spatially-averaged SAR limits of 10 W/kg averaged over 10 g of tissue, are no more 1.4^{o}C above pre-exposure levels (Wainwright, 2007). This is well below the temperature threshold required for the induction of thermally-induced cataract effects, which requires lens temperature to reach ~41^{o}C. Similarly, studies on temperature increases in brain tissue at the ICNIRP (1998) Controlled Environment peak spatially-averaged SAR limit of 10 W/kg averaged over 10 g of tissue, found maximum discrete (10 g) temperature responses in the brain ranging from 0.6-1.2^{o}C (reviewed in IEEE C95.1, 2005). These increases are also well within the normal physiological range for brain tissue and well below the threshold required to induce pathological effects. Since SC6 (2009) specifies peak spatially-averaged SAR limits that are 20% lower than those in specified in ICNIRP (1998) and IEEE C95.1 (2005), and are averaged over 1 g of tissue (instead of 10 g), the relative temperature increases in human brain and eye tissues from peak spatially-averaged SARs at the Controlled Environment peak spatially-averaged SAR limit outlined in SC6 (2009) would be much lower than that estimated above.

The following table lists the basic restrictions on peak spatially-averaged SAR in SC6 (2009), ICNIRP (1998) and IEEE C95.1 (2005):

Exposure Group	**Tissue**	**Frequency range**	**Peak spatially-averaged SAR limit (W/kg)**	**Averaging Volume (g)**
SC6- Controlled Environment	Head, trunk	100 kHz- 6 GHz	8*	1
	Limbs		20*	10
SC6- Uncontrolled Environment	Head, trunk	100 kHz- 6 GHz	1.6*	1
	Limbs		4*	10
ICNIRP/IEEE-C95.1 Controlled	Head, trunk	100 kHz- 6 GHz	10*	10
	Limbs		20*	10
ICNIRP/IEEE-C95.1 Uncontrolled	Head, trunk	100 kHz- 6 GHz	2	10
	Limbs		4	10

*averaged over any 6 minute reference period.

While the peak spatially-averaged SAR limits in ICNIRP (1998) and IEEE C95.1 (2005) are biologically-based (cataract formation) and those in SC6 (2009) and FCC (2006) were derived from early dosimetric considerations, the peak spatially-averaged SAR limits in ICNIRP (1998) and IEEE C95.1 (2005) are less restrictive than those in SC6 (2009) for two reasons: 1) for localized exposures in the head, neck and trunk, SC6 (2009) specifies a maximum SAR of 1.6 W/kg and 8 W/kg for Uncontrolled and Controlled Environments, respectively, compared to 2 W/kg and 10 W/kg in the ICNIRP (1998) and IEEE C95.1 (2005) guidelines for the Uncontrolled and Controlled Environments, respectively; and 2) the peak spatially-averaged SAR in the head, neck and trunk is calculated over 1 g of tissue in the SC6 (2009) standard, whereas the peak spatially-averaged SAR is calculated over 10g of tissue in the ICNIRP (1998) and IEEE C95.1 (2005) standards. The lower tissue averaging volume in SC6 (2009) results in a more restrictive peak spatially-averaged SAR limit, as it provides more protection against the occurrence of small regions with thermal hot-spots. Based upon the uncertainties in exposure assessment, the occurrence of relatively higher brain peak spatially-averaged SARs in children compared to adults from near-field sources (e.g. cell phones) (Wiart et al., 2008; Christ et al., 2010), the uncertainty in possible long-term health risks associated with cell phone use and ongoing public concern about cell phone safety, it is recommended that the basic restriction for peak spatially-averaged SAR limits in SC6 (2013) remain unchanged from those in the previous version of SC6 (2009) to maintain an additional margin of safety.

Reference Levels

In this frequency range, electric and magnetic fields display characteristics similar to static fields in that they are, to a large extent, uncoupled and therefore can be treated separately. In addition, due to the long wavelengths at these frequencies, exposure from a source is typically in the near-field region and power density is not a useful metric. This means that, in general, both the electric field strength and magnetic field strength should be characterized when assessing electromagnetic safety.

In the quasi-static frequency range, the induction of internal voltages and currents in the body due to externally applied electric and magnetic fields is strongly determined by the constituent electrical parameters of tissue, namely the magnetic permeability, electrical permittivity and conductivity. The magnetic permeability of tissue is identical to that of free space and the induction of electric fields and currents in tissues from externally applied magnetic fields is governed by faraday’s law. For electric field exposure, the high permittivity and conductivity of tissues result in the coupling of strong surface charges on the body and relatively weak electric field strengths and currents within the body.

As indicated above, two biological phenomena exist that require two separate basic restrictions in this frequency range. Since PNS and thermal effects have significantly different latency times (onset from exposure to effect), the specification of two different sets of reference levels is warranted. PNS–based basic restrictions and reference levels require an effectively instantaneous reference period, for comparison to the exposure limits in SC6 (2013), due to the ability of induced electric fields to cause an instantaneous alteration of the resting membrane potential of neurons. Therefore, basic restrictions and reference levels for the avoidance of PNS require limits on the instantaneous peak (RMS) amplitudes of internally-coupled or external fields. Alternatively, SAR-based basic restrictions and reference levels are related to thermal effects and are therefore influenced by the thermal time constant of the human body to externally applied thermal influences. For the purposes of establishing SAR-based basic restrictions and reference levels, a six-minute reference period, based upon the thermal time constant of living tissues (i.e. the time it takes for tissue temperature to begin to rise in the case of sufficiently high exposure), has been selected to restrict the temporally averaged internally-coupled or external fields.

For pulsed RF field strengths at frequencies where both types of basic restrictions exist (0.1-10 MHz for magnetic fields and 1-10 MHz for electric fields), the effect of having the two sets of reference levels is to limit both the peak amplitude and duty factor, such that both sets of basic restrictions are respected.

Magnetic Fields

Two simultaneous criteria were considered in the setting of reference levels for SC6 (2013) in the 3 kHz to 10 MHz frequency range. These were: 1) the adoption of separate basic restrictions for PNS and thermal effects, and 2) harmonization with the ICNIRP (1998) and ICNIRP (2010) exposure guidelines, where feasible. For protection against PNS, the ICNIRP (2010) magnetic field strength reference levels (uncontrolled and controlled) are proposed for adoption in SC6 (2013) (see Figures 1 and 2).

For SAR-based magnetic field reference levels, the sloped portion of the ICNIRP (1998) limits, extended back to 100 kHz (uncontrolled) or beginning at 100 kHz (controlled) are proposed for SC6 (2013). Both sets of frequency dependent limits are extended to 10 MHz as shown in Figs. 1 and 2. This approach gives a common start frequency for controlled and uncontrolled reference levels and the same frequency dependency (f^{-1}). The ICNIRP (1998) magnetic field reference levels below 100 kHz were meant to protect against PNS, however this frequency range is covered by the new PNS–based reference levels proposed in SC6 (2013). Therefore, it was decided to begin the proposed SAR-based reference levels only at 100 kHz. The resulting reference levels are slightly more restrictive than the SAR-based reference levels in SC6 (2009).

In order to verify that the proposed reference levels ensure compliance with the basic restrictions, data from the dosimetry literature published up to the current date was used to estimate the external field strength that would produce basic-restriction level internal electric fields and/or SARs. These are also plotted in Figs 1 and 2.

A number of computational dosimetry studies utilizing realistic voxel models of the human body and establishing levels of induced electric field (99^{th} percentile) for worst-case uniform magnetic field exposure have been reported. Most have used calculations at the power frequency of 50/60 Hz, which can be scaled to SC6-relevent frequencies under the quasi-static assumption. An example is the data from Caputa et al. (2002) that is plotted in Figs. 1 and 2. This data is an average of the induced electric field (99^{th} percentile) for fat and skin tissues in the torso, which represent some of the highest magnetic field coupled doses of all body tissues and organs. Since the quasi-static scaling assumes a f^{1} frequency dependence while the PNS basic restrictions also have a f^{1} frequency dependence, the external magnetic field required to induce basic restriction-level internal electric fields show up as a flat line in the figures.

In addition, a few studies have made computational dosimetry calculations directly at frequencies of 3 kHz and beyond (Dimbylow, 2005; Bakker et al., 2012). Their results are shown in Figs. 1 and 2, also. Their results, when plotted, are almost flat with frequency, indicating that the quasi-static assumptions remain valid in this frequency range. From Figs 1 and 2, it can be seen that the proposed PNS-based reference levels provide an adequate level of protection against exceeding the proposed basic restrictions for PNS.

Also shown in the Figures 1 and 2 are the lowest external uniform magnetic field strengths required to produce the worst-case WBA-SAR basic restrictions, based on calculations on adult-sized homogeneous ellipsoidal models (Note: in this frequency range, child-sized models respond with lower WBA-SARs for exposures at the same magnetic field strength; Kaune et al., 1997). Based upon the dosimetry data depicted in Figures 1 and 2, there is a large margin of compliance of the proposed SAR-based reference levels to the basic restrictions. This may be warranted given the high level of approximation used in the homogeneous ellipsoid model. The margin of compliance for the PNS-based reference levels is much smaller, however, given that the dosimetry models for this case are much more refined (numerical voxel models), the margin is deemed adequate.

Electric Fields

As with magnetic fields, two simultaneous criteria were considered when establishing the proposed electric field reference levels for SC6 (2013). These were: 1) the adoption of separate basic restrictions for PNS and thermal effects, and 2) harmonization with the ICNIRP (1998) and ICNIRP (2010) exposure guidelines, where feasible. Over the frequency range 3 kHz to 10 MHz, the ICNIRP (2010) electric field strength reference levels (uncontrolled and controlled) are proposed for adoption in SC6 (2013) (see Figures 3 and 4). The relevant dosimetry literature (Dimbylow, 2005) shows that these electric field strength reference levels provide a high level of protection against exceeding the PNS basic restrictions for the case of the body coupling to an external, unperturbed electric field. These calculations correspond to the case of grounded, adult-sized voxel-model bodies exposed to a vertically polarized uniform electric field (the worst case scenario for all body sizes and field orientations). (For illustration purposes only, the dosimetry data for isolated ellipsoidal models from Kaune et al. (1997) are shown in Figures 3 and 4 demonstrating that much higher electric field strengths are necessary to meet the basic restrictions for ungrounded or isolated bodies).

In the case of the SAR-based reference levels, harmonization of the reference levels in SC6 (2013) with those of ICNIRP (1998) is relatively straight-forward for Uncontrolled Environments since the SAR-based and PNS based curves intersect at approximately 1 MHz (the precise frequency is 1.10 MHz). Therefore, the proposed Uncontrolled Environment SAR-based reference level for SC6 (2013) was applied at 1.10 MHz and follows the ICNIRP (1998) Uncontrolled Environment reference level up to 10 MHz. This also provides a match to the 10 MHz – 6 GHz electric field strength reference levels where the two frequency ranges meet and results in a convenient $f^{-0.5}$ frequency dependency.

For Controlled Environments, harmonization with ICNIRP (1998) was somewhat more difficult because of the f^{-1} frequency dependency of ICNIRP (1998) SAR-based Controlled Environment reference level. It was decided that matching the Controlled Environment electric field strength reference level at 10 MHz to the value proposed for the 10 MHz - 6 GHz range and maintaining the same frequency dependency as for the Uncontrolled Environment, were the most important factors. The resulting Controlled

Environment SAR-based reference level curve is shown in Figure 4. It can be seen that the SAR-based and PNS-based reference level curves do not conveniently intersect at 1 MHz. The precise frequency of intersection is 1.29 MHz and therefore, it was decided to apply the Controlled Environment SAR-based reference levels at 1.29 MHz.

Comparison of the proposed SAR-based electric field strength reference levels to the minimum electric field strengths required to meet the basic restrictions in Figures 3 and 4, demonstrates that compliance for whole body SAR is achieved (Durney et al., 1986), however peak spatially-averaged SAR in the limbs at ~10 MHz is not (Gandhi et al., 1985). At this specific frequency, the margin of non-compliance is small (this case is due to induced current flowing in the ankles, with good contact to the ground and a vertically polarized electric-field). However, this situation is likely also non-compliant with induced current reference levels proposed in SC6 (2013), see Section 2. This reinforces the notion that even though electric field strength levels may be compliant with the reference levels, induced current reference levels may be exceeded. Therefore, measurement of induced current is a necessary component of a complete RF compliance assessment.

Similarly, this same situation can occur with contact currents, as illustrated in Figures 5 and 6. In these figures, the levels of incident electric field strength of sufficient intensity to cause perception-level and let-go level contact currents are plotted for different ungrounded objects and are compared to the proposed Uncontrolled- and Controlled-Environment electric field strength reference levels in SC6 (2013). Let-go level currents are defined as the maximum current at which a person can release an energized conductor using muscles that have been stimulated by the current. The amount of current is highly variable from person to person and is dependent upon the type of contact (finger touch versus hand grasp). All data represents the 50th percentile response (Gandhi et al., 1982; Bernhardt, 1988).

In Figures 5 and 6, it can be seen that both the proposed Uncontrolled and Controlled Environment reference levels provide a greater level of protection from potential contact currents as compared to SC6 (2009). It also helps to explain why the reference levels are set so far below the threshold for direct coupling effects as illustrated in Figures 3 and 4; that is electric field reference levels are designed more for protection of indirect effects (i.e. contact currents) as opposed to direct effects (IEEE C95.1, 2005).

It should also be emphasized that there are still situations in the Uncontrolled Environment where the electric field reference levels may be complied with, but contact current limits are exceeded. Therefore, in situations where contact with energized, ungrounded conductors can occur, assessment of compliance to the contact current reference levels in SC6 (2013) is necessary.

Based upon the above dosimetric information, the proposed electric- and magnetic-field strength reference levels in the 3 kHz – 10 MHz frequency range of SC6 (2013) are:

Proposed Electric Field Strength Reference Levels in SC6 (2013)

Frequency (MHz)	Reference Level Basis	Reference Level E_{RL}, (V/m) (rms)		Reference Period
		Uncontrolled Environment	Controlled Environment	
0.003 – 10	PNS	83	170	Instantaneous
1.0 – 10	SAR	$87 / f^{0.5}$	$193 / f^{0.5}$	6 minutes

- Frequency, *f*, is in MHz.
- PNS, peripheral nerve stimulation
- SAR, specific absorption rate
- The precise frequencies at which SAR-based electric field strength reference levels for Uncontrolled and Controlled Environments begin are 1.01MHz and 1.29 MHz, respectively.

Proposed Magnetic Field Strength Reference Levels in SC6 (2013)

Frequency (MHz)	Reference Level Basis	Reference Level H_{RL}, (A/m) (rms)		Reference Period (min)
		Uncontrolled Environment	Controlled Environment	
0.003 – 10	PNS	21	80	Instantaneous
0.1 – 10	SAR	$0.73 / f$	$1.6 / f$	6 minutes

- Frequency, *f*, is in MHz.
- PNS, peripheral nerve stimulation
- SAR, specific absorption rate

Recommendations for Spatial Averaging:

In this frequency range the proposed basic restrictions for PNS effects are given in terms of internally induced electric field strength. The value to be compared to the BR is the 99th percentile value of the induced electric field strengths that are averaged over a cube of tissue that is 2 mm on a side. For both external magnetic field and electric field exposures, higher induced electric field strengths tend to occur in low conductivity tissues while higher induced current densities occur in high conductivity tissues.

For electric field exposure, the highest induced field strengths and current densities occur for the condition where the external electric-field vector is parallel to the long axis of the body and the body is standing on a conductive earth. At these frequencies, the body behaves similarly to a conductor where the distorted external field lines terminate perpendicularly on the surface of the body and induce a surface charge. At any horizontal cross-section through the body, the total current flowing towards ground is dependent on the total surface charge above that cross-section (Dimbylow, 2005). The result is that the highest current densities and induced electric field strengths occur in the ankle area and are a function of the surface area of the body above. This implies that a spatial average over the vertical extent of the body is a reasonable estimate of the equivalent uniform electric field strength that was used in the derivation of the reference levels.

For magnetic field exposure, the highest internally induced electric field strengths occur for geometries of the tissue or organs with the lowest conductivities that present the highest cross-sectional area to the field vector. A low-conductivity tissue or organ surrounded by high-conductivity tissue will selectively respond with higher induced electric-field strengths than the surrounding tissues despite the fact that the exposure field is uniform (Dimbylow, 2005). This implies that a spatially non-uniform external magnetic field and a uniform one with the same spatial peak magnitude could potentially induce the same internally induced electric-field strength in a target tissue or organ. In this case, spatial averaging of the non-uniform external magnetic field would give an under-estimate of the corresponding internally induced electric field strength. Thus, to ensure that the basic restriction for PNS is complied with, comparison of the spatial peak magnetic field strength (instead of the spatially-averaged magnetic field strength) should be made to the reference level at frequencies less than 100 kHz.

At frequencies where both PNS- and SAR-based BRs exist and beyond, spatial averaging of both the external electric- and magnetic-field strength are permitted since the SAR-based reference levels are based on whole-body absorption.

Section 2 Induced and Contact Currents (3 kHz – 110 MHz)

Introduction

Contact currents can occur when a person simultaneously touches two conductive objects that are at different electrical potentials, resulting in current flowing through the body. The magnitude of the current is proportional to the electrical resistance between those two points (WHO 2007). Induced currents can occur when a person is exposed to EMF, typically in close proximity to the source, whereby internal body electric currents are induced by external fields. The magnitude of the induced current is dependent on the proximity to the source, frequency, orientation/polarization of the body to the incident field and grounding (e.g. footwear).

In the previous version of SC6 (2009), the induced and contact current limits were based upon avoidance of PNS (perception and/or pain) at frequencies from 3 – 100 kHz and thermal effects (thermal perception and/or pain) for frequencies from 0.1 – 110 MHz. These effects are known to be frequency-dependent in the 3 - 100 kHz frequency range, but quite stable at frequencies from 0.1 -110 MHz. However, the basic restrictions in SC6 (2009) were derived from volunteer studies conducted using adult men.

Additional studies assessing men, women and children exposed to EMF in the 3- 100 kHz range have identified the threshold for PNS (perception of tingling sensation) of induced/contact current to be in the range of ~1 – 25 mA for the most sensitive individuals under worst-case conditions across this frequency range. For finger-touch contact current, the threshold for pain on finger contact is estimated to be in the range of ~2 – 33 mA, dependent on frequency. The let-go threshold for painful shocks are estimated to be ~15 – 112 mA, dependent on frequency. Based upon this information, IEEE 95.1 (2005) and ICNIRP (2010) have established maximum contact current limits of 167f and 200f (f is frequency in MHz), respectively, for exposures in the Uncontrolled Environment in the 3 – 100 kHz frequency range. While the basic restrictions in SC6 (2009) for contact current are below the threshold for the occurrence of painful let-go shocks for both the Uncontrolled and Controlled Environments, the occurrence of field perception (tingling sensation) and painful finger-contact shocks cannot be ensured. While perception of a tingling sensation is not considered an adverse health outcome and therefore the avoidance of this phenomenon is not considered mandatory for the development of reference levels for contact current, it is recommended that the contact current limits in SC6 (2013) be revised to avoid the occurrence of finger-touch shocks in the 3 – 100 kHz frequency range.

Studies on volunteers exposed to EMF in the 0.1 – 110 MHz frequency range have indicated thermal perception in the limbs at an internal current of 100 mA and the possibility of burns at exposure levels of 200 mA. This effect is not frequency-dependent. The current version of SC6 (2009) set basic restrictions for the avoidance of thermal effects from induced and contact currents (one foot) at 100 mA and 45 mA for the Controlled and Uncontrolled Environments, respectively. Alternatively, IEEE C95.1 (2005) and ICNIRP (2010, 1998) have established exposure limits for contact currents at lower levels, providing an additional margin of safety from the occurrence of such effects.

Basic restrictions on Induced- and Contact Currents at 3 – 100 kHz specified in SC6 (2009), ICNIRP (2010) and IEEE C95.1 (2005) are:

Exposure Group	**Type of Exposure (Environment)**	**Maximum Induced Current (mA) (One foot)**	**Maximum Contact Current (mA)**
SC6 (2009)	Controlled	1000*f*	1000*f*
	Uncontrolled	450*f*	450 *f*
ICNIRP (2010)	Controlled	n/a	400 *f*
	Uncontrolled	n/a	200 *f*
IEEE C95.1 (2005)	Controlled	500 *f*	500 *f*
	Uncontrolled	167 *f*	167 *f*

f – denotes frequency in MHz

Basic restrictions on Induced- and Contact Currents in the 0.1 – 110 MHz range specified in SC6 (2009), ICNIRP (1998, 2010) and IEEE C95.1 (2005) are:

Exposure Group	**Type of Exposure (Environment)**	**Maximum Induced Current (mA) (One foot)**	**Maximum Contact Current (mA)**
SC6 (2009)	Controlled	100	100
	Uncontrolled	45	45
ICNIRP (2010,	Controlled	n/a	40

1998)	Uncontrolled	n/a	20
IEEE C95.1 (2005)	Controlled	100	50
	Uncontrolled	45	16.5

f – denotes frequency in MHz

While the basic restrictions in SC6 (2009) are below the threshold for the occurrence of RF shocks and burns for both the Uncontrolled and Controlled Environments, the occurrence of thermal perception in the Controlled Environment cannot be excluded. It is recommended that the induced- and contact-current reference levels in SC6 (2013) should be revised to take into account recent dosimetric information and to provide a larger safety margin for the avoidance of painful RF shocks and burns.

Since induced- and contact current limits are actually derived from the basic restrictions for internal electric field strength and SAR (except for contact current below 100 kHz whose limits are based on results from human volunteer studies), these limits should be specified as reference levels in SC6 (2013).

Reference levels

Induced Current

For the purposes of most electromagnetic exposure guidelines, induced current is usually defined as the longitudinal flow of current through a body that is in good electrical contact with the ground (often defined as standing barefoot). At frequencies at and below the whole body resonance, the response of a grounded body to an incident vertically-polarized electric field is to behave somewhat like a short-circuited metallic monopole where the induced current distribution is greatest near the ground and diminishes towards the upper parts of the body (Gandhi et al., 1986). The implication of this is that the largest currents flow through the ankles, which have a narrow cross-section of conductive tissue to carry the current. This results in relatively high SAR in the ankle at frequencies where tissue heating is of concern or results in high current density and induced electric field strength for frequencies where PNS is the limiting factor.

The empirical formula that relates induced current magnitudes to electric field strength states that the ratio of current to field strength is proportional to frequency and to the square of the body height (Gandhi et al., 1985; 1986). This would imply that for the same frequency, taller individuals would be subjected to greater induced currents. This relationship is valid up to the whole body resonance frequency (under grounded conditions), which is approximately 40 MHz for a 1.75m adult, 51 MHz for a 1.38m (10y old) child and 63MHz for a 1.12m (5y old) child (Gandhi et al., 1986).

The resulting SAR or current density is a function of the effective cross sectional area, A_e, of current flow. In the case of SAR, it is equal to $SAR=I^2/(A_e^2\sigma\rho)$, where I is the induced current through one limb, σ is the conductivity of the current carrying wet tissues and ρ is the mass density (usually taken to be 1000 kg/m^3). In the case of current density J, it is given by $J=I/A_e$, while the resulting induced electric field, E_i, is related to the current density through Ohm's law: $E_i = J/\sigma$. Thus, the resulting SAR or induced electric field is strongly dependent on the reciprocal of the effective cross section, $1/A_e$, which would typically be larger for smaller sized bodies (short adults and children). This effect partially compensates for the increase in induced current for larger sized bodies, suggesting that at the same frequency, SARs between children and adults may be similar. However, it is also noted that induced current magnitudes reach a peak at whole body resonance and given the higher frequencies at which these occur for children and the fact that conductivity increases with frequency, it is expected that worst-case ankle SAR for constant incident electric field strength would be higher for smaller bodies. This can be observed in Figure 16 both from the empirical data from (Gandhi et al., 1986) and the numerically-simulated data from realistic voxel models of a male and female (Dimbylow, 2002; 2006).

Since the conditions for optimal induction of current are not common in practice, separate reference levels for induced current are usually provided in most exposure standards. This allows electric field strength reference levels to be less restrictive than if they had to protect against peak spatially-averaged SAR in the ankles, however the measurement of induced current becomes and additional requirement in order to demonstrate compliance to all of the basic restrictions. Admittedly, it is not always easy to judge under what circumstances measurement of induced current is warranted. Some guidance on this is given in IEEE C95.1 (2005, p22-23), where it is suggested that for electric field strengths greater than approximately 16 or 17% of the reference levels, the induced current reference level may be exceeded (for frequencies from about 1 MHz to whole body resonance). Induced current can also be mitigated by footwear and in occupational settings, by floor coverings and operator training.

3 kHz to 400 kHz

ICNIRP (1998) does not specify reference levels for induced current at frequencies below 10 MHz, while ICNIRP (2010) makes no recommendations for induced current reference levels. Thus harmonization with these two standards would involve removing induced current reference levels from SC6 (2013) in this frequency range. There is also a paucity of human experimental data on the stimulatory effects of induced current in the frequency range 3 - 400 kHz in the scientific literature upon which to base reference levels. However, estimation of induced currents in the ankles of sufficient magnitude to exceed the basic restrictions for induced electric field can be made. This was the approach used to derive reference levels for induced current in the 3 kHz to 400 kHz range.

In this frequency range, the basic restrictions for both Controlled- and Uncontrolled Environments for induced electric field has the form $E=k\,f$, where f is the frequency in hertz and k is a constant. An approximation of the reference level current flowing through the ankles, I_{RL} required to meet the basic restriction can be written as $I_{RL}= \sigma\, A_e\, E$ where the terms σ and A_e are defined in the paragraphs above. If the effective area and conductivity are assumed to be constant over this frequency range, then it can be seen that the reference level induced current should have a f^{1} frequency dependency.

Figures 7 and 8 depict the proposed induced current reference levels in SC6 (2013) and calculated estimates of the induced currents necessary to meet the basic restrictions for

PNS (induced electric field) in the 3 kHz – 1 MHz frequency range. The sloped portions of the reference level curves (controlled and uncontrolled) were designed to have a f^{1} frequency dependency and approximately follow the dosimetric data derived from (Dimbylow, 1988). The flat portion was based on thermal considerations and is discussed in the following section. The two curves intersect at 400 kHz (thus explaining why 400 kHz was chosen as the frequency boundary between PNS and SAR-based reference levels). Extending the PNS (sloped) reference level curve beyond the intersection frequency (as was done for electric field reference levels) may result in unacceptably high induced currents in the 400 kHz – 10 MHz frequency range that could lead to RF burns. Therefore, it was decided to extend the PNS-based induced current reference levels, with their associated reference time, only to 400 kHz where they meet the frequency independent SAR-based reference levels (with a reference period of 6 minutes).

The method for estimating the dosimetric data derived from Dimbylow (1988) in Figures 7 and 8, was based on calculations of current densities in the ankle of a realistic voxel model of an adult. For comparison to the basic restriction, the maximum current densities given in Table 4 (model C) of Dimbylow (1988) were divided by the conductivity of muscle to obtain the equivalent maximum induced electric field for a predefined induced current amplitude. It should be remembered that the proposed basic restrictions for PNS in SC6 (2013) refer to the 99th percentile value of induced electric fields, averaged over a 2x2x2 mm^3 volume of contiguous tissue. The values derived from the data in Dimbylow (1988) pertain to voxel sizes of approximately 4 mm on a side. Thus the effective averaging volume can be considered to be larger than that stipulated by the proposed basic restrictions in SC6 (2013). This would probably lead to a somewhat lower estimate of the maximum induced electric field strength required to meet the basic restrictions, however, this is offset by the fact that the values reported in Dimbylow (1988) are peak values and not based upon the 99th percentile of electric field strength.

The method for estimating the other dosimetric data in Figures 7 and 8 is from the formula: $I = \sigma A_e E_{BR}$ where $A_e = 9.5$ cm^2 for the effective cross-section of current flow along with values of muscle conductivity ranging from 0.44 S/m at 10 kHz to 0.55 S/m at 1 MHz (Gandhi, [7]). As seen in Figures 7 and 8, the resulting estimates using this method are only slightly lower than the ones derived from the voxel model calculations (Dimbylow, 1988). In either case, given the approximate nature of the dosimetric data, it is difficult to estimate to what extent the proposed induced current reference levels are protective of the basic restrictions.

400 kHz to 110 MHz

Figure 9 shows the proposed Uncontrolled induced current reference level of 40 mA for this frequency range, which is based on avoidance of peak spatially-averaged SAR in the ankles. A proportionate value of 90 mA is proposed for Controlled environments based on the standard ratio 2.2:1 for SAR-based current or field strength quantities.

In the frequency range from 400 kHz to 110 MHz, the magnitude of induced current required to meet the basic restriction for SAR in the limbs rises slowly with frequency.

This can be observed in Figure 9 where the induced currents in the ankles required to meet the Uncontrolled Environment basic restriction for SAR of 4 W/kg (averaged over 10 g) are plotted. The data from Gandhi et al. (1986) was calculated using the relationship between SAR and induced current I : $SAR=I^2/(A_e^2\sigma\rho)$, where the effective cross-sectional area estimated by Gandhi was 9.5 cm^2 (for a 1.75m adult) and conductivity data versus frequency was obtained from Dimbylow (1997). The SAR, so calculated, is effectively averaged over an approximate area of 10 cm^2. If it is assumed that the longitudinal SAR distribution is uniform over a 1 cm vertical distance, then the SAR values can be considered to be an approximate 10 g average as well.

These values can also be compared to actual 10 g averaged SARs computed from realistic voxel models of a 1.76m male (Dimbylow, 1997) and a 1.63m female (Dimbylow, 2006). In all cases, it can be seen that the proposed Uncontrolled Environment induced current reference level in SC6 (2013) provides sufficient protection to ensure that the basic restriction for SAR in the ankles is not exceeded. The same relationships hold for the proposed Controlled Environment induced current reference levels in SC6 (2013), since the reference levels and the basic restrictions have the same ratio for controlled-to-uncontrolled on a power basis (5:1).

Proposed Induced Current Reference Levels in SC6 (2013)

Frequency (MHz)	Reference Level Basis	Reference Level (I_{RL}), through a single foot (mA) (rms)		Reference Period
		Uncontrolled Environment	Controlled Environment	
0.003 – 0.4	PNS	100 *f*	225 *f*	Instantaneous
0.4 – 110	SAR	40	90	6 minutes

- Frequency, *f*, is in MHz.
- PNS, peripheral nerve stimulation
- SAR, specific absorption rate

Contact Current

Contact current is usually termed an indirect effect of exposure to electromagnetic fields. It can be defined as the flow of current from an insulated, conductive object energized by an ambient electromagnetic field, through a body that is in physical contact with the object, to ground. Conversely, it can also be defined as the current that flows from an insulated, energized body in contact with a grounded conductive object. In either case the factor that makes contact current potentially hazardous is the current flowing through parts of the body with narrow cross-section (fingers, wrists, ankles) that can give rise to large current densities and limb SARs.

As seen from Figures 5 and 6, adherence to the electric field reference levels may not preclude contact currents that can be perceived either as a tingling sensation or if flowing long enough, as heat. Unlike all other dosimetric quantities, contact currents not only depend on the electrical parameters of the human body and the field intensity and polarization, but also on the shape and size of the conductive object being contacted as well as the type of contact (finger touch as opposed to hand grasp). Since finger touch appears to have the lowest perception thresholds (Chatterjee et al., 1986), it forms the basis for the proposed contact current reference levels in SC6 (2013).

Finger touch can be described as touching the energized conductor with the tip of a single finger, while hand grasp implies that the conductor is gripped in a closed hand. Human volunteer experiments on perception and pain from contact current in Chatterjee et al. (1986) suggest a marked delineation of effects at ~100 kHz. Contact currents at frequencies below 100 kHz, at sufficient intensities, typically results in a tingling sensation, while sufficiently intense contact currents at frequencies above 100 kHz tend to cause heating effects. Perception of tingling or warmth during a finger touch is usually localized in the finger near the point of contact. Hand grasp, with its significantly larger surface area of contact, results in much higher perception thresholds. At frequencies below 100 kHz, the location of sensation is near the electrode being grasped while above this frequency, it is localised in the wrist where current flow is restricted to a small area of relatively high conductivity tissue (Chatterjee et al., 1986).

In terms of latency times, Chatterjee et al. (1986) observed that perception-level currents applied for only 10 to 20 seconds caused pain when the frequency was greater than 100 kHz, but painful sensations were not experienced at frequencies below 100 kHz for similar durations of exposure. This would suggest that a latency time considerably less than 6 minutes needs to be adopted for the contact current reference levels for frequencies up to 10 MHz. Therefore, as a precautionary measure, it is recommended that the effective reference period for contact current reference levels should be specified as instantaneous for frequencies from 3 kHz to 10 MHz, and 6 minutes for frequencies from 10 MHz to 110 MHz. In view of this, overlapping stimulation-based and SAR-based reference levels in the frequency range from 100 kHz to 10 MHz were deemed unnecessary.

The proposed Uncontrolled- and Controlled-Environment contact current reference levels are plotted in Figures 10 to 13. Figures 10 and 11 depict the proposed Uncontrolled- and Controlled Environment contact current reference levels in the 3 – 100 kHz range, while Figures 12 and 13 depict the proposed contact current reference levels in the 100 kHz – 10 MHz frequency range. In keeping with the goal of harmonization, the proposed contact current reference levels in SC6 (2013) are identical to those specified in ICNIRP (1998) and ICNIRP (2010). Also plotted are the experimentally- and dosimetrically-derived threshold contact currents required to meet the basic restrictions in SC6 (2013).

In Figure 10, it can be seen that estimated perception thresholds for children are almost one half of that for male adults. ICNIRP (2010) uses this as the rationale for setting their general public (Uncontrolled Environment) reference levels to be one half of those for the Controlled-Environment. Considering that the perception threshold data is based upon the 50^{th} percentile of a given population group, it can assumed that some members of the population group would perceive contact currents at the reference levels. This is also true for the Controlled Environment (Figure 11). Thus, the proposed reference levels in SC6 (2013) for contact current in the 3 – 100 kHz frequency range provide some protection against, but do not prevent, the occurrence of perception (tingling sensation or warmth). However, these reference levels do provide protection against painful contact current exposures.

In the 100 kHz – 110 MHz frequency range, experimental perception data from Chatterjee et al. (1986) is nearly frequency independent. The Uncontrolled-Environment contact current reference level in Fig 12 appears to protect against the 50th percentile for perception by children with the same proviso that some members of the child population group may perceive contact currents at reference levels.

Fig 13 demonstrates that the Controlled-Environment contact current reference level is approximately at the 50^{th} percentile perception threshold for adult males and below the corresponding pain threshold for the same group. It is not known what percentage of adult males would experience pain at reference level contact currents. However, opportunities for mitigation of painful contact current exposures are readily available in occupational environments for the avoidance of such effects.

Wrist currents that meet the basic restriction for SAR, averaged over 10 g in the limbs and calculated from realistic voxel models, are also plotted in Figures 12 and 13. This data is pertinent to the case of hand grasp, where the bulk of the power deposition is in the wrist. Unfortunately no similar data on SAR in the finger resulting from a finger touch could be found. The result is that the empirical data from human volunteer studies constitutes the foundation for establishing reference levels.

Proposed Contact Current Reference Levels in SC6 (2013)

Frequency (MHz)	Reference Level Basis	Reference Level (I_{RL}), (mA) (rms)		Reference Period
		Uncontrolled Environment	Controlled Environment	
0.003 – 0.10	PNS	200 *f*	400 *f*	Instantaneous*
0.10 – 10	SAR	20	40	Instantaneous*
10 – 110	SAR	20	40	6 minutes

- Frequency, *f*, is in MHz.
- PNS, peripheral nerve stimulation
- SAR, specific absorption rate

Section 3 Electric fields, Magnetic Fields and Power Density (10 MHz – 6 GHz)

Basic Restrictions

In the frequency range 10 MHz – 6 GHz, the threshold for adverse effects in SC6 (2009) was based upon the avoidance of tissue heating and basic restrictions have been specified for whole-body average SAR and peak spatially-averaged SAR. Since the last revision of SC6 (2009), no new adverse health effects have been established in this frequency range (SCENHIR 2009; ICNIRP 2009; AGNIR 2012). Therefore, the avoidance of thermal effects remains the basis for the basic restrictions in this frequency range.

Recently, the International Agency for Research on Cancer (IARC) classified RF energy as "possibly carcinogenic to humans" (Class 2B) (Baan et al., 2011). The IARC classification on RF fields reflects the fact that some (limited) evidence exists that RF fields may be a risk factor for cancer. This classification was largely based upon epidemiological investigations of brain cancer incidence in cell phone users over time. While the largest of these studies (INTERPHONE Study Group, 2010) found no overall risk among cell phone users, they identified a subset of long-term 'heavy-users' in which elevated odd-ratios were observed. It is unclear whether these observations were the result of methodological confounding or represent a true biological effect. The vast majority of supporting scientific information to date, from animal and cellular studies, does not support a link between RF energy exposure and carcinogenesis. Recent studies of national brain cancer incidence rates (Northern Europe, UK, US) have also reported no relative increase in glioma rates over the past 10-15 years, despite a dramatic increase in cell phone users over the same time period (Deltour et al., 2009, 2012; Frei et al., 2011; De Vocht et al., 2011; Little et al., 2012). Such information, while tentative at this time due to a possible delayed latency time for the onset of neoplasms from cell phone use, adds to the weight of evidence that does not support a causal link between cell phone use (and therefore exposure to RF fields in the 900-1900 MHz range) and brain cancer development. At present, no national or international science-based exposure standards have established basic restrictions or reference levels for the avoidance of cancer risks from radiofrequency fields in the frequency range 10 MHz – 6 GHz, as the science supporting this health endpoint is not sufficiently well established.

Based upon the uncertainty surrounding a possible long-term risk of cancer, Health Canada recently updated its advice to cell phone users, describing practical ways of reducing exposure to radiofrequency (RF) energy from these devices (such as reducing call time, using hands-free devices or texting). This advice pertains only to cell phone use and not to RF field exposures from other wireless devices (such as Wi-Fi, Smart Meters, baby monitors), since the intensity and distribution of the RF energy absorbed within the body from these devices are very different than those from cell phones. This is deemed the most appropriate precautionary approach for dealing with the current uncertainty regarding possible long term risks from cell phone use.

As indicated in Section 1, the basic restriction against thermal effects in SC6 (2009) consists of WBA-SAR and peak spatially-averaged SAR limits. The limits outlined for the avoidance of thermal effects in the 100 kHz- 10 MHz range also apply in the 10 MHz- 6 GHz range.

Proposed WBA-SAR and peak spatially-averaged SAR in SC6 (2013):

Exposure Group	Tissue	Frequency range	Peak spatially-averaged SAR (W/kg)	WBA-SAR (W/kg)
SC6- Controlled	Head, trunk	10 MHz - 6 GHz	8	0.4

Environment	Limbs		20	
SC6- Uncontrolled Environment	Head, trunk	10 MHz - 6 GHz	1.6	0.08
	Limbs		4.0	

Since no additional adverse health effects have been established at exposure levels below the basic restrictions specified in SC6 (2009), no changes to the basic restrictions are recommended for SC6 (2013). Since the last revision of SC6 (2009), it is now recognized that when anatomically-derived models of children are used to assess the adequacy of the existing reference levels, the basic restrictions for WBA-SAR may not be respected in the frequency range of body resonance (~100 MHz) and from 1 - 4 GHz for the Uncontrolled Environment for the WBA-SAR limit of 0.08 W/kg (Wang et al., 2006; Dimbylow and Bolch 2007; Conil et al., 2008; Nagaoka et al., 2008; Kühn et al., 2009). For this reason, it is recommended that the reference levels in SC6 (2013) should be re-evaluated in the 10 MHz- 6 GHz frequency range based upon these dosimetric refinements.

Note: Ocular Effects

As mentioned in Section 1, ocular effects on cataractogenesis from intense RF field exposures have been established for many years with a threshold response of ~100-150 W/kg in experimental animals. In previous versions of SC6 (1991, 1999, 2009), basic restrictions and/or recommendations were specified for the local SAR in the eye. This guidance was not based upon the avoidance of cataractogenesis, but rather represented a conservative approach based upon observations of transient lesions in the corneal endothelium of anaesthetized monkeys following exposure to pulsed or continuous-wave 2.45 GHz RF fields at 2.6 W/kg from one laboratory (Kues et al., 1985; 1992). This effect was reported to be enhanced by pre-treatment with the ophthalmic drug timolol maleate, whereby the threshold for effect was reduced to 0.26 W/kg (Kues et al., 1992). A similar study by the same group reported transient changes in electroretinogram activity in conscious monkeys following exposure to 1.25 GHz pulsed RF fields at a SAR of 4.0 W/kg (Kues and Monohan, 1992). However, later studies by Kamimura et al. (1994) and Lu et al., (2000) found no evidence of optical (including corneal) lesions in the eyes of conscious monkeys following exposure to 1.25 or 2.45 GHz RF fields at similar or higher intensities than those employed by Kues et al. (1985, 1992). Lu et al. (2000) did observe changes in the electroretinogram response in conscious monkeys at SARs > 8 W/kg, but the authors noted that these were transient changes and that no pathological changes were observed.

The use of anaesthesia in exposed animals (rabbits and monkeys) has been suggested to have compromised heat dissipation in the eyes of RF exposed animals, potentially leading to an artificially enhanced sensitivity to thermal effects in early RF field studies (Kamimura et al, 1994). This phenomenon was observed by Kojima et al. (2004) and Hirata et al. (2006) in rabbit eyes following exposure to 2.45 GHz RF fields, where markedly increased temperatures were observed in anaesthetized animals compared to non-anaesthetized animals. Observations of corneal lesions and vascular leakage in the eyes of anaesthetized monkeys in early studies in one laboratory were not confirmed in later studies in other laboratories using conscious monkeys.

Overall, there is an inadequate body of scientific evidence upon which to support the causality of adverse health effects of RF fields on the human eye at exposure levels below the peak spatially-averaged SAR limits in SC6 (2013). Despite the widespread use of a variety of consumer devices (e.g. cell phones, push-to-talk radios) over the past 15 years by the general population in Canada and abroad, Health Canada has not received any complaints and is not aware of any ocular injuries that have occurred from RF field exposures at levels below the current basic restrictions on peak spatially-averaged SAR outlined in SC6 (2009). Since the basic restrictions and reference levels in SC6 (2013) are intended to be based upon established adverse health effects, it is not considered scientifically-justifiable to establish basic restrictions or to maintain separate 'recommendations' for peak spatially-averaged SAR for the eye, since the available scientific evidence for non-cataractogenic effects on the eye below the current peak spatially-averaged SAR limits in SC6 (2009) is extremely limited, contradictory and not causally-established. A similar conclusion has been established by IEEE C95.1 (2005), ICNIRP (1998) and ICNIRP (2009, 2010).

Health Canada will continue to monitor the scientific literature related to this issue and will revise/create relevant basic restrictions if/when scientifically warranted.

Reference Levels

Recent developments in electromagnetic dosimetry using MRI-derived voxel models of the human body have shown that for certain body dimensions and frequencies, the basic restriction of whole-body SAR may be exceeded for exposure field strengths (or power densities) at reference levels corresponding to SC6 (2009) and ICNIRP (1998). This is shown in Figure 14 and Figure 15 for Uncontrolled- and Controlled-Environments, respectively.

When establishing the proposed Uncontrolled- and Controlled-Environment reference levels, the criteria considered were to harmonize with ICNIRP (1998) where feasible, while ensuring that basic restrictions were maintained at all frequencies. In response to these goals, the proposed Uncontrolled- and Controlled-Environment reference levels were established at levels equal to those of ICNIRP (1998) in the 10 to 65 MHz frequency range. However, for frequencies from 65 - 100 MHz, the proposed reference levels in SC6 (2013) deviate from those of ICNIRP (1998) by decreasing with increasing frequency (at a chosen rate of f^{-1}) to accommodate the dosimetry data that point to greater whole body resonance absorption for children than previously thought (Conil et al., 2008; Kühn et al., 2009; Nagaoka et al., 2008); Dimbylow and Bolch, 2007).

In the 100 MHz to 6 GHz frequency range, the proposed reference levels are allowed to increase with frequency at a rate that provides protection from exceeding basic restrictions for small children in the 2–4 GHz range, as shown by the data in Figures 14 and 15. The uppermost frequency of the sloped line corresponds to 6 GHz, which is the proposed upper limit for consideration of SAR as a basic restriction. The rate of increase with frequency was chosen to be $f^{0.5}$ for power density and $f^{0.25}$ for field strength. The first frequency break point, 65 MHz, and the reference level value at 100 MHz are consequences of the choice of rates of frequency dependence for the two sloped parts, and the choice of 100 MHz and 6 GHz as beginning and end-points for the positively sloped part of the curve.

The proposed Uncontrolled-Environment reference levels meet the goal of compliance to the basic restrictions, as seen in Figure 14, but the proposed Controlled-Environment reference levels may appear to be slightly over-protective in view of the fact that most of the dosimetry data below the ICNIRP (1998) line in Figure 15 (1-4 GHz range) pertain to small children. However, to take into account that adults of small stature may possibly occupy Controlled-Environments for occupational purposes and for the sake of preserving the 5:1 ratio between Controlled- and Uncontrolled-Environment power density reference levels (2.2:1 for field strengths), it was decided to maintain the same frequency dependence for the two reference level curves.

The dosimetry data in Figures 14 and 15 correspond to the case of an isolated body and worst-case polarization of the incident fields. Usually this occurs when the incident electric field vector is oriented parallel to the long axis of the body. In situations where the body is standing and in good electrical contact with the ground and where the polarization of the incident electric field is vertical (aligned along the long axis of the body), large induced currents can flow through the feet to ground, resulting in relatively high ankle SAR.

Estimates of ankle SAR for the 10 MHz to 100 MHz frequency range can be found in references (Gandhi et al., 1986; Dimbylow, 2002, Tofani et al., 1995; Dimbylow, 2006). From these estimates, the smallest incident electric field strength required to meet the Uncontrolled-Environment basic restriction of 4 W/kg (limbs) for different body sizes is plotted in Figure 16, along with the proposed- and current Uncontrolled-Environment reference levels for electric field strength. It should be noted that the data derived from Dimbylow (2002, 2006) are based on actual peak spatially-averaged SAR (10 g averaged) calculations, while those of Gandhi et al. (1985) and Tofani et al. (1995) are based on the calculation of SAR from ankle currents passing through an effective area of 9.5 cm^2 [7] (physical ankle cross-sections are closer to 40 cm^2). A similar situation occurs in the Controlled-Environment (Figure not shown) since the Controlled-to-Uncontrolled Environment ratio of 5:1 for power, and 2.2:1 for field strength, is maintained.

From Figure 16, it can be observed that the proposed Uncontrolled Environment electric field strength reference levels, along with the current SC6 (2009) and other reference levels, do not protect against excessive limb SAR (SAR in the limbs as averaged over 10 g of tissue) for grounded individuals. However, separate reference levels are specified in SC6 (2013) for contact- and induced-currents that provide protection. Thus, assessment of limb current is an important factor to be considered in compliance assessment with SC6 (2013) in situations where personnel are in contact with a conductive ground and polarization of the incident fields are favourable for the generation of significant limb current.

Proposed Uncontrolled Environment Reference Levels for Electric- and Magnetic-field strength and Power Density in the 10 MHz – 6 GHz frequency range in SC6 (2013).

Frequency (MHz)	Electric Field Strength, E_{RL} (V/m) (rms)	Magnetic Field Strength, H_{RL} (A/m) (rms)	Power Density, S_{RL} (W/m^2)	Reference Period (minutes)
10 – 65	27.5	0.073	-	6
65 – 100	$221 / f^{0.5}$	$0.585 / f^{0.5}$	$129.1 / f$	6
100 – 6000	$6.97 f^{0.25}$	$0.0185 f^{0.25}$	$0.129 f^{0.5}$	6

Frequency, *f*, is in MHz.

Proposed Controlled Environment Reference Levels for Electric- and Magnetic-field strength and Power Density in the 10 MHz – 6 GHz frequency range in SC6 (2013).

Frequency (MHz)	Electric Field Strength, E_{RL} (V/m) (rms)	Magnetic Field Strength, H_{RL} (A/m) (rms)	Power Density, S_{RL} (W/m^2)	Reference Period (minutes)
10 – 65	61.4	0.163	-	6
65 – 100	$493 / f^{0.5}$	$1.309 / f^{0.5}$	$645.5 / f$	6
100 – 6000	$15.6 f^{0.25}$	$0.0414 f^{0.25}$	$0.6455 f^{0.5}$	6

Frequency, *f*, is in MHz.

Peak Pulsed RF field levels

SC6 (2009), IEEE C95.1 (2005) and ICNIRP (1998) have all contained provisions to limit the intensity of individual or infrequent RF field pulses. This is to avoid excessive pressure waves in the head from rapid thermo-elastic expansion of tissues caused by absorption of intense RF field pulses (Elder and Chou, 2003). The proposed limits for power density in Tables 5 and 6 of Safety Code 6 (2013) include a note (6) which limits the temporal peak power density for pulsed RF fields (in the 10 MHz – 300 GHz frequency range) to no more than 1000 times the reference level for power density. This provision was included as part of the harmonization effort with the ICNIRP (1998) exposure limits, and replaces the previous guidance on pulsed RF field power density in SC6 (2009). The following analysis demonstrates that the adoption of note 6 in Tables 5 and 6 of SC6 (2013) provides approximately equivalent protection as the specifications for peak power density of pulsed RF fields contained in SC6 (2009).

In Section 2.2.1 of SC6 (2009), the limit for the peak power density was specified as:

$\sum S_{PK}\, T_p \leq (S_{RL} * T_a)/5$ (Criterion 1)

where S_{PK} = peak power density limit
S_{RL} = power density reference level
T_p = pulse duration
T_a = averaging time
and the summation on the left hand side is over 0.1s

Criterion 1 states that the total energy density in any 0.1s period within the averaging time should not exceed one-fifth of the total energy density permitted during the entire averaging time of a continuous field. A maximum of 5 pulses with pulse durations of less than 0.1s are permitted in any period equal to the averaging time. If it is assumed that either a single pulse occurs in the 0.1s period or 5 or fewer pulses occur all having the same amplitude, the criterion for the peak power density, S_{PK}, can be written as:

$S_{PK} \leq (S_{RL} * 72) / \sum T_p$ (Criterion 2)

Here it is assumed that the frequency range corresponds to the one for which the averaging time is 6 minutes or 360s.

The criterion in note 6 of Tables 5 and 6 of SC6 (2013) can be written as,

$S_{PK} \leq (S_{RL} * 1000)$ (Criterion 3)

Examination of the Criterion 2 reveals that the allowable peak power density is inversely proportional to the amount of pulse “ON” time in the 0.1s period (given by the term $\sum T_p$). Thus, the criterion for peak power density is the most restrictive (i.e. has the smallest value) when, for a single pulse, the pulse period is the full 0.1s allowed, or in the case of multiple pulses, their “ON” times occupy almost the full 0.1s. In either case the resulting criterion for peak power density becomes: $S_{PK} \leq (S_{RL} * 720)$.

The criterion in note 6 of SC6 (2013) and that in SC6 (2009) become identical for cases where the sum of the pulse periods, $\sum T_p$, is equal to 72 ms, while for smaller pulse periods, note 6 of SC6 (2013) becomes more restrictive. In the worst case, the criterion in note 6 of SC6 (2013), allows 39% higher pulsed power density amplitudes for pulse durations between 72-100 ms, when compared to the criterion in SC6 (2009). However, the proposed provisions in SC6 (2013) still provides several orders of magnitude of protection against the pressure wave effect (Elder and Chou, 2003).

Section 4 Electric fields, Magnetic Fields and Power Density (6 GHz – 300 GHz)

Basic Restrictions

In the frequency range from 6 - 300 GHz, since measurements of whole-body SAR and peak spatially-averaged SAR are not readily achievable or appropriate due to the superficial nature of energy deposition within tissue, reference levels for electric- and magnetic-fields and power density form the basis of the human exposure limits in this frequency range. Since the last revision of SC6 (2009), no new health effects have been established in this frequency range (SCENHIR 2009; ICNIRP 2009). Therefore, the avoidance of thermal effects remains the basis for the reference limits in this frequency range and no changes in the basic restrictions are required.

Reference Levels

The proposed reference levels for RF fields in the 6 – 300 GHz range remain unchanged from SC6 (2009).

Proposed Uncontrolled Environment Reference Levels for Electric- and Magnetic-field strength and Power Density in the 6 – 300 GHz frequency range in SC6 (2013).

Frequency (GHz)	Electric Field Strength, E_{RL} (V/m) (rms)	Magnetic Field Strength, H_{RL} (A/m) (rms)	Power Density, S_{RL} (W/m^2)	Reference Period (minutes)
6 –15	61.4	0.163	10	6
15 – 150	61.4	0.163	10	$616000 / f^{1.2}$
150 – 300	$0.158 f^{0.5}$	$4.21\text{x}10^{-4} f^{0.5}$	$6.67\text{x}10^{-5} f$	$616000 / f^{1.2}$

Frequency, *f*, is in MHz.

Proposed Controlled Environment Reference Levels for Electric- and Magnetic-field strength and Power Density in the 6 – 300 GHz frequency range in SC6 (2013).

Frequency (GHz)	Electric Field Strength, E_{RL} (V/m) (rms)	Magnetic Field Strength, H_{RL} (A/m) (rms)	Power Density, S_{RL} (W/m^2)	Reference Period (minutes)
6 – 15	137	0.364	50	6
15 – 150	137	0.364	50	$616000 / f^{1.2}$
150 – 300	$0.354 f^{0.5}$	$9.40\text{x}10^{-4} f^{0.5}$	$3.33\text{x}10^{-4} f$	$616000 / f^{1.2}$

Frequency, *f*, is in MHz.

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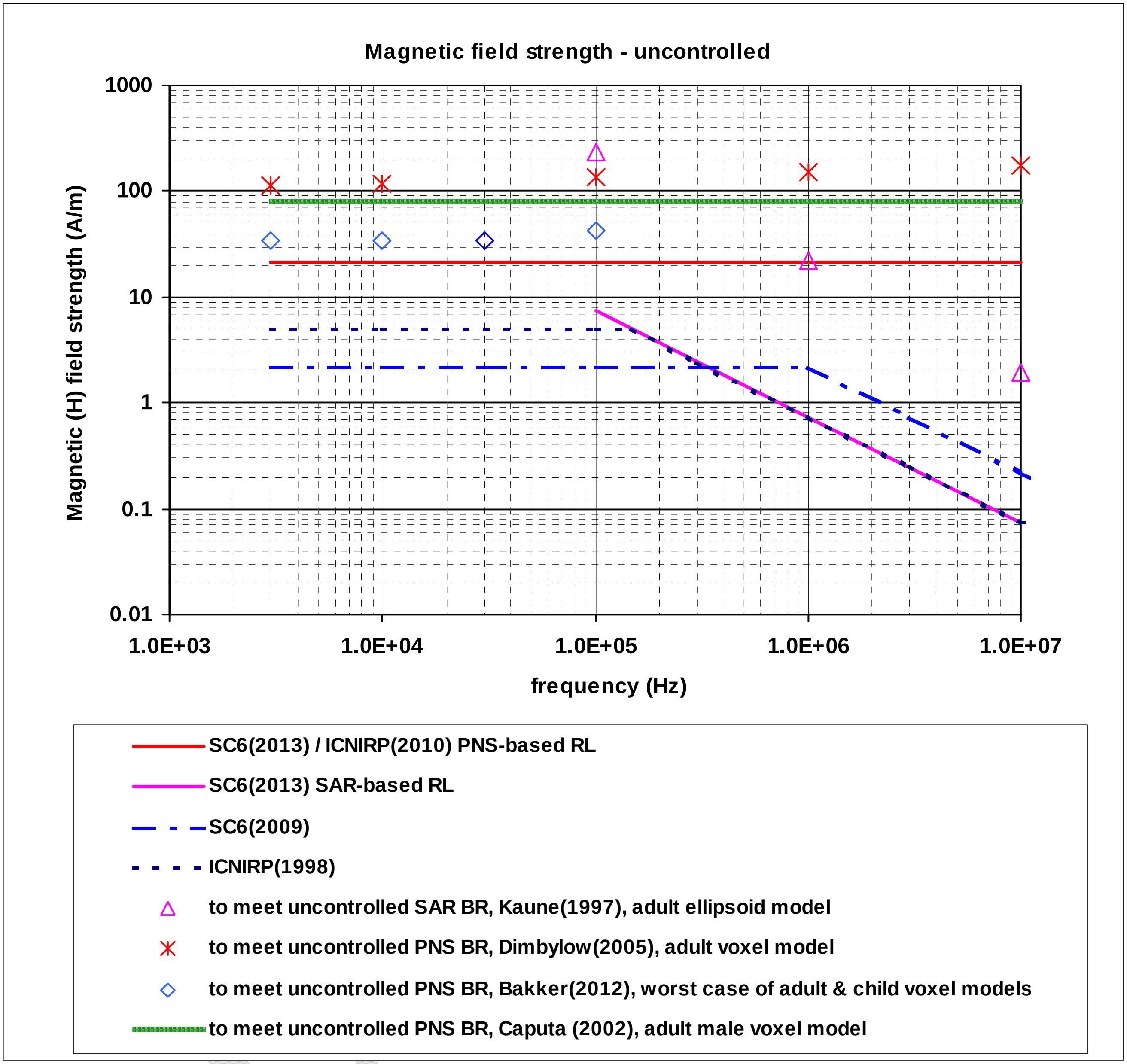

Figure 1. Proposed magnetic field strength reference levels for Uncontrolled Environments in SC6 (2013) and magnetic field strengths required to meet the PNS and/or SAR-based Uncontrolled Environment basic restrictions in SC6 (2013) (in various numerical models exposed under worst-case conditions).

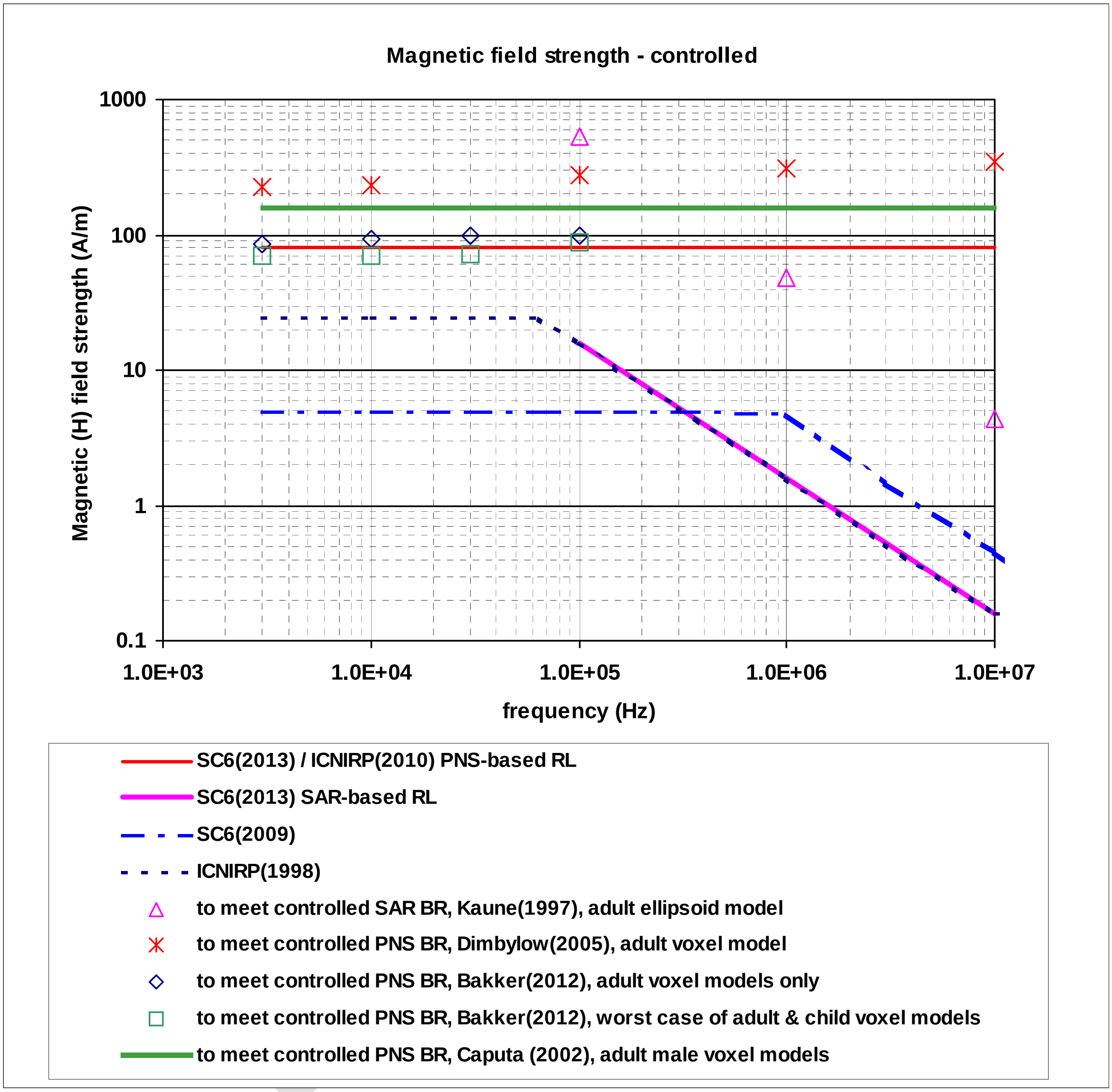

Figure 2. Proposed magnetic field strength reference levels for Controlled Environments in SC6 (2013) and magnetic field strengths required to meet the PNS and/or SAR-based Controlled Environment basic restrictions in SC6 (2013) (in various numerical models exposed under worst-case conditions).

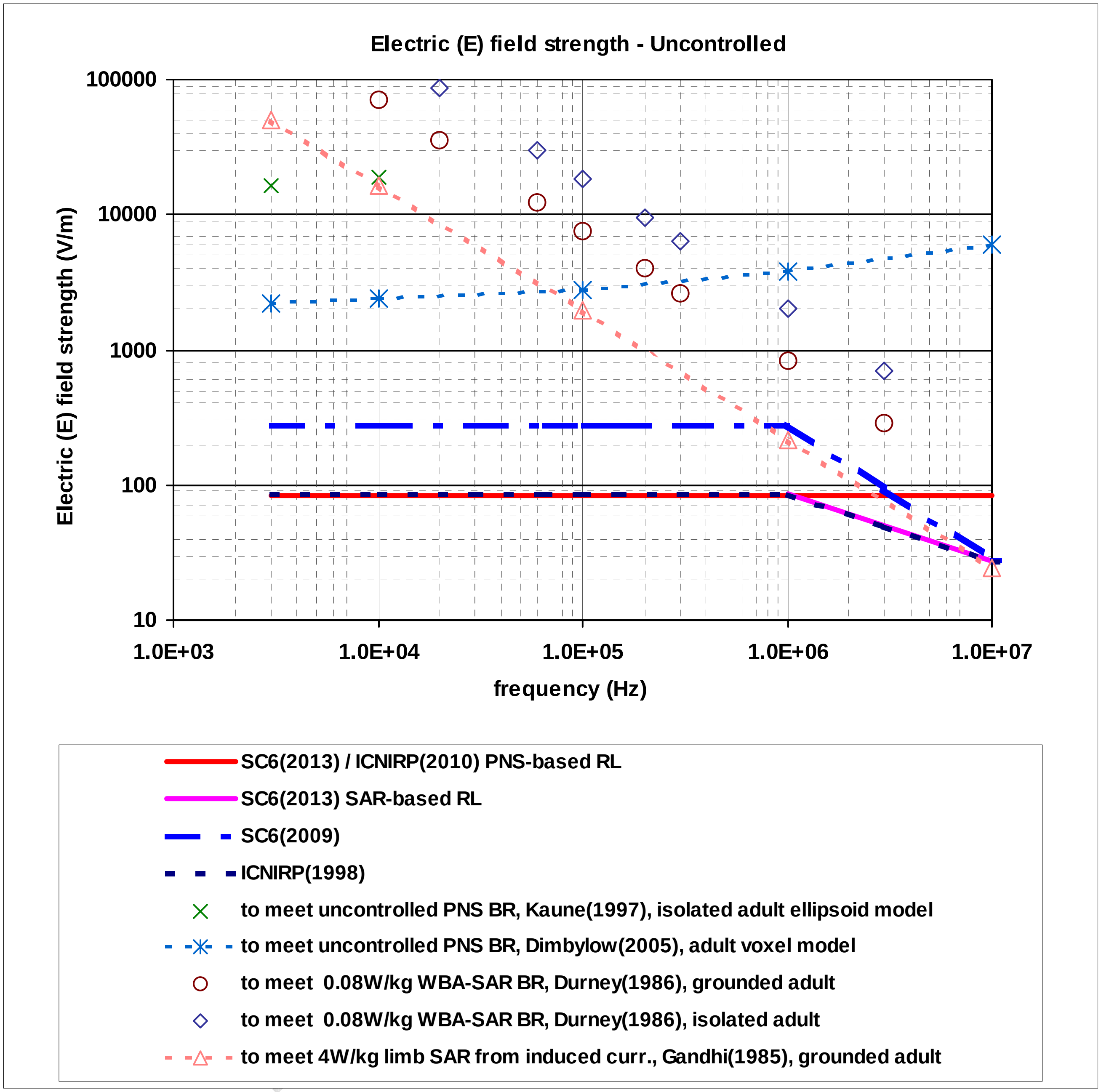

Figure 3. Proposed electric field strength reference levels for Uncontrolled Environments in SC6 (2013) and electric field strengths required to meet the PNS- and/or SAR-based Uncontrolled Environment basic restrictions in SC6 (2013) (in various numerical models exposed under worst-case conditions).

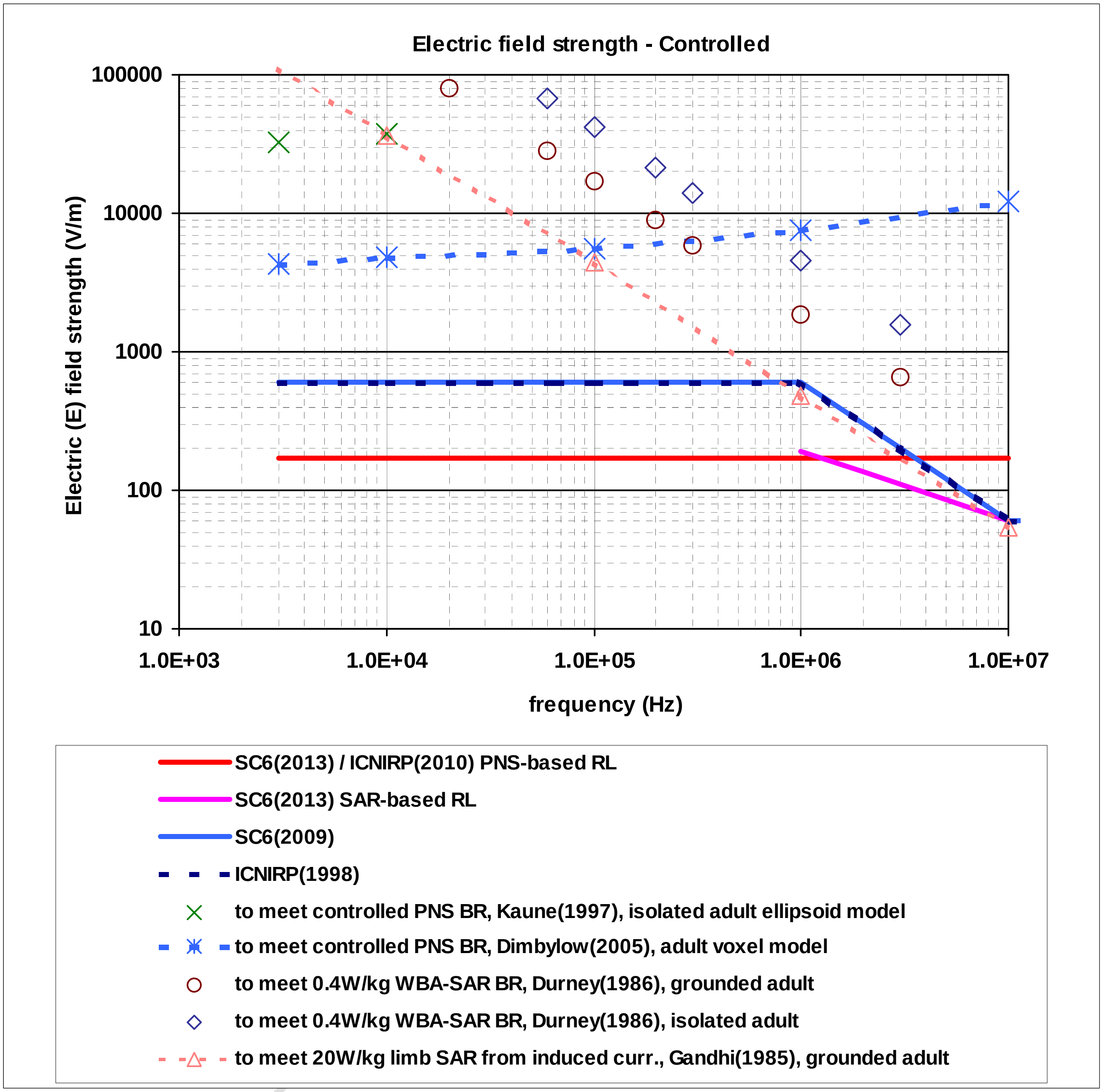

Figure 4. Proposed electric field strength reference levels for Controlled Environments in SC6 (2013) and electric field strengths required to meet the PNS- and/or SAR-based Controlled Environment basic restrictions in SC6 (2013) (in various numerical models exposed under worst-case conditions).

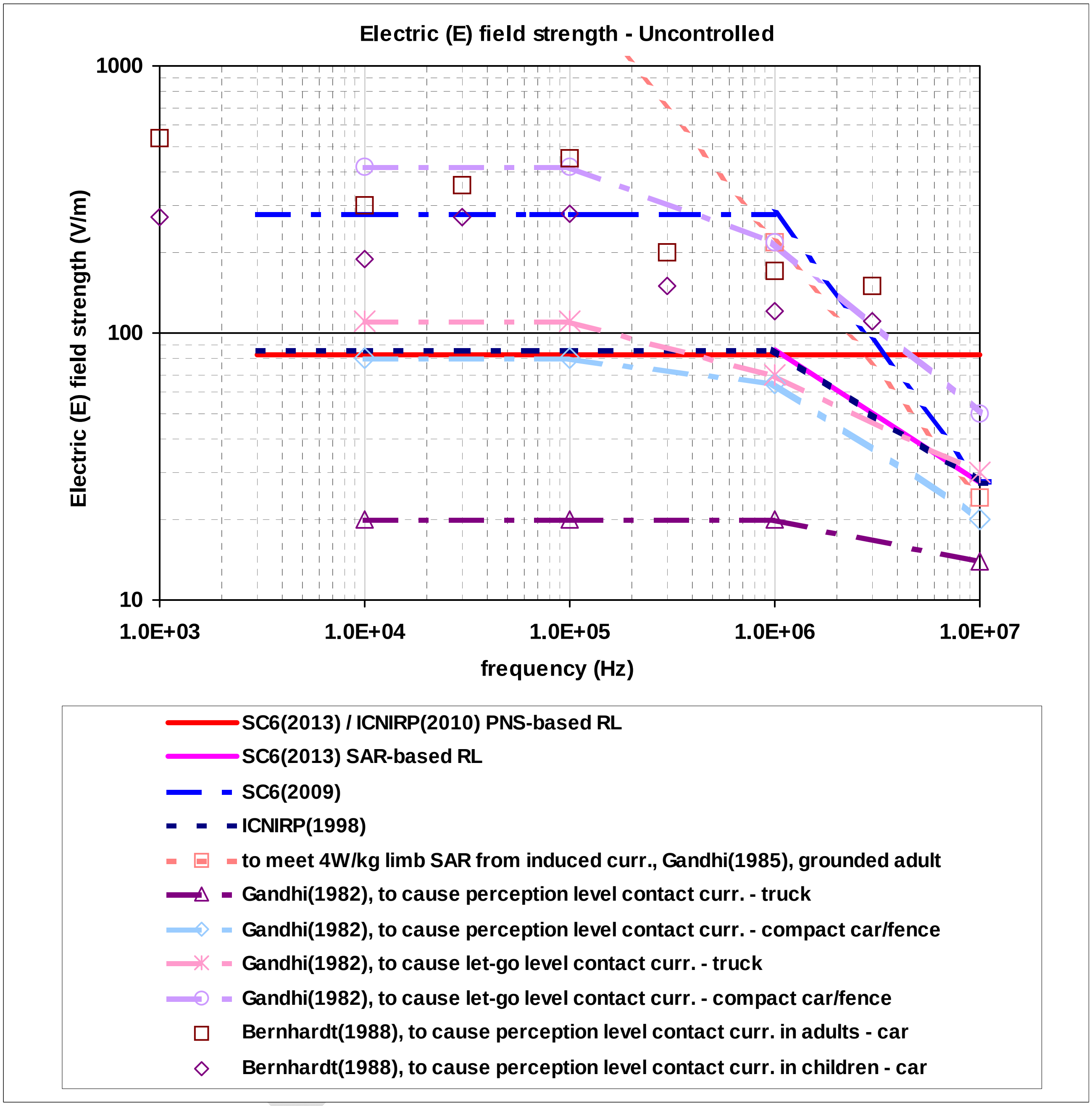

Figure 5. Proposed electric field strength reference levels for Uncontrolled Environments in SC6 (2013) and electric field strengths of sufficient intensity to cause perception-level and let-go level contact currents for different objects under worst-case conditions.

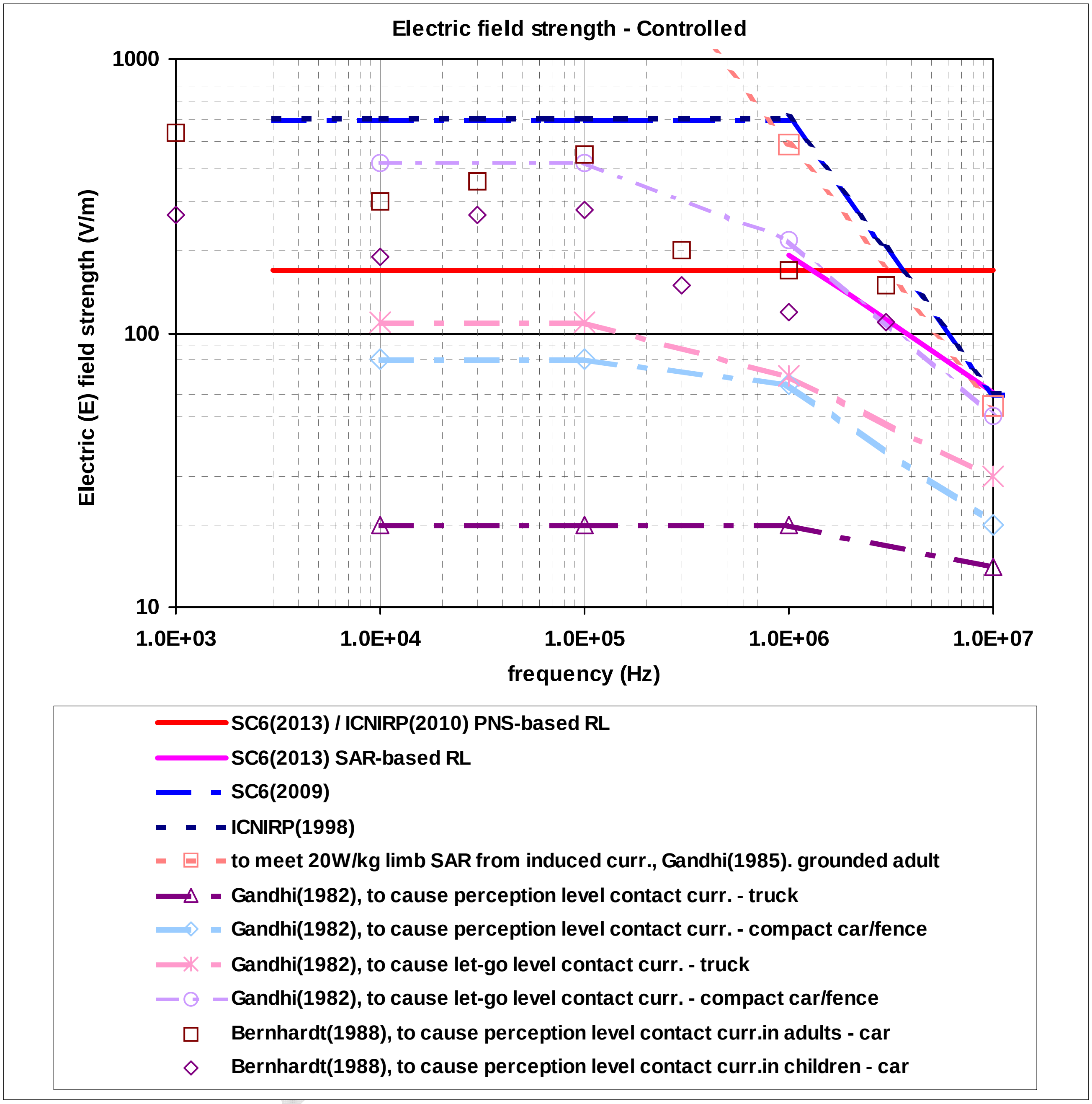

Figure 6. Proposed electric field strength reference levels for Controlled Environments in SC6 (2013) and electric field strengths of sufficient intensity to cause perception-level and let-go level contact currents for different objects under worst-case conditions.

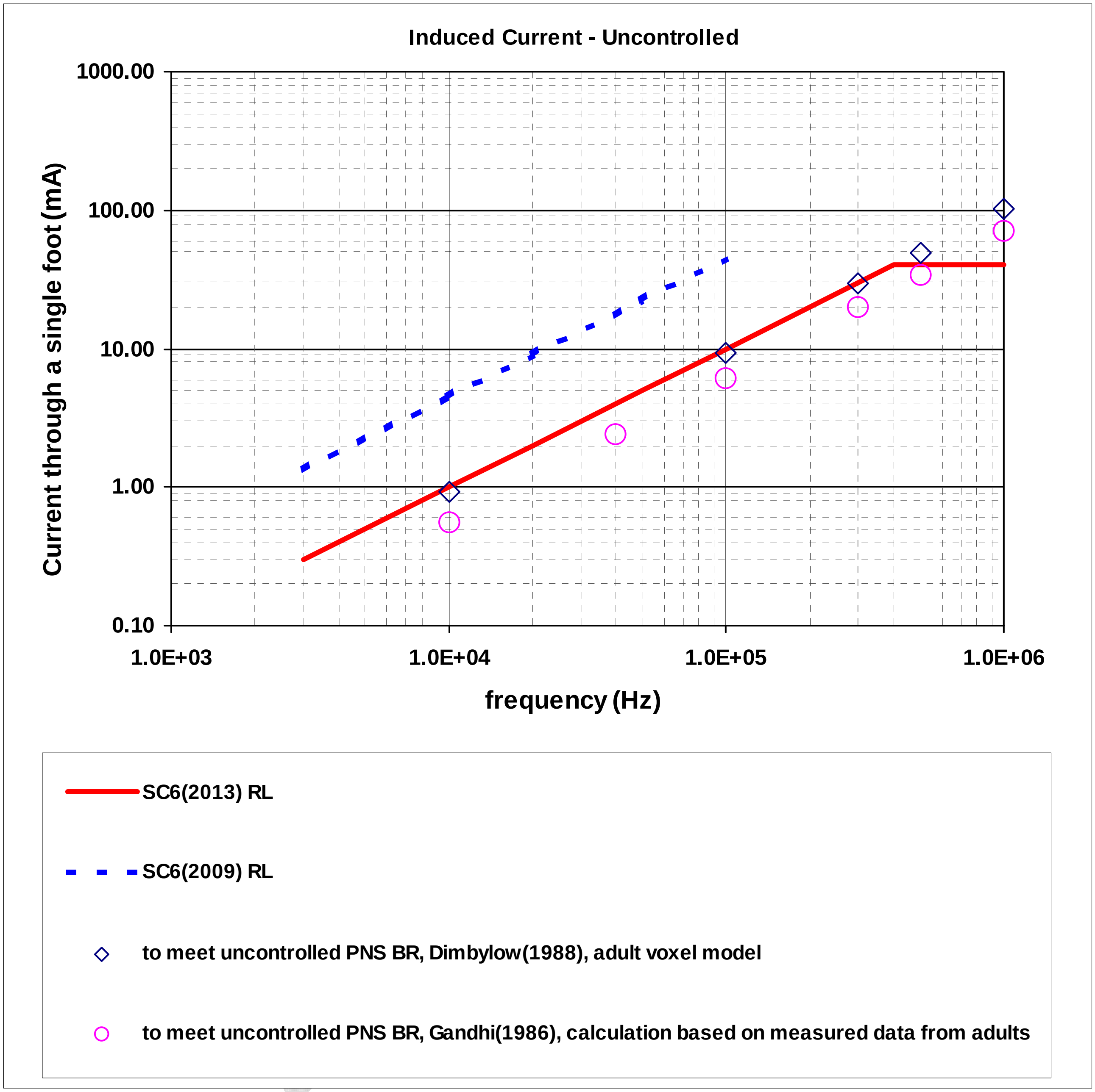

Figure 7. Proposed induced current reference levels for Uncontrolled Environments for the frequency range 3 kHz to 1 MHz in SC6 (2013). Also shown are estimates of induced current required to meet the Uncontrolled Environment basic restriction for induced electric field.

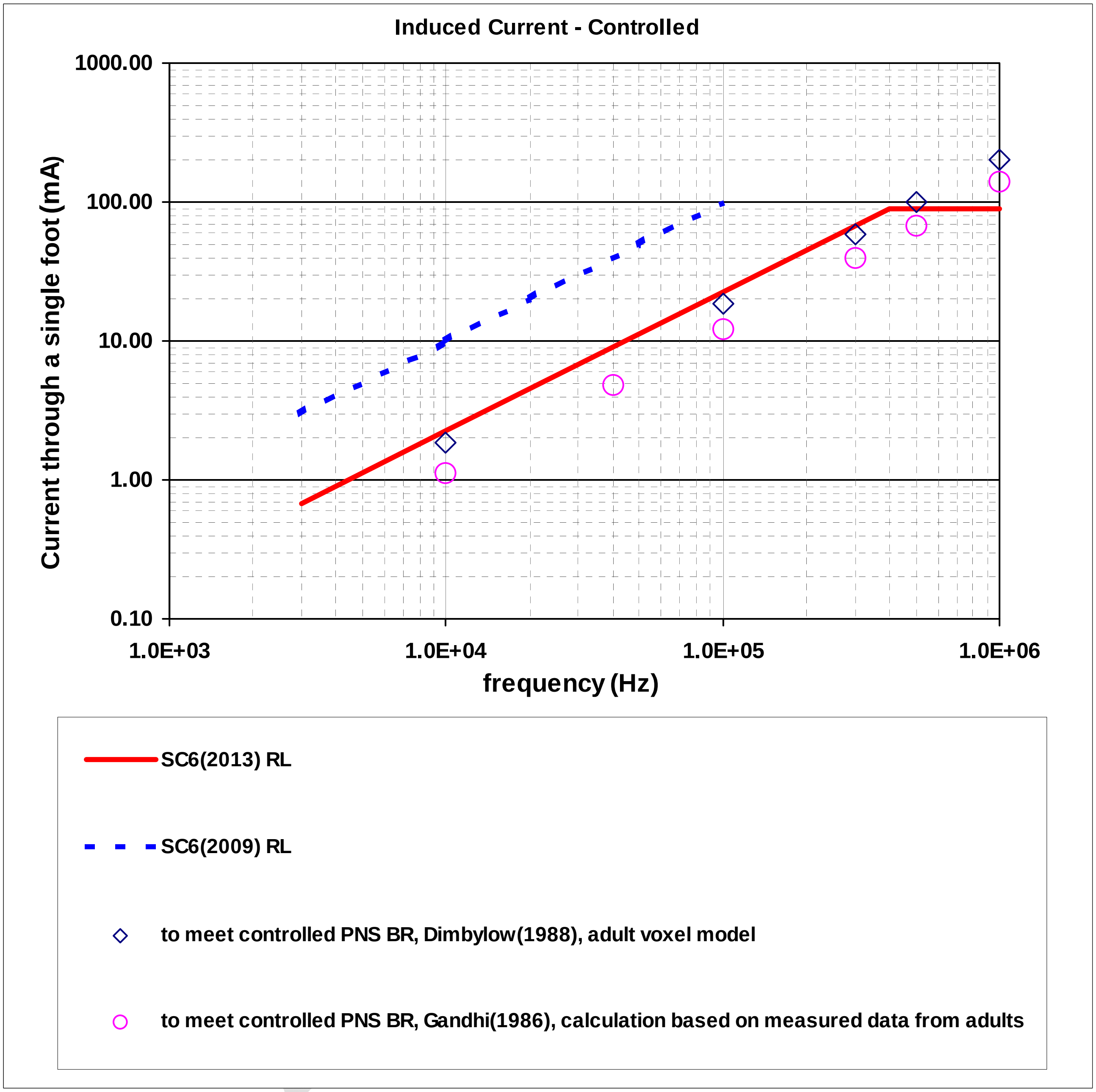

Figure 8. Proposed induced current reference levels for Controlled Environments for the frequency range 3 kHz to 1 MHz in SC6 (2013). Also shown are estimates of induced current required to meet the Controlled Environment basic restriction for induced electric field.

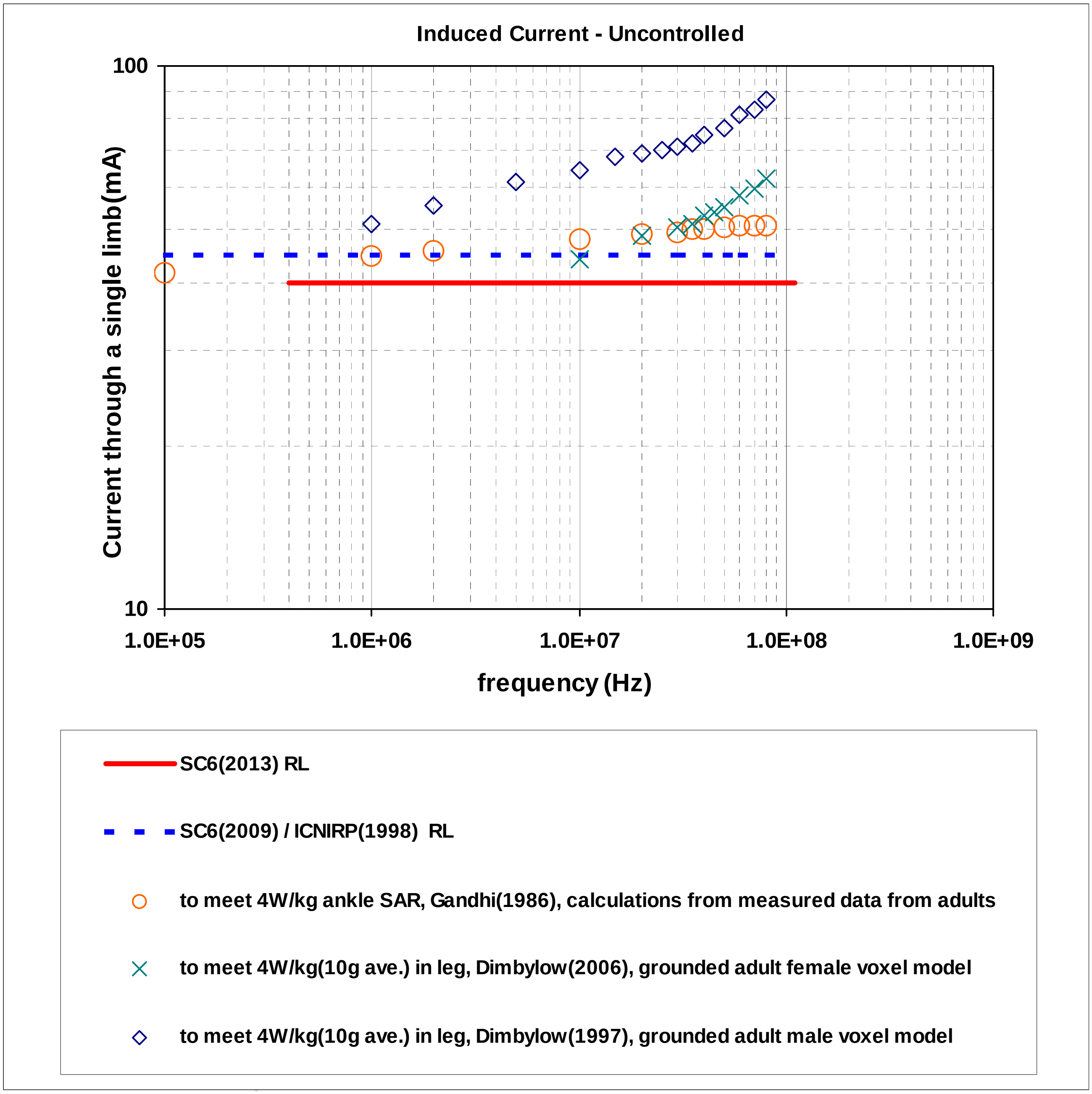

Figure 9. Proposed induced current reference levels for Uncontrolled Environments for the frequency range 400 kHz to 10 MHz in SC6 (2013). Also shown are estimates of induced current required to meet the Uncontrolled Environment basic restriction for peak spatially-averaged SAR in the limbs (4 W/kg averaged over 10 g).

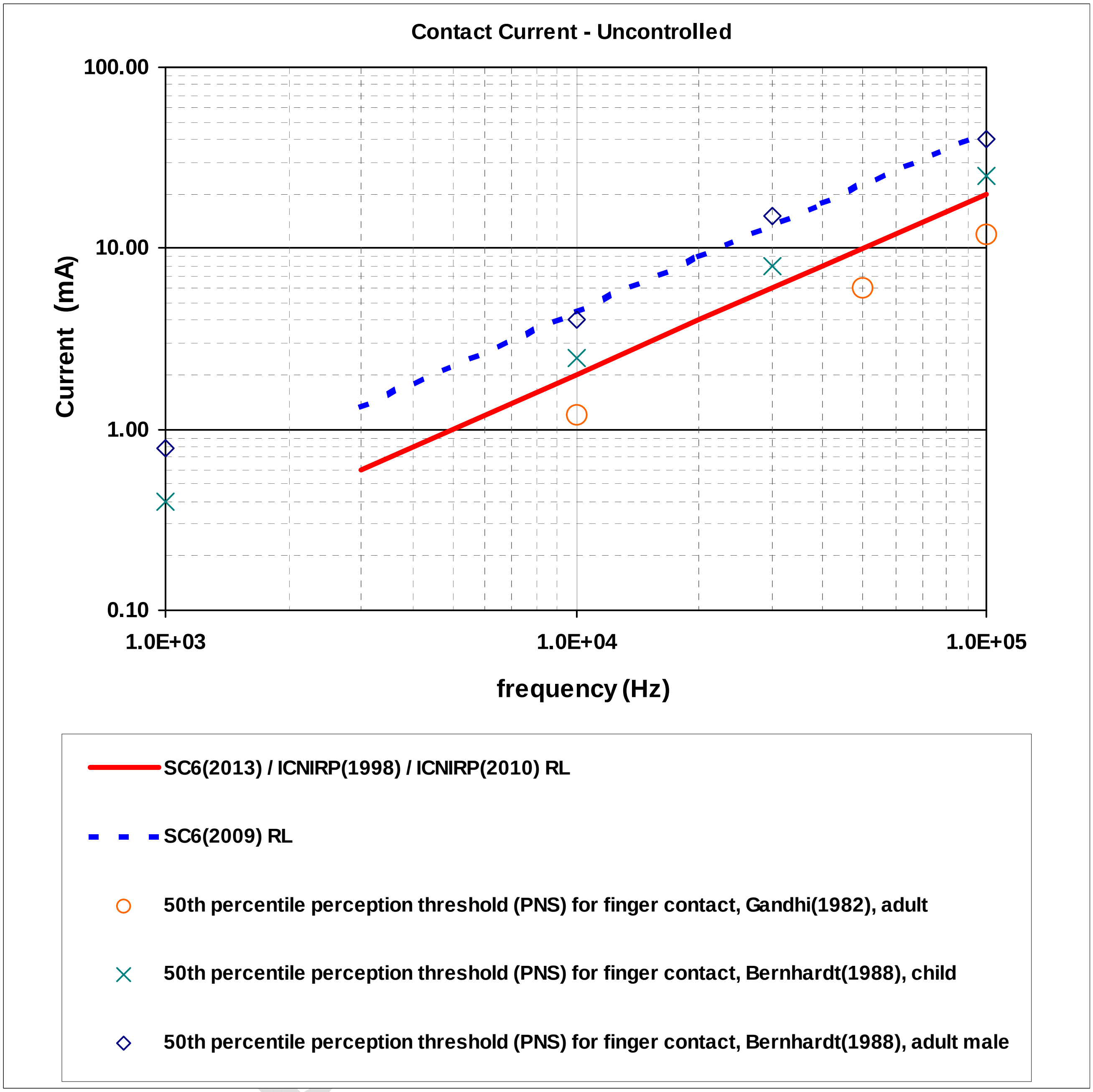

Figure 10. Proposed Uncontrolled-Environment contact current reference levels for the 3 - 100 kHz frequency range in SC6 (2013). Also depicted are the 50th percentile perception threshold currents (adult and children) for finger contact.

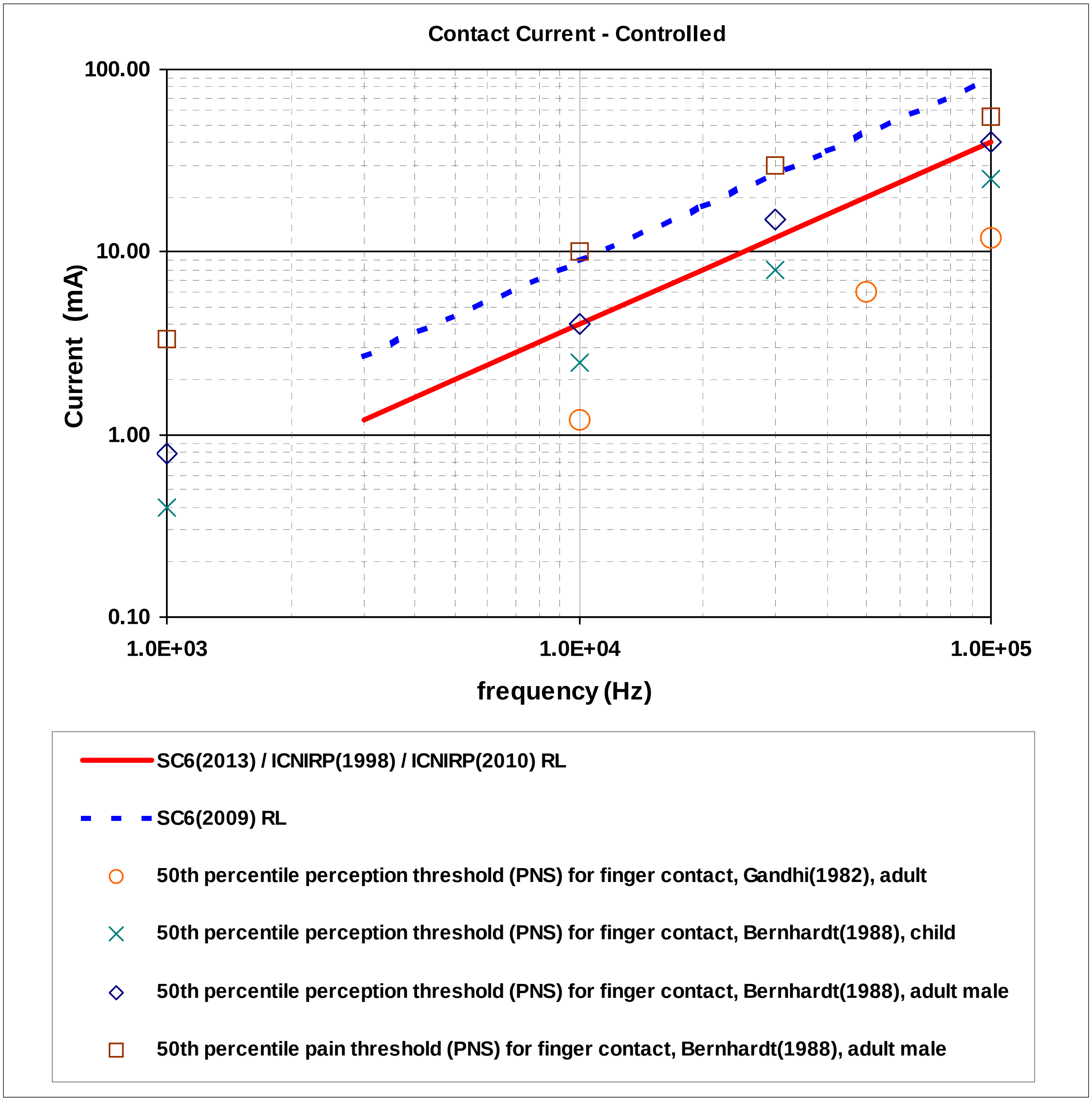

Figure 11. Proposed Controlled-Environment contact current reference levels for the 3 - 100 kHz frequency range in SC6 (2013). Also depicted are the 50th percentile perception threshold currents (adult and children) for finger contact.

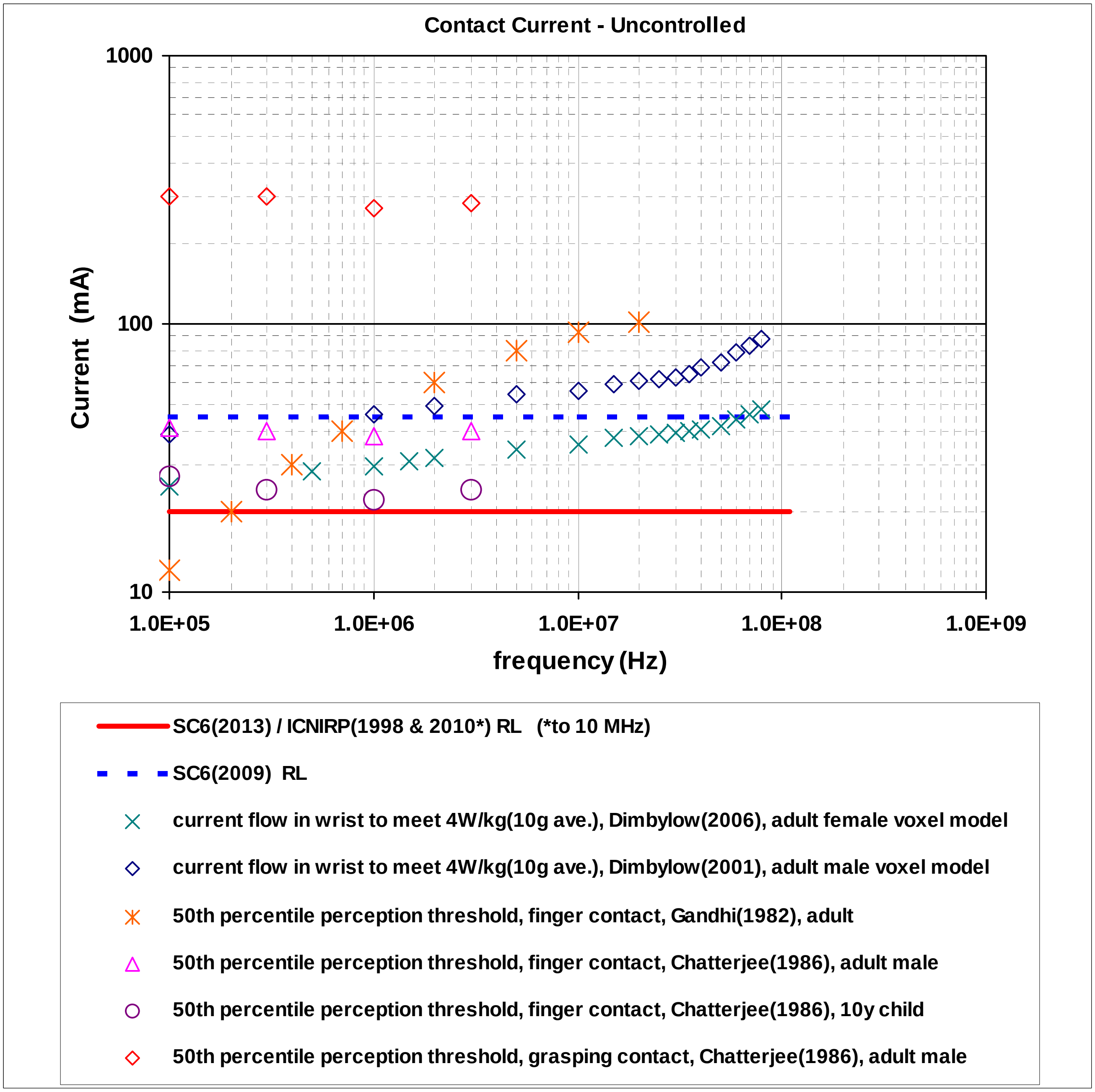

Figure 12. Proposed Uncontrolled-Environment contact current reference levels in SC6 (2013) in the 100 kHz – 110 MHz frequency range. Also plotted are the 50th percentile perception currents for finger-contact for adults and children, and the contact currents flowing in the wrist required to meet the basic restriction on peak spatially-averaged SAR in the limbs of 4 W/kg averaged over 10 g.

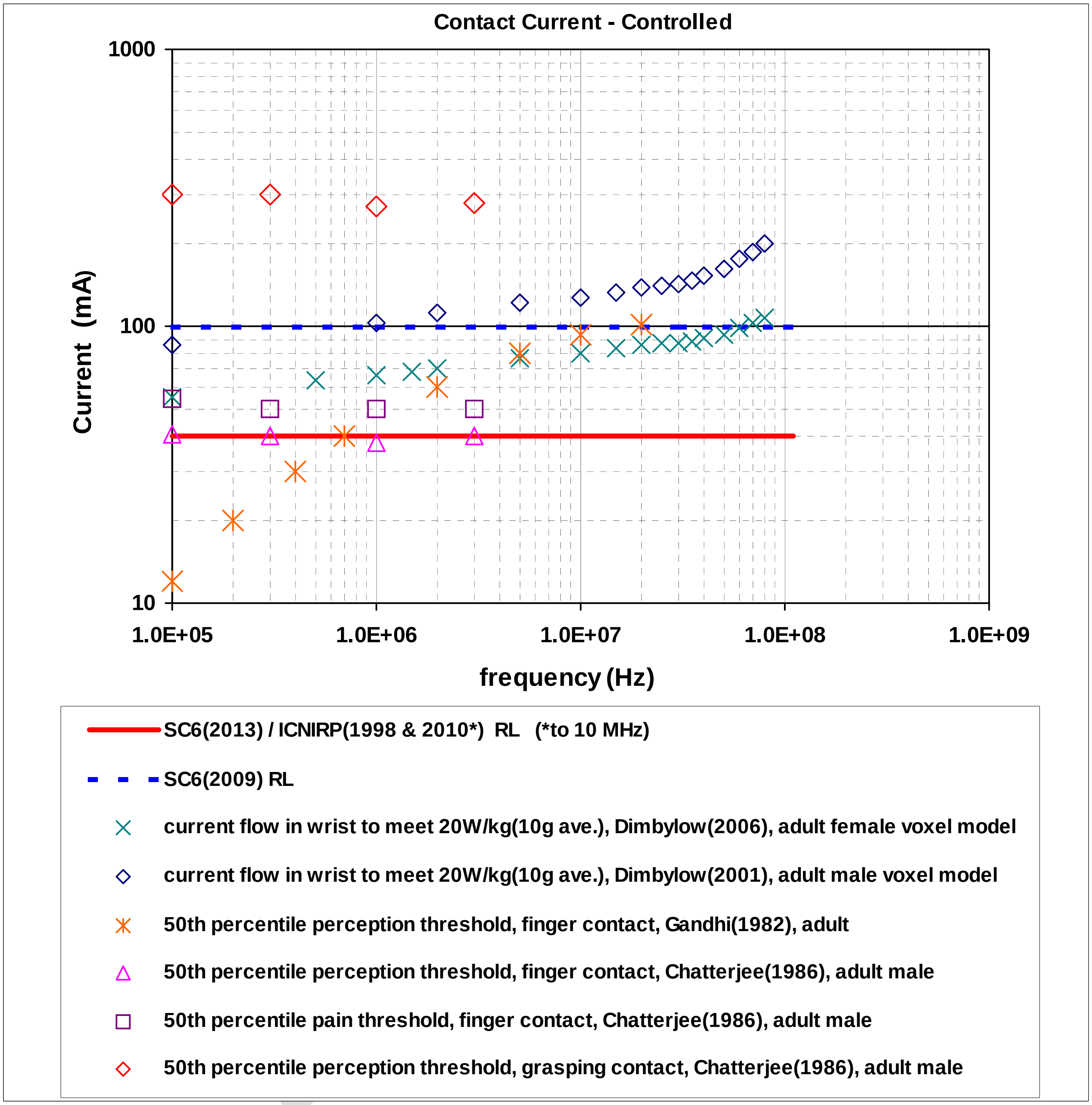

Figure 13. Proposed Controlled-Environment contact current reference levels in SC6 (2013) in the 100 kHz – 110 MHz frequency range. Also plotted are the 50th percentile perception currents for finger-contact for adults and children, the pain threshold for adults for finger contact, and the contact currents flowing in the wrist required to meet the basic restriction on peak spatially-averaged SAR in the limbs of 20 W/kg averaged over 10 g.

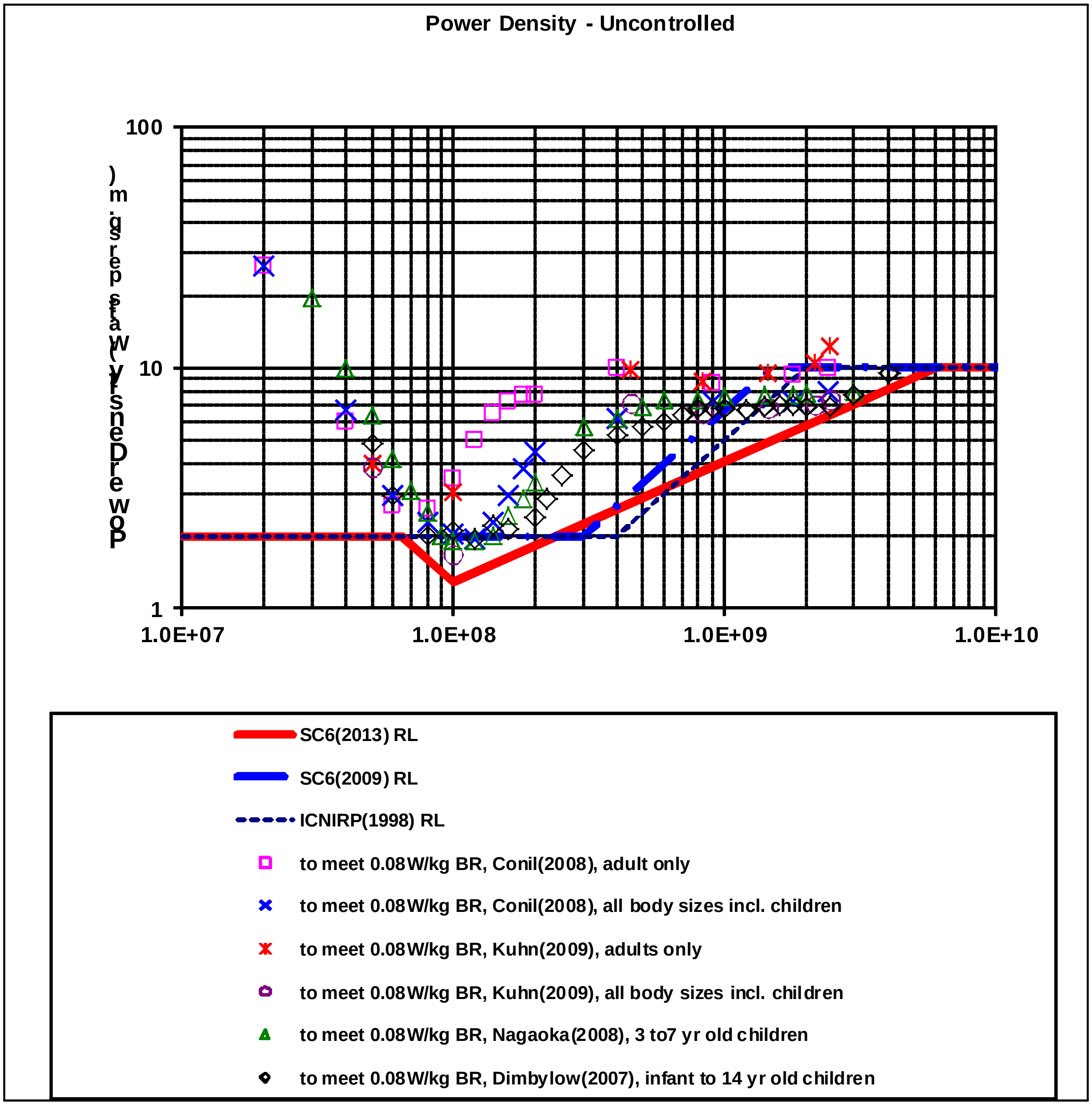

Figure 14. Proposed- and current SC6 Uncontrolled-Environment reference levels for Power Density with respect to frequency. Also shown is the amount of equivalent plane-wave power density required to produce a WBA-SAR of 0.08 W/kg for various body sizes including children and infants as young as 9 months old. These results are based on computational modelling using MRI-based whole-body voxel models.

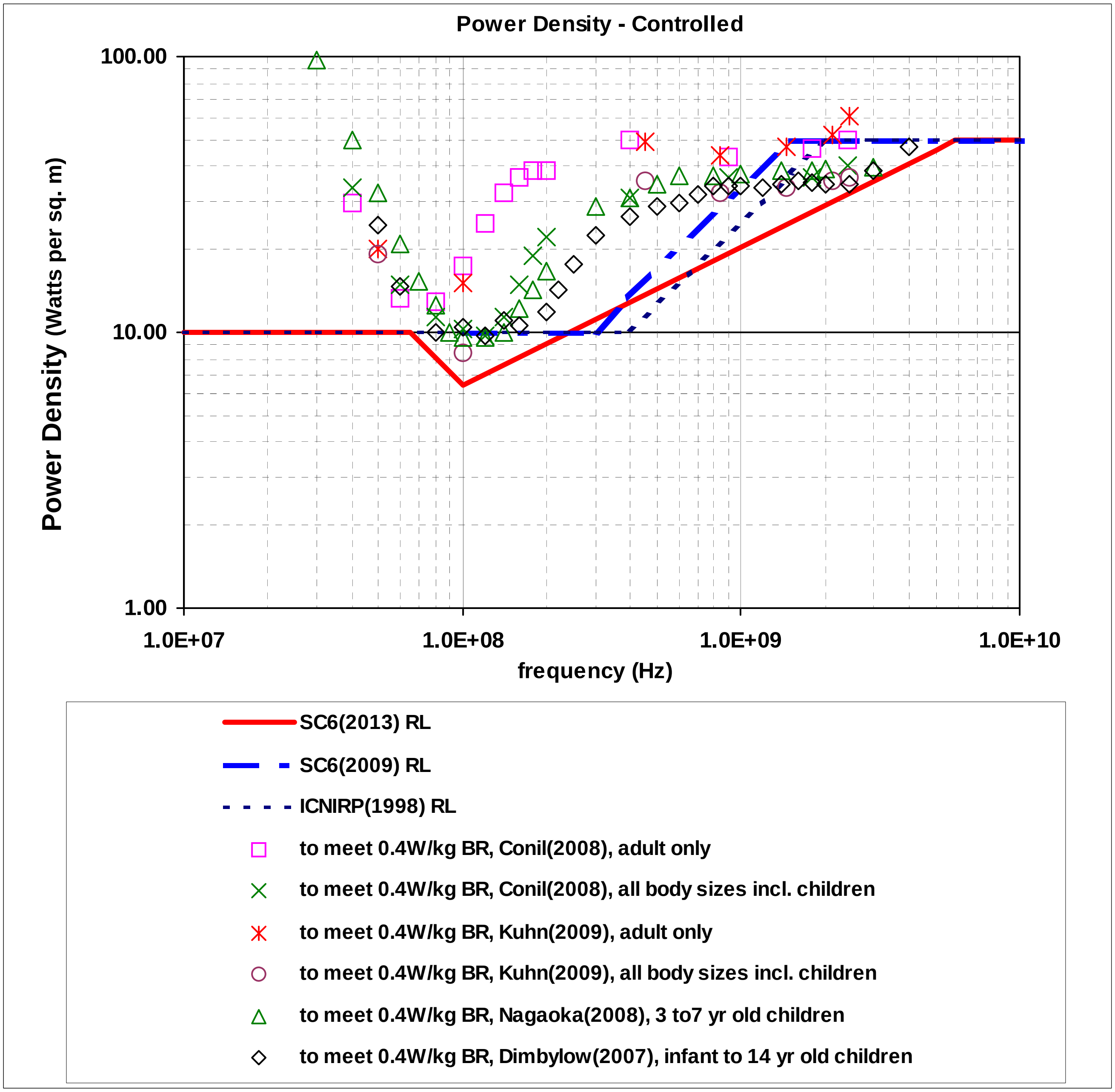

Figure 15. Proposed- and current SC6 Controlled-Environment reference levels for Power Density with respect to frequency. Also shown is the amount of equivalent plane-wave power density required to produce a WBA-SAR of 0.4 W/kg for various body sizes including children and infants as young as 9 months old. These results are based on computational modelling using MRI-based whole-body voxel models.

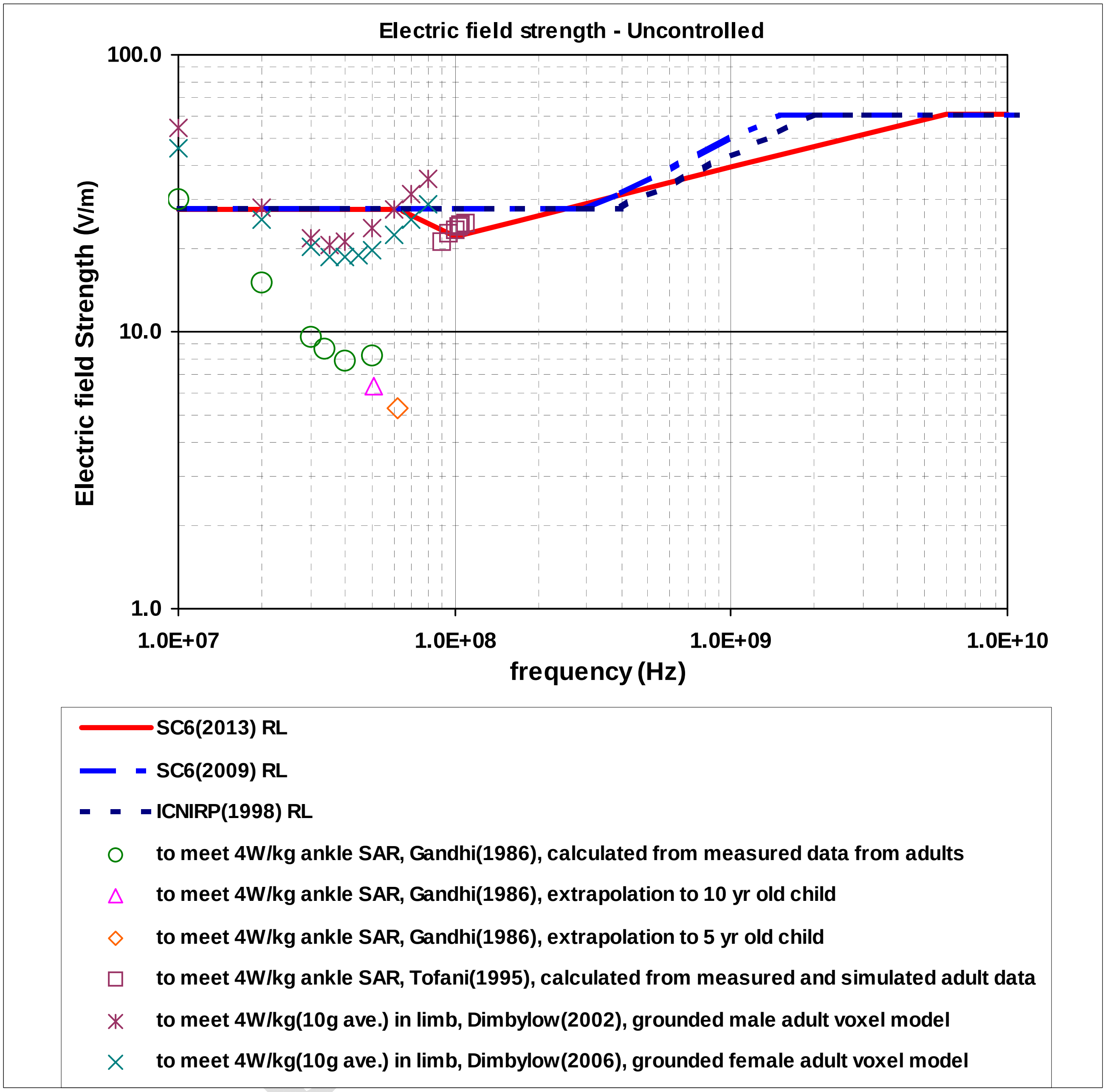

Figure 16. Proposed Uncontrolled Environment electric field strength reference levels and electric field strengths (vertically polarized, plane-wave) of sufficient intensity to produce limb SAR that meet the Uncontrolled Environment basic restriction of 4 W/kg in SC6 (2013).

Addendum to SC6 Rationale (2014)

Update of Uncontrolled Reference levels, 10 MHz – 6 GHz

As pointed out in the 2013 RSC Expert panel review, for specific circumstances, the proposed SC6 2013 reference levels did not provide the 50-foldmargin of safety for all population sub-groups in all exposure situations, as originally thought. In other words, meeting the reference levels for these specific cases did not assure compliance with the SC6 (2013) basic restrictions. It was shown that the proposed reference levels needed revision in two general areas:

1) *Arms up posture and Grounded, Whole-body Resonance*: Refers to subjects standing on the ground with their arms held vertically in the air and exposed to a plane wave from the front, where the electric field is aligned with the long axis of the body (Lee & Choi, 2012). In this exposure scenario, the whole-body SAR basic restrictions are exceeded at power density exposure levels below the proposed SC6(2013) reference levels in the frequency range where grounded, whole-body resonance occurs for subjects from 1 yr to 20 years old (approximately 30 -90 MHz).
2) *Isolated, Newborn Model:* In this scenario, a newborn female voxel model (height= 48.7 cm, mass=3.5 kg) is exposed to a variety of plane wave polarizations under isolated conditions. Calculations showed that the whole-body SAR basic restrictions are exceeded at power density exposure levels below the proposed SC6(2013) reference levels in the frequency ranges from 200-450 MHz and 700-1500 MHz.

As per the recommendations of the RSC Expert Panel, the field strength and power density reference levels in the frequency range 10 MHz to 6 GHz were revised to accommodate these exposure circumstances and are shown (as power density versus frequency) in Figure A-1. Also shown in the figure are various calculations of the power density required to yield the basic restriction for WBA-SAR in an uncontrolled environment derived from the dosimetric calculations published in the literature referenced in the RSC report. The formulas for calculating the revised reference levels as a function of frequency are given at the end of this addendum. Further details of the rationale for arriving at the revised reference levels are given below.

Whole–body Resonance, Children and Adults

As explained above, the term "whole-body resonance" is used to describe the peak in whole-body SAR versus frequency when the electric field is aligned along the long axis of the body (i.e. from head to toes). Whole-body resonance occurs for the whole continuum of proximities to the ground (i.e. from being completely isolated to standing directly on the ground). Generally, for the same subject, WBA-SAR at resonance is higher and the resonance frequency is lower for grounded conditions as opposed to isolated conditions. Whole-body resonance frequencies are dependent on the height of the subject and on grounding conditions. Taller subjects have lower resonance frequencies than shorter ones and grounded subjects of the same height have lower resonance frequencies than isolated ones. For the range of body sizes in the human population (tall adults to newborn infants) and the different possible grounding conditions, the range of resonance frequencies varies from approximately 35 MHz to over 200 MHz.

Since the coupling of RF power into the body is strong at whole-body resonance, the frequency range over which it occurs has the lowest external field strength reference levels. In addition to limiting WBA-SAR, the spatial peak SAR (averaged over 10 g) in the lower limbs is of concern for grounded, whole-body resonance. Induced current limits are specified for this purpose and were assumed (perhaps without sufficient supporting data) to protect also against non-compliance with the WBA-SAR basic restriction. With new data available from Hirata et al. (2012), this assumption was tested and is described further on within this addendum.

WBA-SAR and external field reference levels:

In the RSC Expert panel report, studies were described that indicated that exposures at the proposed SC6 (2013) reference levels in the whole-body resonance frequency range would be non-compliant with the WBA-SAR basic restrictions for children and adults under different exposure scenarios. The following table summarizes these findings:

Table A-1: RSC Expert Panel findings in the whole-body resonance frequency range:

Reference	Subject(s)	Condition	Posture	Non-compliance
Dimbylow (2002)	5yr, 10yr	grounded	Normal standing	Marginal
Findley (2009)	7yr	isolated	Standing, arms up	Marginal
Lee and Choi (2012)	7yr, adult	isolated	Standing, arms up	Marginal
Lee and Choi (2012)	1yr, 5yr, 7yr, adult	grounded	Standing, arms up	Significant

(Note: in the above table, the term “marginal’ implies a level of non-compliance to the WBA-SAR basic restriction of 10 % or less)

The last scenario, that of grounded subjects standing with arms up, suggests that the proposed SC6 (2013) reference levels should be revised. The data for the worst case amongst the different ages (i.e. lowest incident power density to produce the WBA-SAR basic restriction) for grounded, arms up (row 4 in Table A-1) is plotted in Figure A-1. Also plotted in Figure A-1 is data from Findley (2009) for a grounded 7yr with arms up posture. This data was not highlighted in the RSC report, but appears to corroborate the data in Lee and Choi (2012).

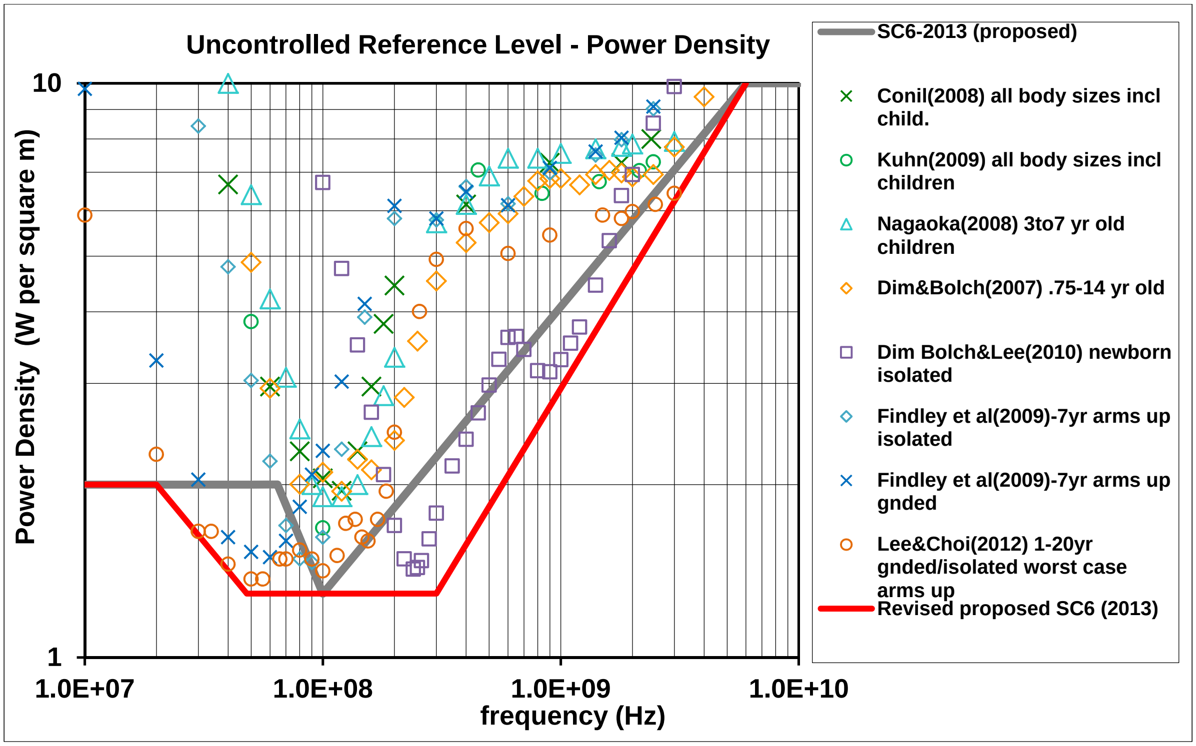

Figure A-1, Plane–wave power densities necessary to produce the WBA-SAR basic restriction of 0.08 W/kg in different voxel models under various exposure conditions. Also plotted are the originally proposed SC6 (2013) uncontrolled power density reference levels (grey line) and the revised power density reference levels (red line) resulting from suggestions made in the RSC report.

Lee and Choi (2012) show from their calculations that for the same aged voxel model, the “arms up” posture has the effect of increasing the WBA-SAR for the same incident power density and slightly decreasing the whole-body resonance frequency. The data in both Lee and Choi (2012), Findley et al. (2009) and others confirm that WBA-SARs at the whole-body resonance frequency are greatest for grounded conditions as opposed to isolated conditions.

The question therefore arises as to what other postures may possibly increase the resonant WBA-SAR further? Some clarity on this question is found in Hirata et al. (2012) where an empirical relationship between the WBA-SAR at grounded, whole-body resonance and body mass index (BMI) is derived. Their analysis shows that the ratio of the WBA-SAR to incident power density (at grounded, whole-body resonance) is directly proportional to the square of the individuals height divided by his or her body mass. Since BMI is defined as the mass divided by the square of the height, the maximum WBA-SAR attained at grounded, whole-body resonance is entirely proportional to the inverse of the BMI. This would suggest that thin individuals (low BMI) have the highest WBA-SARs at resonance per unit incident power density than heavier persons of the same height.

This relationship also helps to explain the results of Lee and Choi (2012), since raising the arms can be seen as a means of increasing the overall body height without increasing the mass (i.e. lowering the effective BMI). In terms of answering what other postures may increase the WBA-SAR at grounded resonance, the relationship observed by Hirata et al. (2012) suggests that postures that reduce the overall height are likely to reduce the WBA-SAR and that the posture with arms up is likely the worst-case scenario.

Having a formula for predicting the WBA-SAR for grounded, whole-body resonance allows the use of population BMI statistics to predict an upper bound WBA-SAR for a given percentile of the population's BMI distribution. Hirata et al. (2012) presents the upper bound of WBA-SAR per incident power density level for the 2.5th percentile of the Japanese population versus age (Figure 8 in Hirata 2012). The ages with the lowest BMI are in the 5yr to 7yr age range and result in an upper bound of approximately 0.06 W/kg per W/m^2. This value, when translated to a power density reference level, implies that over the grounded whole-body resonance frequency range and with an "arms down" posture, the power density limit should be 1.3 W/m^2. The revised proposed SC6 (2013) reference level in this frequency range is 1.29 W/m^2 which compares favourably with the value extracted from Figure 8 in Hirata, 2012.

A final point to consider is what happens when an individual with low BMI is standing either isolated or grounded with the arms up posture. Lee and Choi present calculations for 1yr, 5yr and 20yr models that have arms up and have been modified to approximately conform to the 10th percentile of the US population in terms of BMI (Figure 2 in Lee and Choi, 2012). The highest WBA-SAR at whole-body resonance is for the isolated 5yr model. The value of reference level power density that would confer compliance to the 0.08 W/kg BR for this case is 1.29 W/m^2, which is also the revised reference level in the 48-300 MHz range in SC6 (2014).

Applicability of induced current reference levels as a proxy for meeting WBA-SAR basic restriction:

As pointed out in several places in the RSC review (for instance, page 79), reliance that meeting the induced current reference level implied compliance with the WBA-SAR basic restriction was perhaps somewhat unjustified considering the paucity of data available. Data in Hirata et al. (2012) allows this assumption to be tested for a limited number of grounded body models with their hands at their sides (normal posture; these body models are somewhere near the 50th percentile BMI in their respective age classes). Hirata et al. (2012) presents values of the "vertical component of the conduction current ... at their respective resonance frequencies" for 3yr, 7yr, adult female and adult male (all Japanese models). If the induced current (i.e. leg current) is assumed to be primarily made-up of the vertical conduction current then the response of this reference level quantity can be compared to the WBA-SAR basic restriction at the same exposure level. The results are tabulated in Table A-2.

Table A-2, Grounded, whole-body (WB) resonance frequencies, original SC6(2013; before RSC review) power density reference levels (RLs), revised SC6(2014; after RSC review) power density RLs, fraction of the induced current RL and fraction of the WBA-SAR basic restriction (BR) for 3yr, 7yr, adult female and adult male body models from Hirata et al. (2012).

	Grounded WB resonance freq. (MHz)	Original SC6(2013) Power Density RL (W/m^2)	Revised SC6(2014) Power Density RL (W/m^2)	Fraction of Induced Current RL (0.08A, both feet) for		Fraction of WBA-SAR BR (0.08W/kg) for	
				Exposure at original power density RL (%)	Exposure at revised power density RL (%)	Exposure at original power density RL (%)	Exposure at revised power density RL (%)
Adult male	39	2.0	1.43	200	169	101	72
Adult female	45	2.0	1.33	150	122	91	60
7yr	61	2.0	1.29	113	90	122	79
3yr	85	1.52	1.29	71	65	91	77

Note: Induced current is proportional to the electric field strength or the square root of the power density while WBA-SAR is proportional to the square of the electric field strength or to power density directly.

Adult male and Adult female: The fraction of the induced current RL exceeds the fraction of the WBA-SAR BR for exposure to both the original and revised reference level power densities. Thus, the induced current is the more restrictive quantity for both the original and revised power density RLs and complying with the induced current RL confers compliance to the WBA-SAR BR.

7yr: For the original power density RL, compliance for the induced current also confers compliance for the WBA-SAR since the reduction in power density to comply with the induced current RL is 78% while the reduction required to comply with the WBA-SAR BR is 82%. For the revised power density RL, both are in compliance for exposure at the reference level power density, however, if the exposure level is increased such that the induced current RL is reached, the WBA-SAR will still be in compliance. Thus, for this case, compliance to the induced current RL confers compliance to the WBA-SAR BR.

3yr: For the original and revised power density RLs, both the induced current and WBA-SAR are in compliance for exposures equal to their respective reference level power densities. However, if the exposure level is increased such that the induced current RL is reached, the WBA-SAR will not be in compliance. For both the original and revised limits, compliance to the induced current RL does not confer compliance to the WBA-SAR BR.

To summarize these findings, for grounded adults and probably larger children at their respective resonance frequencies, compliance to the WBA-SAR BR does not confer compliance to the induced current RL (or likely the spatial-peak 10g average SAR in the lower limbs for which the induced current RL is intended to protect against). This is the case for both the original and revised SC6 (2013) RLs. For this reason, induced current measurements are advised at whole-body resonance frequencies of adults and large children when the exposure field levels begin to be an appreciable fraction of the RL. Conversely, if the induced current limits are respected then the WBA-SAR BRs will also likely be respected.

For smaller children under the same type of exposure conditions, both the WBA-SAR and induced current are likely to be in compliance at reference level power densities. This can partly be explained by the relationship between induced current and body height as pointed out in Gandhi et al. (1985) where the induced current is proportional to the square of the height. Shorter subjects will experience dramatically lower induced currents than taller ones for the same exposure conditions unlike WBA-SAR, which is dependent only on the reciprocal of the BMI. Height plays only a partial role in determining the WBA-SAR at resonance. For small children, there is probably no need to measure the induced current if the power density limits are respected. However, these conclusions are based on a small data set pertaining to average BMI subjects.

Isolated Newborn

The power density levels required to produce the WBA-SAR basic restriction are plotted in Figure A-1 as purple squares. The data is a composite of the worst case (i.e. lowest power density) of a number of polarizations and incidences (i.e. front-to-back, side-to-side, top-to-bottom etc.). There is a primary resonance at approximately 240 MHz and a secondary one at approximately 900 MHz. The primary resonance is a case of isolated, whole-body resonance where the electric field is parallel to the long axis of the body (Dimbylow et al., 2010). In Figure A-1 it can be seen that these two resonances represent significant non-compliance to the originally proposed SC6 (2013) reference levels.

The question arises as to whether the revised power density RLs in SC6 (2014) are sufficiently restrictive to cover WBA-SAR data from potential, yet to be developed, newborn models or postures. Since isolated whole-body resonance occurs at higher frequencies than grounded whole-body resonance, isolated whole-body resonance of newborns will likely form the upper frequency limit for this phenomenon. It has been demonstrated that the frequency of isolated whole-body resonance occurs when the body height is equal to 0.39 (±0.01) of the free space wavelength (Hirata, 2010). Thus shorter newborn models could potentially have higher resonant frequencies than the one in Dimbylow et al. (2010). The flat portion of the revised reference levels in SC6 (2014) extend to 300 MHz, which could accommodate a model 20% shorter than the one in Dimbylow et al. (2010).

In terms of the WBA-SAR at resonance, Hirata et al. (2010) has developed a formula for estimating WBA-SAR for isolated whole-body resonance that is similar to the one derived for grounded whole-body resonance (Hirata 2012). The main feature of this formula is that WBA-SAR per unit incident power density is again proportional to the reciprocal of the BMI (specifically, WBA-SAR/S_{inc} =0.752/BMI where S_{inc} is the incident power density). The resonant WBA-SAR for the Dimbylow et al. (2010) newborn predicted by this formula is 11% lower than the calculated value for the voxel model. Thus newborn models with lower BMI may possibly yield higher WBA-SAR at resonance. This might also include newborn models with an “arms up” posture.

To gain some insight on how much the “arms up” posture might increase the WBA-SAR of the newborn, the data in Lee and Choi (2012) was used to calculate the increase in WBA-SAR caused by raising the arms for isolated resonance amongst the 4 voxel models used in that study. The WBA-SAR increase was 13%, 20%, 19% and 36% for the 1yr, 5yr, 7yr and 20yr models, respectively. The revised limits shown in Figure A-1 can accommodate an increase in WBA-SAR of the newborn of 10% before a state of non-compliance arises. This is commensurate with the increase in WBA-SAR with "arms up" for the 1yr model in Lee and Choi (2012), but below those for the larger models.

More importantly than accommodating for the "arms up" posture, the revised limits can only accommodate a 10% reduction in BMI of the newborn. To investigate further, data for the 5th percentile BMI of newborns versus gestational age were obtained from Brock et al. (2008) and are given in Table A-3. Also shown in the table are the WBA-SAR per unit incident power density calculated using the estimation formula in Hirata (2010) for isolated, whole-body resonance and the power density reference level that would be required to comply with the 0.08 W/kg basic restriction.

Table A-3, Fifth percentile BMI of Brazilian newborns (male and female) for gestational ages 29, 36 and 42 weeks, WBA-SAR per unit incident power density (S_{inc}) estimated using the formula in Hirata (2010) for isolated, whole-body resonance and power density RL to comply with the 0.08 W/kg BR.

Gestational age **weeks**	**5th percentile BMI (male) kg/m^2**	**5th percentile BMI (female) kg/m^2**	**Greater of the Male or female WBA-SAR/S_{inc} W/kg per W/m^2**	**Required PD RL to Maintain 0.08 W/kg W/m^2**
29	7.31	7.32	0.103	0.78
36	11.14	11.30	0.0675	1.19
42	12.56	12.25	0.0614	1.30

The uncontrolled power density RL in the whole-body resonance frequency range is 1.29 W/m^2 in SC6 (2014), which is compliant with the 0.08 W/kg BR for 42 week gestational age (5th percentile BMI). For the younger gestational ages 29 and 36 weeks, the power density RL does not afford the same level of safety margin (e.g. less than 50-fold). Using the Hirata (2010) formula, a critical value of BMI can be calculated such that the 0.08 W/kg BR is complied with at the RL power density of 1.29 W/m^2. This value is 12.13 kg/m^2. The data in Brock et al. (2008) was searched to find the percentile BMI that is compliant at the various gestational ages. The results for males is plotted in Figure A-3 (female results are similar). Note that some interpolation of the data in the tables in Brock et al. (2008) was necessary.

The interpretation of the curve in Figure A-3 is that, for a given gestational age, the curve defines the smallest percentile of BMI that is still compliant. All percentile BMI values below the curve are non-compliant in the sense that the WBA-SAR will exceed 0.08 W/kg at an exposure equal to 1.29 W/m^2 for isolated, whole-body resonance at the resonant frequency. For instance, at 35 weeks gestational age, newborns having BMI equal to or greater than the 50th percentile value will be in compliance.

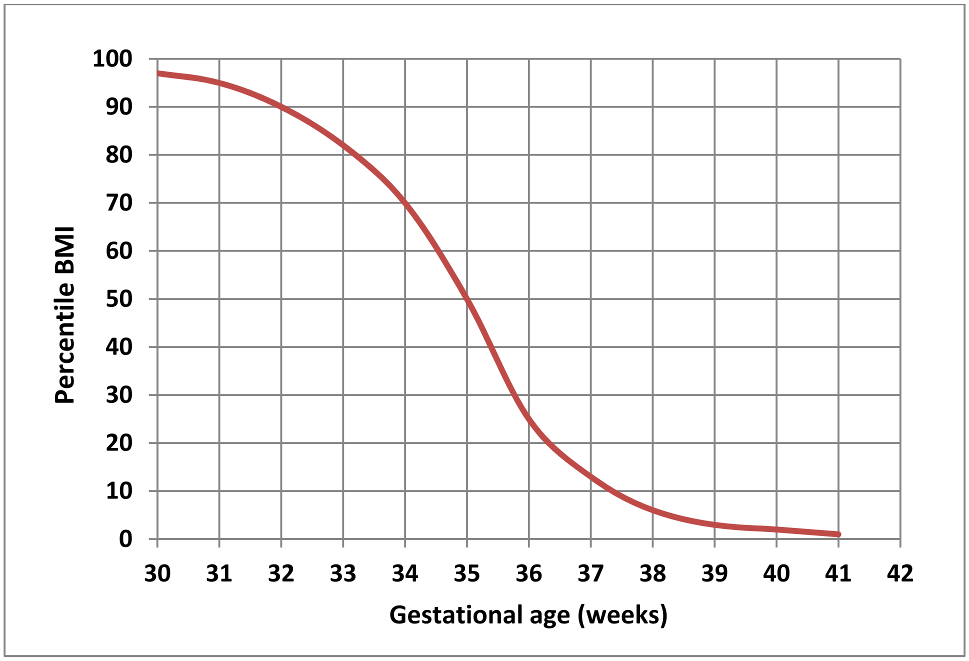

Figure A-3 Percentile BMI versus gestational age for which the power density RL of 1.29 W/m^2 is compliant with the 0.08 W/kg basic restriction based on the isolated, whole-body resonance formula in Hirata (2010).

It should be pointed out that the estimation formula in Hirata (2010) is approximate and that the discrepancy of it versus the SAR calculation of the newborn model in Dimbylow et al. (2010; having a BMI of 14.8 kg/m^2) is an underestimation of 11%. Thus the information in Table A-4 and Figure A-3 should be treated with some caution. However, it can be used to arrive at some qualitative conclusions, the most important of which, is the likelihood that any future calculations of WBA-SAR on models of premature newborns will likely produce non-compliance of the revised power density reference levels to the basic restriction. This cannot be prevented without a further reduction of the power density reference levels at the frequencies of isolated, whole-body resonance. If the revised power density RLs are kept as is, then one can only say that the reference levels provide the full margin of safety (50-fold) for most of the population, but not for all population sub-groups (e.g. low BMI newborns) in all worst-case exposure scenarios. The portion of the population that does not receive the full measure of the intended safety margin (50-fold) is a small one, consisting of low BMI, premature newborns who would be unlikely to be exposed to levels of power density anywhere near the SC6 reference levels, anyway.

Update of Controlled Reference levels, 10 MHz – 6 GHz

The same data that was used to justify the revisions to the uncontrolled reference levels can also be used as a basis for revisions to the controlled environment reference levels. In this case, however, it was decided to exclude data pertaining to body sizes smaller than 7yr since it was felt that this body height (and associated BMI) was a conservative lower bound for adults of short stature. Figure A-2 shows much of the same data in Figure A-1 except scaled to a WBA-SAR of 0.4 W/kg, the controlled basic restriction. The only exceptions are that the data from Findley (2009) and Lee and Choi (2012) only include data for body sizes 7yr and up. Plotted points for the other references contain some data for smaller size bodies but their inclusion does not impact the changes to the RLs required for the whole-body resonance region below 100 MHz.

The revised controlled RLs follow the same slopes and transitional frequencies as the uncontrolled RLs up to 100 MHz. Up to this frequency, the ratio of controlled to uncontrolled PD maintains a value of 5, which is the same as the ratio of the basic restrictions. From 100 MHz to 6000 MHz, the revised controlled environment RLs follow the originally proposed RLs. In this range, the ratio of the two RLs (controlled and uncontrolled) is no longer maintained at 5, but is frequency dependent. At 6000 MHz, both RLs begin to be flat with frequency and again, maintain a ratio of 5.

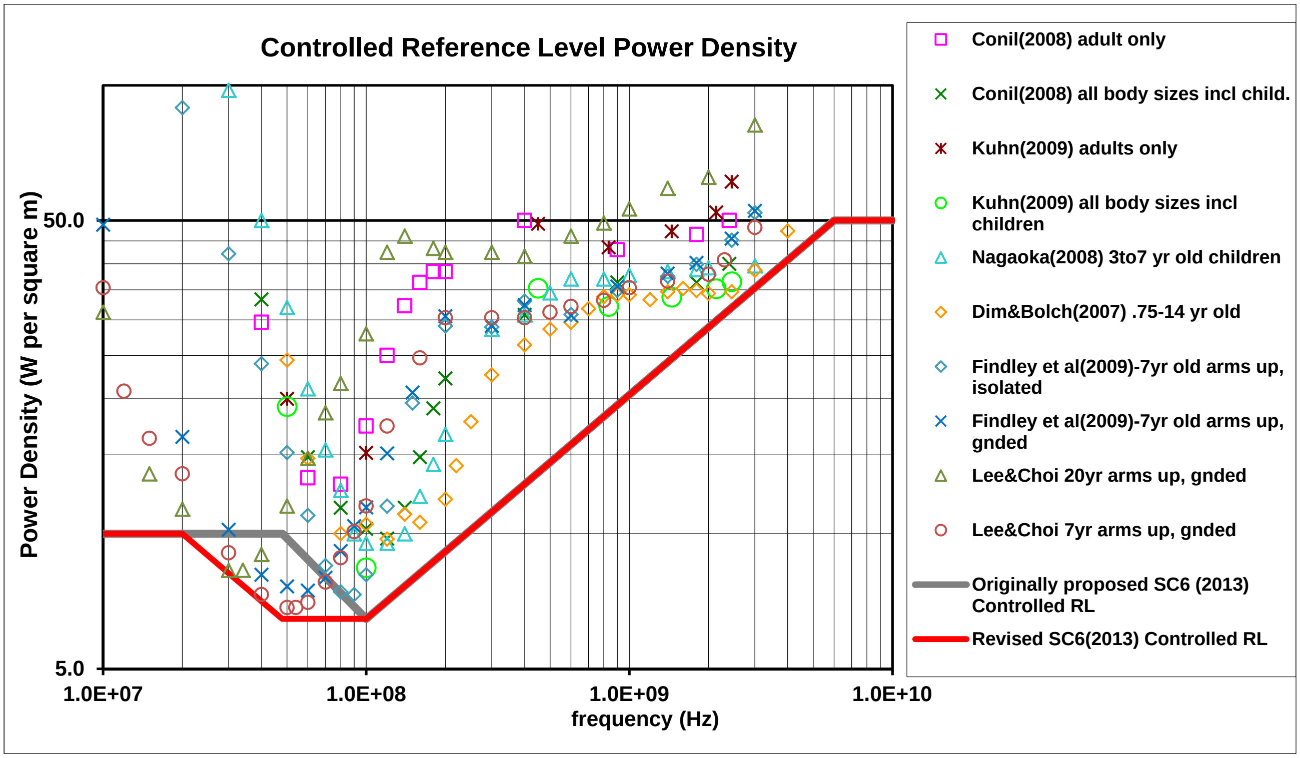

Figure A-2, Plane–wave power densities necessary to produce the WBA-SAR basic restriction of 0.4 W/kg in different voxel models under various exposure conditions. Also, the originally proposed SC6 (2013; grey line) controlled power density reference levels and the revised SC6 (2014; red line) power density reference levels resulting from suggestions made in the RSC report.

Table A-4. Revised Reference Levels for Electric Field Strength, Magnetic Field Strength and Power Density in Uncontrolled Environments

Frequency (MHz)	Electric Field Strength (E_{RL}), (V/m, RMS)	Magnetic Field Strength (H_{RL}), (A/m, RMS)	Power Density (S_{RL}), (W/m^2)	Reference Period (minutes)
10 – 20	27.46	0.0728	2.00	6
20 – 48	$58.07 / f^{0.25}$	$0.1540 / f^{0.25}$	$8.944 / f^{0.50}$	6
48 – 300	22.06	0.05852	1.291	6
300 – 6000	$3.142 f^{0.3417}$	$0.008335 f^{0.3417}$	$0.02619 f^{0.6834}$	6
6000 –15000	61.4	0.163	10	6
15000 – 150000	61.4	0.163	10	$616000 / f^{1.2}$
150000 – 300000	$0.158 f^{0.5}$	$4.21 \times 10^{-4} f^{0.5}$	$6.67 \times 10^{-5} f$	$616000 / f^{1.2}$

- Frequency, *f*, is in MHz.

Table A-5. Revised Reference Levels for Electric Field Strength, Magnetic Field Strength and Power Density in Controlled Environments

Frequency (MHz)	Electric Field Strength (E_{RL}), (V/m, RMS)	Magnetic Field Strength (H_{RL}), (A/m, RMS)	Power Density, (S_{RL}), (W/m^2)	Reference Period (minutes)
10 – 20	61.4	0.163	10.0	6
20 – 48	$129.8 / f^{0.25}$	$0.3444 / f^{0.25}$	$44.72 / f^{0.5}$	6
48 – 100	49.33	0.1309	6.455	6
100 - 6000	$15.60 f^{0.25}$	$0.04138 f^{0.25}$	$0.6455 f^{0.5}$	6
6000 – 15000	137	0.364	50	6
15000 – 150000	137	0.364	50	$616000 / f^{1.2}$
150000 – 300000	$0.354 f^{0.5}$	$9.40 \times 10^{-4} f^{0.5}$	$3.33 \times 10^{-4} f$	$616000 / f^{1.2}$

- Frequency, *f*, is in MHz.

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