Safety Code 6 (2015) –Rationale

Most radiofrequency (RF) field exposure standards express exposure limits in terms of basic restrictions (internal dose quantities) and reference levels (externally applied field strengths or internal body currents). The role of reference levels is to provide an easily measured or calculated field strength or body current that can be used as a reference to judge whether the basic restrictions are exceeded or not. Reference levels prescribe the lowest possible external field strength or body current that produces the basic restriction in the body for the worst case body size and exposure condition (e.g. polarization of the field, grounding of the body, etc.). Standards often make note of the fact that since reference levels are derived from the worst-case conditions, non-compliance with them does not always imply non-compliance with the basic restrictions. Sometimes a further analysis of the specific exposure conditions confirms the basic restrictions are adhered to, despite the reference levels being exceeded.

This document provides an overview of the rationale for the basic restrictions and reference levels within the revised version of Safety Code 6 (SC6, 2015). 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. Such reviews have been recently conducted by other groups (SCENIHR, 2013; AGNIR, 2012; ANSES, 2013; WHO Draft Monograph on RF fields, 2014). 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 magnetic fields. Basic restrictions in this frequency band are specified for electric field strength within the body (internal). 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 specified 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 specified 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 (2015) are intended to protect against all established adverse health effects from electromagnetic radiation in the frequency range 3 kHz – 300 GHz. In the WHO Framework for the Development of EMF Standards (2006), adverse health effects 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 justified, SC6 (2015) has been harmonized with applicable international standards.

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

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 (e.g. 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 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 internal electric field strength threshold for perception of PNS (tingling sensation) to be 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 (Ham et al., 1997; Bourland et al., 1999; Nyenhuis et al., 2001; Den Boer et al., 2002; Zhang et al., 2003; Recoskie et al. 2009). The avoidance of PNS perception serves as the basis for the basic restrictions and reference levels in SC6 (2014).

Magnetic Field PNS-based reference levels and basic restrictions 3kHz-10 MHz

The process of development for most electromagnetic exposure standards is to first derive a basic restriction (in this case, the induced electric field strength in tissue or E_i) that incorporates reduction or safety factors below the threshold for effect. This is followed by development of a reference level (in this case the externally applied magnetic flux density B or magnetic field strength H) that is found from dosimetric analysis (dosimetric analysis can be defined as the estimation of induced electric field strength in the body due to an externally applied magnetic flux density) to determine the flux density that produces the basic restriction.

Historically,PNS-based basic restrictions are developed from empirical data for nerve stimulation from MRI-based human volunteer studies or from in-vitro studies on isolated nerves. In the case of the former, threshold stimulation data is obtained in the form of time-rate-of-change of external magnetic flux density (dB/dt) that human volunteers were exposed to. This data can then be converted into internally–induced electric field strength (the dose quantity) through a dosimetric analysis. Using this approach, dosimetric analysis (modelling) is used (in two stages) when going from the empirical dB/dt data to a basic restriction for E_i and then back again to a reference level for B. Alternatively, basic restrictions have also been developed from electrical threshold data (voltages, currents and electric field strengths) from studies of isolated nerves. Since the dose quantity is applied directly to the nerve, this approach is independent of dosimetric analyses.

Dosimetric analyses or induction modelling has been carried out using a number of computational methods and models. Methods include numerical algorithms such as the scalar potential finite difference (SPFD), quasi-static finite difference time domain (FDTD), finite element and moment methods. Sophisticated models have been developed in the form of realistic 3-dimensional voxel representations of various human body sizes with conductivity assigned to each voxel. In addition to numerical algorithms, induction modelling applied by some organizations have been carried out using Faraday's law applied to simple homogeneous structures such as loops and ellipsoids (IEEE C95.1, ICNIRP 1998).

In general, induction modelling attempts to find the maximum sinusoidal induced electric field strength in the model for a given external sinusoidal magnetic flux density. In most cases, some form of averaging or filtering algorithm is applied to the induced electric field (as either required by an exposure standard or applied by the authors of scientific studies) in order to smooth numerical artefacts. Methods particularly prone to this type of artefact are ones based on finite differences where larger than expected induced electric field strengths occur at the interface of voxels with high conductivity contrast with respect to neighbouring ones (sometimes called "stair-casing error").

The parameter that defines the result of a dosimetric analysis or induction modelling is the induction coefficient C_i given by:

$$C_i = \frac{E_i}{f\ B_{ext}} \tag{1}$$

where E_i is the maximum induced electric field strength in the body or organ of interest (after averaging or filtering) in units of V/m, B_{ext} is the externally applied magnetic flux density in units of T (Tesla) and f is the frequency in Hz (Hertz or cycles per second). The induction coefficient has units of (V/m) per (Hz-T) or (V/m) per (T/s) and is usually frequency independent except where the conductivity in the model changes with frequency. In this case, the change of C_i with frequency is very gradual, in line with the gradual change of tissue conductivity with frequency.

The induction coefficient is useful for calculating a reference level flux density from the basic restriction electric field strength or vice versa by the appropriate manipulation of (1). A review of computational dosimetric analyses was carried out and induction coefficients judged to be representative of worst-case exposure scenarios were calculated from the published results. This is summarized in Table 1 below in terms of the worst-case 99th and 100th (or maximum) percentile induction coefficients found in the studies. The 99th percentile is calculated by using the level of induced electric field strength exceeded by only 1% of the voxels or discrete averaging volumes in the tissue. The 100th percentile is calculated using the maximum averaged E_i in the tissue of interest. Filtering by choosing the 99th percentile value is used by many authors and is specified in the ICNIRP 2010 standard as a means of dealing with stair-casing errors.

Table 1. Summary of worst-case 99th percentile and 100th percentile (maximum) induction coefficients using various anatomical modelling results:

Author(s)	Induction Coefficient (V/m per Hz-T)		Model Grid (mm)	Skin cond. (S/m)	Comments
	99th %tile	100th %tile			
Dimbylow (2005)	1.02	2.6	2	0.1	-adult male & female
So et al., (2004)	1.28	4.7	3.6, 2	0.1	-used non-uniform exposure field, adults only
Schmid et al., (2013)	0.90	3.0	1	0.1	-10 yr old female model
	0.75	88.0	1	0.0002	-10 yr old female model
Bakker et al., (2012)	3.1	N/A	2	0.0002	-6 yr old male model
Caputa et al., (2001)	1.63	19.3	2	0.0002	-76 kg male model
	1.68	22.5	2	0.0002	-104 kg male model

ICNIRP 2010	1.20	n.a.	n.a.	-value used in the derivation of magnetic flux density reference levels
IEEE 2005	1.03	n.a.	n.a.	-obtained from homogeneous ellipsoidal model. Used in the derivation of reference level.

n.a.- not applicable, N/A – not available

As can be observed from Table 1, the induction coefficients derived from the various induction modelling studies outlined above are variable and known to be influenced by voxel (grid) size, numerical modelling procedures, body model size, applied conductivity parameters and tissues chosen as part of the modelling exercise, among others. With the exception of the results of Bakker et al., (2012), the 99th percentile induction coefficients ranged from 0.75 to 1.68 V/m per Hz-T, with a mean of approximately 1.2.

Derivation of magnetic flux density reference level

For the frequency range applicable to SC6 (i.e. greater than 3 kHz), the IEEE C95.1-2005 and ICNIRP 2010 standards specify the basic restriction for induced electric field strength in the form:

$$\mathrm{E_{BR}}(f) = \frac{\mathrm{E_o}}{\mathrm{K}}\frac{f}{f_\mathrm{e}} \quad \text{for} \quad f \geq f_\mathrm{e} \tag{2}$$

where E_o is the rheobase threshold induced electric field strength, K is a safety or reduction factor (reduction factors are typically 5 or 10 depending on the protected population group) and f_e is the transition frequency beyond which, the basic restriction has a linear dependence on frequency. For example, the ICNIRP 2010 general public basic restriction has E_o/Kf_e =1.35 x 10^{-4} V/m/Hz, K = 10 and f_e = 3000 Hz.

The flux density reference level can be calculated by rearranging (1) to give:

$$\mathrm{B_{RL}} = \frac{\mathrm{E_{BR}}}{f\,\mathrm{C_i}} = \frac{\mathrm{E_o}/\mathrm{K}f_\mathrm{e}}{\mathrm{C_i}} \tag{3}$$

It can be seen from (3) that the large disparity of induction coefficients obtained through induction modelling would lead to a wide variation in derived reference levels. In addition, ICNIRP 2010 specifies So et al. (2004) as its reference for its adopted value of E_o = 4 V/m. The study of So et al. (2004) was essentially a dosimetric analysis of induced electric fields in 3 different realistic anatomical voxel models exposed to MR gradient coils. So et al. (2004) used their calculated induction coefficients obtained from induction modelling to convert empirical, rheobase threshold dB/dt data from Den Boer et al. (2002) into a rheobase threshold electric field strength E_o. Thus, the steps in going from the original empirical dB/dt data to the calculation of a reference level B in ICNIRP 2010, ultimately relied upon two dosimetric modelling steps.

An alternate approach to the derivation of flux density reference levels that does not rely on dosimetric analysis is based on the strength-duration relationship for electro-stimulation of nervous tissue written in terms of dB/dt (Den Boer et al. 2002) as:

$$\left(\frac{\mathrm{dB}}{\mathrm{dt}}\right)_{\mathrm{Th}} = \left(\frac{\mathrm{dB}}{\mathrm{dt}}\right)_{\mathrm{Rh}} \left(1 + \frac{\tau_{\mathrm{e}}}{\mathrm{t_p}}\right) \tag{4}$$

where $(dB/dt)_{Th}$ is the nerve stimulation threshold as a function of stimulus duration t_p , τ_e is the "chronaxie" or SD time constant and $(dB/dt)_{Rh}$ is the rheobase time-rate-of-change of the magnetic flux density B(t).

Relationship (4) has been found to accurately describe the empirical threshold response in a wide range of experimental studies on human volunteers using magnetic resonance imaging (MRI) gradient systems and other means of magnetically-induced electro-stimulation (Den Boer et al., 2002; Bourland et al., 1999; Recoskie et al., 2009). Rheobase thresholds and chronaxie times vary for different nervous tissue types (Reilly 1998) and for different individuals.

Reference levels are usually derived for exposure to continuous sinusoidal fields while the relationship (4) is obtained from so-called "trapezoidal" waveforms of B(t) consisting of ramps of duration t_p followed by flat-topped plateaus. To derive a reference level, it is assumed that the stimulus waveform for which the parameters in (4) were found, consists of a triangular wave with stimulus duration $t_p = T/2 = 1/2f$, where T is the period and f is the frequency of the waveform. A sinusoidal flux density with amplitude B_o and the same frequency f will have its maximum derivative equal to $2\pi f B_o$. Equating the maximum derivative of the sinusoid to the nerve stimulation threshold in (4), divided by a reduction factor K, gives:

$$2\pi f \mathrm{B_o} = \frac{1}{\mathrm{K}}\left(\frac{\mathrm{dB}}{\mathrm{dt}}\right)_{\mathrm{Rh}} (1 + 2f\,\tau_{\mathrm{e}}) \tag{5}$$

The peak sinusoidal flux density B_o in (5) is equivalent to a peak sinusoidal reference level since it should not be exceeded by an environmental field. As is customary in most standards, for the range of frequencies $f > 1/2\tau_e$, the asymptotic form of (5) is used (i.e. the "1" inside the brackets is ignored) and the RMS reference level becomes:

$$\mathrm{B_{RL,RMS}} = \frac{\tau_e}{\pi\sqrt{2}\,\mathrm{K}} \left(\frac{\mathrm{dB}}{\mathrm{dt}}\right)_{\mathrm{Rh}} \tag{6}$$

where the factor √2 arises from the conversion of a sinusoidal peak to RMS quantity.

Using (6), magnetic flux density reference levels can be calculated using data from a number of empirical human MR studies. Table 2 outlines mean (50% percentile) rheobase threshold levels, chronaxie times and calculated reference levels (for a reduction factor K=10) from the human volunteer study data summarized by Zhang et al., 2003; Table 5.

Table 2. Mean threshold magnetic flux density for perception of PNS with a reduction factor K=10 incorporated, calculated using (6).

Study	Number of Subjects	Waveform	Rheobase $(dB/dt)_{Rh}$ (T/s)	Chronaxie τ_e (ms)	Magnetic flux density B_{RL} (μT RMS)
Ham et al. (1997)	4	Trapezoidal	n/a	0.810	n/a
Bourland et al. (1999)	84	Trapezoidal	14.9	0.365	122
Hebrank & Gebhardt (2000)	65	Trapezoidal	16.3	0.526	193
		Sinusoidal	12.4	0.672	232
Zhang et al. (2003)	22	Trapezoidal	23.8	0.370	198
Den Boer et al. (2002)	153*	Trapezoidal	18.8	0.360	153

Note (*) – This study was a meta-analysis of 3 previous studies, comprised of results from 153 subjects.

The meta-analysis study of Den Boer et al. (2002) combined data from 3 separate studies (Ham et al., 1997; Bourland et al., 1999; and Hebrank et al., 2000) using a total of 153 volunteers and provided statistics concerning the weights, heights and ages of the subjects, which indicated that they were mostly young, fit adults. This exposure group represents the most sensitive population for PNS as children and individuals suffering from a variety of peripheral neuropathies display higher perception thresholds (i.e. rheobase) for PNS and longer chronaxie than young healthy adults (Karup and Moldovan, 2009; Farrar et al., 2013; Bae et al., 2008; Yerdelen et al., 2010). The meta-analysis data of Den Boer et al. (2002) represents the most reliable estimate of human PNS perception thresholds.

Using the reported means and standard deviations of the rheobase threshold and chronaxie times (18.8±0.6 T/s and 0.36±0.02 ms, respectively) in Den Boer et al. (2002), reference levels based on different coverage factors (other than the 50th percentile) using the expanded uncertainty can be calculated. An RMS magnetic flux density value of 153 µT is obtained for the mean (50th percentile) value of PNS perception for the uncontrolled environment (with a safety factor of 10 incorporated). Standard uncertainties of both rheobase and chronaxie parameters were calculated as the decibel equivalent of one standard deviation below the mean, normalized to the mean, resulting in standard uncertainties of -0.28 dB and -0.50 dB, respectively, with a combined standard uncertainty of -0.78 dB. By applying these uncertainty factors, Table 3 indicates that at a RMS magnetic flux density of 117 µT, there is a probability greater than 99% (coverage factor of 3) that the mean threshold for perception of PNS falls above this value, with a 10-fold margin of safety incorporated.

Table 3. Estimated temporal peak magnetic flux density reference levels for different expanded uncertainty coverage factors. Data for mean and standard deviation of rheobase threshold and chronaxie was from Den Boer et al. (2002).

Coverage factor	Expanded Uncertainty	B_{RL} at coverage factor (RMS values)
1	-0.78 dB	139 μT
2	-1.56 dB	127 μT
3	-2.34 dB	117 μT

Based upon the above considerations, the RMS magnetic flux density value at a coverage factor of 3 can be used for deriving Uncontrolled Environment magnetic field strength reference levels in SC6 (2015). Conversion into RMS magnetic field strength (H) and rounding down yields reference levels for Uncontrolled- and Controlled-Environments of 90 A/m and 180 A/m, respectively.

PNS-based basic restrictions from empirical human MR data

So far the reference levels derived in the previous section pertain to exposure of the main trunk of the body since they were ultimately based on whole body MRI gradient coil exposure data. The main trunk of the body, having the largest cross-sectional area, has the lowest perception thresholds in terms of dB/dt. If trunk-only exposure were the only consideration in the standard, then the need for a basic restriction, at least in regards to magnetically-induced stimulation, might be thought of as unnecessary. However, it is known from Faraday induction principles that body parts with smaller cross-sectional areas can be exposed to higher external magnetic flux densities at the same level of induced electric field strength as for larger cross-sectional areas. Thus, having a basic restriction is useful for allowing the estimate of an effective reference level for limbs if an induction coefficient for that part of the body and exposure field orientation is known. For example, an induction coefficient corresponding to an axially-oriented magnetic flux density in the arm or leg can be calculated using a simple homogeneous loop model. In this case the induction coefficient is known to be equal to the number pi times the radius of the limb (in m) (ICNIRP, 1998).

If the trunk-only reference level $B_{RL,RMS}$ is established, the basic restriction can be calculated by rearranging (1) into:

$$E_{BR} = C_i \, f \, B_{RL,RMS} \tag{7}$$

where E_{BR} is the sinusoidal RMS basic restriction for the affected nerve tissues in the trunk arising from whole body exposure. If it is assumed that the nerve tissues in the limbs exhibit similar threshold behaviour as nervous tissue in the trunk, then the E_{BR} from (7) can be considered a universal basic restriction for PNS throughout the body.

Using (7) and an assumed induction coefficient of 1.2 V/m per Hz-T (mean value in Table 1) and the RMS flux density reference level of 113 μT (converted from $H_{RL,RMS}$ =90 A/m) for uncontrolled environments , an RMS internal electric field strength basic restriction of 1.36 x$10^{-4}f$ is computed for the Uncontrolled Environment. Since ICNIRP (2010) has specified a similar basic restriction of 1.35 x$10^{-4}f$ for Uncontrolled Environments, which is slightly lower than the value derived above, SC6 (2015) will harmonize its basic restriction for the avoidance of PNS perception in the 3 kHz to 10 MHz frequency range with that of ICNIRP (2010) for the Uncontrolled Environment at 1.35 x$10^{-4}f$. The Controlled Environment basic restriction in SC6 (2015) would therefore also be harmonized with ICNIRP (2010) at 2.7 x$10^{-4}f$. These values provide an estimated 10 fold (for uncontrolled environment) safety margin for perception of PNS at the assumed induction coefficient of 1.2 V/m per Hz-T.

Therefore, the basic restrictions for the avoidance of PNS perception in SC6 (2015) are:

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

- *f* denotes frequency in Hz

For localized exposures to the limb (which have small cross-sectional areas and therefore lower rates of induction), the reference levels of 90 A/m (Uncontrolled) and 180 A/m (Controlled) may be exceeded provided that the basic restrictions within the limb are not exceeded.

Thermal Effects: SAR-based basic restrictions

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). These basic restrictions remain unchanged in the revised version of SC6 (2015) since no new adverse health effects have been identified at exposures below these levels since the last version of SC6 (2009).

The basic restrictions specified for WBA-SAR in SC6 (2015) are:

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

* - 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).

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 (2015), ICNIRP (1998) and IEEE C95.1 (2005):

Exposure Group	**Tissue**	**Frequency range**	**Peak spatially-averaged SAR limit (W/kg)**	**Averaging Volume (g)**
SC6 (2014) Controlled Environment	Head, neck, trunk	100 kHz- 6 GHz	8*	1
	Limbs		20*	10
SC6 (2014) Uncontrolled Environment	Head, neck, trunk	100 kHz- 6 GHz	1.6*	1
	Limbs		4*	10
ICNIRP/IEEE-C95.1 Controlled	Head, neck, trunk	100 kHz- 6 GHz	10*	10
	Limbs		20*	10
ICNIRP/IEEE-C95.1 Uncontrolled	Head, neck, 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, the basic restriction for peak spatially-averaged SAR limits in SC6 (2015) remain unchanged from those in the previous version of SC6 (2009) to maintain an additional margin of safety.

SAR-based reference levels, 100 kHz-10 MHz

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 (2015), 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.

SAR-based Magnetic Field Reference Levels, 3kHz – 10 MHz

Two simultaneous criteria were considered when establishing the reference levels for SC6 (2015) 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 international standards, where justified.

SAR in a discrete volume of tissue is proportional to the local conductivity and the square of the magnitude of the induced electric field strength. Therefore, SARs (whole-body-averaged and spatial-peak, 1g) from purely magnetic field exposure in this frequency range are due to the induction of internal electric fields. The distribution of SAR intensities in the body follow the patterns of induced electric field strength and locations of spatial peak 1g SAR in the body are likely to be close to those for peak induced electric field strength that are of interest to PNS dosimetry.

As in the case for PNS-oriented dosimetric analyses, a SAR-based induction coefficient similar to (1) can be defined as the square root of either the whole-body-averaged SAR (WBA-SAR) or spatial-peak, 1g SAR (SP1g-SAR) divided by the frequency, *f*, and the external magnetic field strength (usually uniform), H_{ext}:

$$\mathrm{K_{WBA}} = \frac{\sqrt{\mathrm{WBA-SAR}}}{f\ \mathrm{H_{ext}}} \quad , \quad \mathrm{K_{SP1g}} = \frac{\sqrt{\mathrm{SP1g-SAR}}}{f\ \mathrm{H_{ext}}} \tag{8}$$

where K_{WBA} and K_{SP1g} are the SAR-based induction coefficients corresponding to whole-body-averaged and spatial-peak, 1g SARs, respectively.

For sinusoidal, external magnetic field exposure, the induced electric field strength is proportional to frequency. Thus, for a frequency-invariant conductivity, the square roots of whole-body-averaged or spatial-peak, 1g SARs are proportional to frequency and the resulting SAR-based induction coefficients are constant. However, in this frequency range, tissue conductivities slowly increase with frequency, yielding slowly changing values of K_{WBA} and K_{SP1g} with frequency (since they vary with the square root of conductivity, their change with frequency is relatively small). An in-house dosimetric study using 2mm voxel models and conductivity data from Gabriel (1996), resulted in values of K_{WBA} and K_{SP1g} that increased by 36% from 100 kHz to 10 MHz. Below 100 kHz, their values changed by less than 3%.

From the definition of the SAR-based induction coefficients in (8) and the fact that basic restrictions for WBA-SAR and SP-1g SAR are frequency independent, a SAR-based reference level with f^{-1} dependence would be appropriate in this frequency range. This is evidenced in the IEEE C95.1-2005 and ICNIRP 1998 standards (see Figures 1(b) and 2(b), respectively).

Limited SAR-based dosimetric analyses have been reported for pure magnetic field exposure in this frequency range (Kaune et al., 1997, Dawson & Stuchly, 1998). The results from these studies have been converted into values of H_{ext} that produce the uncontrolled and controlled environment WBA-SAR basic restrictions of SC6 (2014) and are plotted in Figures 1(b) and 2(b). The models include a homogeneous adult ellipsoid (Kaune et al., 1997) and an adult male voxel model (Dawson & Stuchly, 1998). For the latter, SAR calculations were performed only at 60 Hz so it was necessary to extrapolate to higher frequencies using the known variation of conductivity with frequency in the Gabriel, 1996 dataset.

In addition, an in-house study using voxel models of a 19.4 kg six year old and a 72.6 kg adult male (Christ et al. 2010) was undertaken (HC internal report, 2014). These models also utilized the conductivity data in Gabriel (1996) and computations were made using the magneto quasi-static FDTD solver available in the commercial software SEMCAD V14. Results from that study in terms of H_{ext} that produces the uncontrolled and controlled environment WBA-SAR and SP1g-SAR basic restrictions are also plotted in Figures 1(b) and 2(b).

From Figures 1(b) and 2(b) it can be seen that the homogeneous ellipsoid model produced the highest K_{WBA} of all the models and consequently the lowest threshold of H_{ext} that produces the basic restriction, for each frequency. The larger of the two different-sized voxel models used in the in-house study produced the higher K_{WBA} as expected from consideration of Faraday's law (i.e. the larger the cross-sectional area normal to the incident magnetic field, the greater the induced electric field strength). Also, it was found that K_{SP1g} is marginally greater than K_{WBA} for the 72.6 kg adult voxel model, suggesting that the spatial-peak, 1g SAR basic restriction is the most limiting factor for voxel-model-based dosimetry. Interestingly, it was observed that the locations of maximal SP1g-SAR in the adult voxel model, for frequencies at 100 kHz and higher, tended to be on the periphery of the trunk, in the general area of the hips. This is also the same general location as the maximum induced electric field strength and is an area often given as the site of experimentally-induced peripheral nerve stimulation in magnetic resonance imaging (MRI) studies (Glover, 2009)

A SAR-based reference level, when plotted versus frequency, should be below the lowest value of H_{ext} that produces the basic restriction (see Figures 1(b) and 2(b)). If set at the same rate of fall-off as the dosimetry H_{ext} data, it should have an f^{-1} dependence (as explained previously). Ideally, it should begin at the frequency where the NS-based reference level and the SAR-based reference level curves intersect. This is based on the consideration that NS-based RLs limit the temporal maximum of a waveform while the SAR-based ones limit the time averaged values, which must always be less that the temporal maximum.

For the SC6 (2015) SAR-based magnetic field reference levels, the sloped portion of the ICNIRP (1998) limits were extended back to 100 kHz (for the Uncontrolled Environment) or set to begin at 100 kHz (for the Controlled Environment). Both sets of frequency dependent limits are extended to 10 MHz as shown in Figures 1(b) and 2(b). 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 specified in SC6 (2015). Therefore, it was decided to begin the 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). Based upon the dosimetry data depicted in Figures 1(b) and 2(b), there is a large margin of compliance of the SC6 (2015) SAR-based reference levels to the basic restrictions.

Magnetic Field Strength Reference Levels in SC6 (2015)

Frequency (MHz)	Reference Level Basis	Reference Level H_{RL}, (A/m) (rms)		Reference Period (min)
		Uncontrolled Environment	Controlled Environment	
0.003 – 10	PNS	90	180	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

Electric Field Reference Levels, 3kHz-10MHz

As with magnetic fields, two simultaneous criteria were considered when establishing the electric field reference levels for SC6 (2015). These were: 1) the adoption of separate basic restrictions for PNS and thermal effects, and 2) harmonization with international standards, where justified. Over the frequency range 3 kHz to 10 MHz, the ICNIRP (2010) NS-based electric field strength reference levels (uncontrolled and controlled) have been adopted in SC6 (2015) (see Figures 3 and 4).

For SAR-based reference levels, harmonization of the reference levels in SC6 (2015) with those of ICNIRP (1998) is relatively straight-forward for Uncontrolled Environments since the SAR-based and PNS-based reference levels intersect at approximately 1 MHz (the precise frequency is 1.10 MHz). Therefore, the Uncontrolled Environment SAR-based reference level for SC6 (2015) 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 specified 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 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 specified in SC6 (2015), 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 Uncontrolled- and Controlled-Environment electric field strength reference levels in SC6 (2015). 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 Uncontrolled and Controlled Environment reference levels provide a greater level of protection from potential contact currents in SC6 (2015) as compared to SC6 (2009). However, it should be recognized 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 (2015) is necessary.

Based upon the above dosimetric information, the electric- and magnetic-field strength reference levels in the 3 kHz – 10 MHz frequency range of SC6 (2015) are:

Electric Field Strength Reference Levels in SC6 (2015)

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.

Recommendations for Spatial Averaging

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)

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 $200f$ (where 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. SC6 (2015) has been 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, 1998)	Controlled	n/a	40
	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. Therefore, the induced- and contact-current reference levels in SC6 (2015) have been 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 are now specified as reference levels in SC6 (2015).

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 7 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 ankle 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 an 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. While there is only limited 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, an 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 have 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 8 and 9 depict the induced current reference levels in SC6 (2015) 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 8 and 9, 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 pre-defined induced current amplitude.

The method for estimating the other threshold data in Figures 8 and 9 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 8 and 9, 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 induced current reference levels are protective of the basic restrictions.

400 kHz to 110 MHz

Figure 10 shows the Uncontrolled Environment 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 for the Controlled Environment is 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 10 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 Uncontrolled Environment induced current reference level in SC6 (2015) provides sufficient protection to ensure that the basic restriction for SAR in the ankles is not exceeded. The same relationships hold for the Controlled Environment induced current reference levels in SC6 (2015), since the reference levels and the basic restrictions have the same ratio for controlled-to-uncontrolled on a power basis (5:1).

Induced Current Reference Levels in SC6 (2015)

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 contact current reference levels in SC6 (2015).

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, an effective reference period for contact current reference levels are 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 PNS-based and SAR-based reference levels in the frequency range from 100 kHz to 10 MHz were deemed unnecessary.

The Uncontrolled- and Controlled-Environment contact current reference levels are plotted in Figures 11 to 14. Figures 11 and 12 depict the Uncontrolled- and Controlled Environment contact current reference levels in the 3 – 100 kHz range, while Figures 13 and 14 depict the contact current reference levels in the 100 kHz – 10 MHz frequency range. The contact current reference levels in SC6 (2015) 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 (2015).

In Figure 11, 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 50th 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 12). Thus, the reference levels in SC6 (2015) 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 Figure 13 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.

Figure 14 demonstrates that the Controlled-Environment contact current reference level is approximately at the 50th 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 13 and 14. 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.

Contact Current Reference Levels in SC6 (2015)

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; SCENHIR, 2013; ANSES, 2013; WHO, 2014). 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.

WBA-SAR and peak spatially-averaged SAR in SC6 (2015):

Exposure Group	**Tissue**	**Frequency range**	**Peak spatially-averaged SAR (W/kg)**	**WBA-SAR (W/kg)**
SC6- Controlled Environment	Head, neck, trunk	10 MHz - 6 GHz	8	0.4
	Limbs		20	
SC6- Uncontrolled Environment	Head, neck, 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 (2015). 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 (~50 MHz to 6 GHz) for the Uncontrolled Environment for the WBA-SAR limit of 0.08 W/kg (Dimbylow, 2002; Wang et al., 2006; Dimbylow and Bolch 2007; Conil et al., 2008; Nagaoka et al., 2008; Kühn et al., 2009; Findlay et al. 2009; Lee and Choi, 2012). For this reason, the reference levels in SC6 (2014) have been revised in the 10 MHz- 6 GHz frequency range based upon 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 (2015). 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 (2015) 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.

Uncontrolled-Environment 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) . Figures 15 and 16 depict the Uncontrolled- and Controlled-Environment reference levels in SC6 (2015), in comparison to calculated power densities required to meet the basic restriction. These reference levels are intended to provide a full 50-fold margin of safety for all members of the population under worst-case exposure scenarios.

Reference Levels for Electric Field Strength, Magnetic Field Strength and Power Density in Uncontrolled Environments in SC6 (2015) are:

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.

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.

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 old 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 basic restriction for this case is 1.29 W/m^2.

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

Reliance on meeting the induced current reference level to ensure compliance with the WBA-SAR basic restriction may be 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 3.

Table 3. Grounded, whole-body (WB) resonance frequencies, 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 frequency (MHz)	SC6 (2014) Power Density RL (W/m^2)	Fraction of Induced Current RL (0.08A, both feet)	Fraction of WBA-SAR BR (0.08W/kg)
Adult male	39	1.43	169%	72%
Adult female	45	1.33	122%	60%
7yr	61	1.29	90%	79%
3yr	85	1.29	65%	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 reference level exceeds the fraction of the WBA-SAR basic restriction for exposure to reference level power densities. Thus, the induced current is the more restrictive quantity for power density reference levels and complying with the induced current reference level confers compliance to the WBA-SAR basic restriction.

7yr: For the power density reference level, compliance is respected at the reference level power density, however, if the exposure level is increased such that the induced current reference level is reached, the WBA-SAR will still be in compliance. Thus, for this case, compliance to the induced current reference level confers compliance to the WBA-SAR basic restriction.

3yr: For power density reference levels, 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 reference level is reached, the WBA-SAR will not be in compliance. Compliance to the induced current reference level does not confer compliance to the WBA-SAR basic restriction.

To summarize these findings, for grounded adults and probably larger children at their respective resonance frequencies, compliance to the WBA-SAR basic restriction does not confer compliance to the induced current reference level (or likely the spatial-peak 10g average SAR in the lower limbs for which the induced current reference level is intended to protect against). 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 reference level. Conversely, if the induced current limits are respected then the WBA-SAR basic restrictions 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 reference levels required to produce the WBA-SAR basic restriction are plotted in Figure 15 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).

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 SC6 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 4. 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 4. 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 BR (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 Environment power density reference level in the whole-body resonance frequency range is 1.29 W/m^2 in SC6 (2015), which is compliant with the 0.08 W/kg basic restriction for 42 week gestational age (5th percentile BMI). For the younger gestational ages (29 and 36 weeks), the power density reference levels do 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 basic restriction is complied with at the power density reference level 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 17 (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 17 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.

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 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. Thus, the power density reference levels in SC6 (2015) 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 (2015) reference levels under any conceivable scenario.

Controlled Environment Reference Levels

The same data that was used to justify the revisions to the uncontrolled environment 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 7 yr old children since it was felt that this body height (and associated BMI) was a conservative lower bound for adults of short stature. Figure 16 shows much of the same data in Figure 15 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 for ages 7 yrs 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 reference levels required for the whole-body resonance region below 100 MHz.

Reference Levels for Electric Field Strength, Magnetic Field Strength and Power Density in Controlled Environments in SC6 (2015) are:

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.

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 limits for power density in Tables 5 and 6 of Safety Code 6 (2015) 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 (2015) 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 (2015) 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 (2015) 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 (2014) becomes more restrictive. In the worst case, the criterion in note 6 of SC6 (2015), allows 39% higher pulsed power density amplitudes for pulse durations between 72-100 ms, when compared to the criterion in SC6 (2009). However, SC6 (2015) 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; AGNIR 2012; ANSES, 2013; SCENIHR, 2013; WHO, 2014)). 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 reference levels in the 6 – 300 GHz range remain unchanged from SC6 (2009).

Uncontrolled Environment Reference Levels for Electric- and Magnetic-field strength and Power Density in the 6 – 300 GHz frequency range in SC6 (2015).

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.

Controlled Environment Reference Levels for Electric- and Magnetic-field strength and Power Density in the 6 – 300 GHz frequency range in SC6 (2015).

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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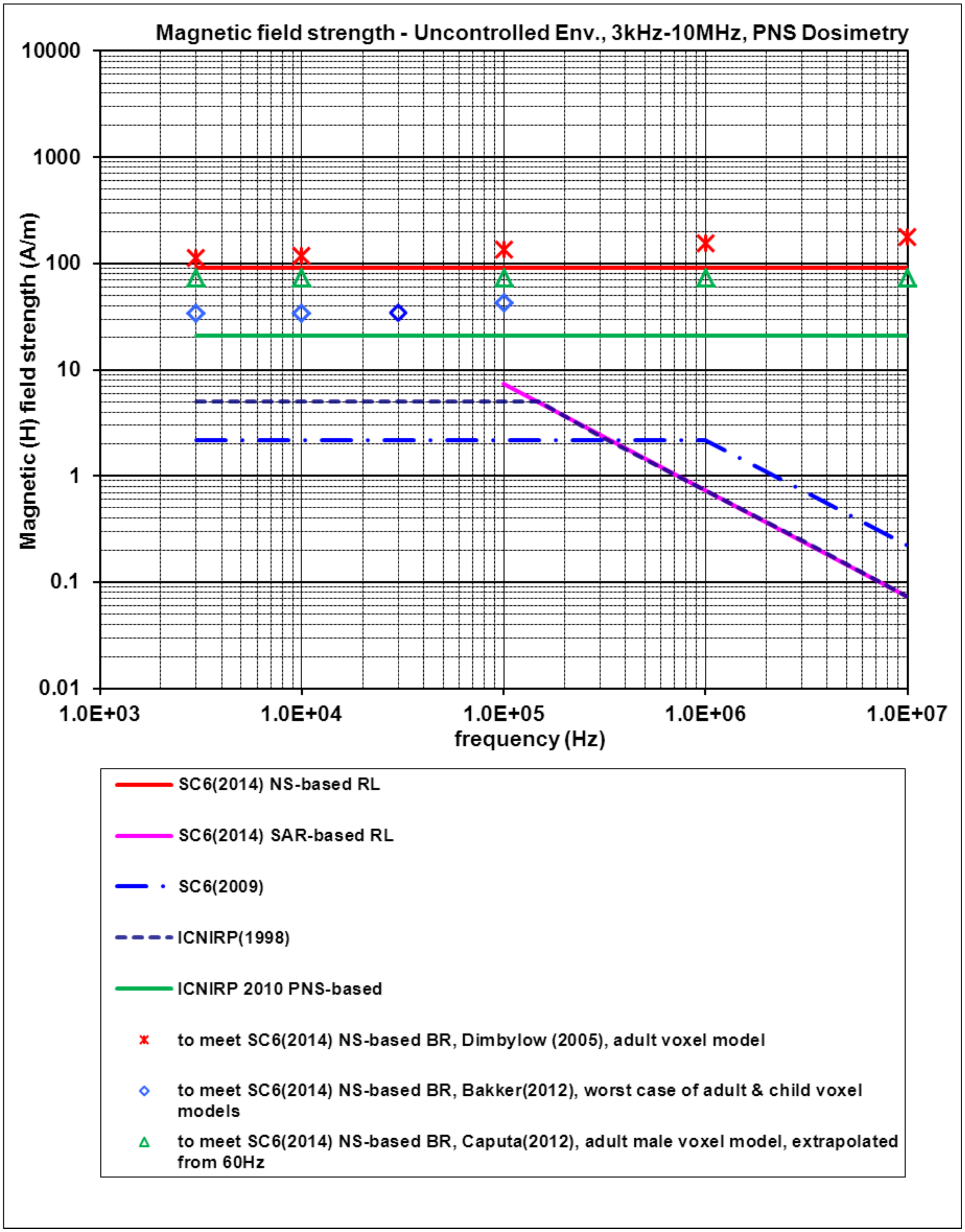

Figure 1(a). Magnetic field strength reference levels for Uncontrolled Environments in SC6 (2015) and other standards. Also shown are magnetic field strengths required to meet the NS-based Uncontrolled Environment basic restrictions in SC6 (2015) for different PNS dosimetric analyses under worst-case conditions.

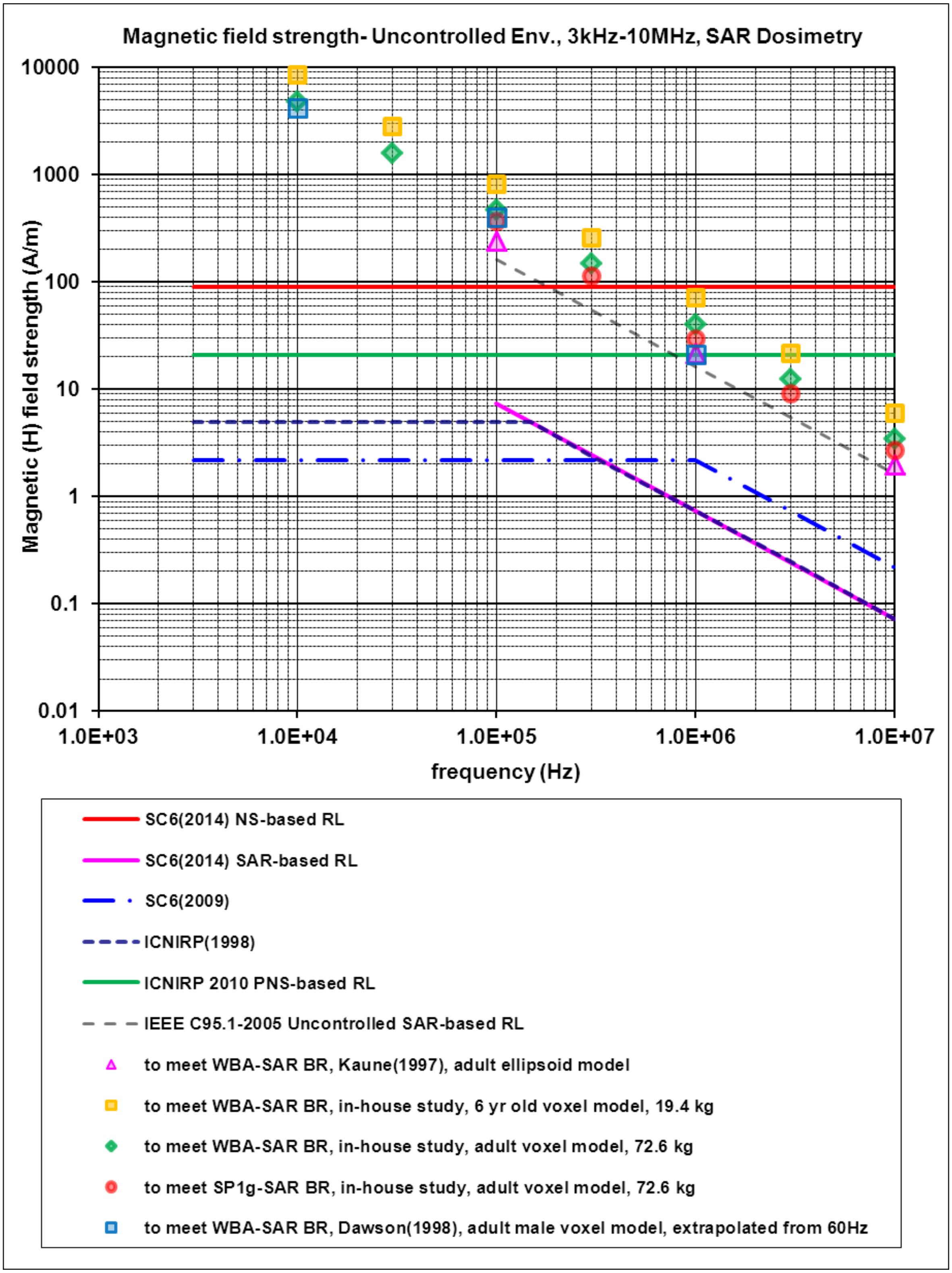

Figure 1(b). Magnetic field strength reference levels for Uncontrolled Environments in SC6 (2015) and other standards. Also shown are magnetic field strengths required to meet the SAR-based Uncontrolled Environment basic restrictions in SC6 (2015) for different SAR dosimetric analyses under worst-case conditions.

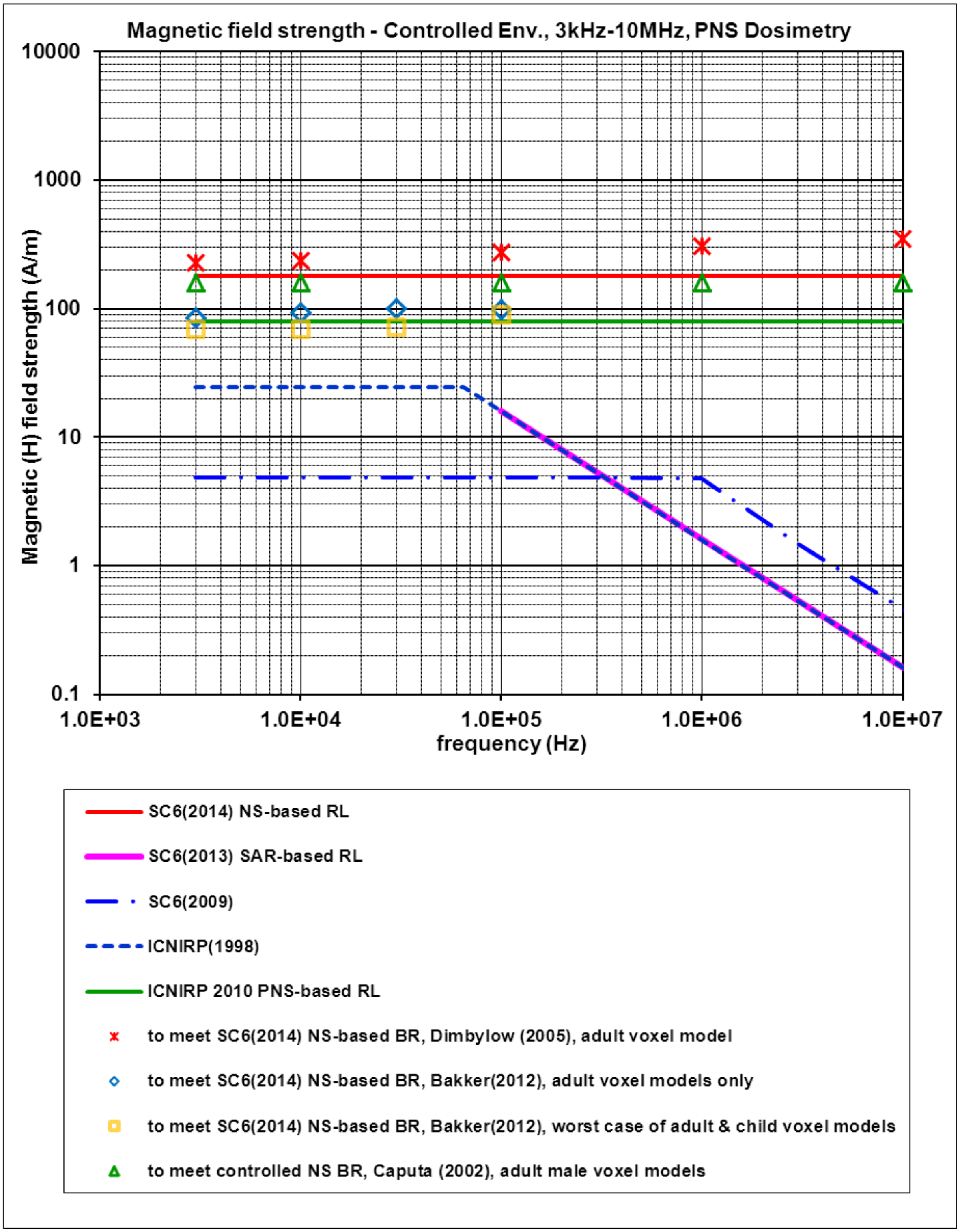

Figure 2(a). Magnetic field strength reference levels for Controlled Environments in SC6 (2015) and other standards. Also shown are magnetic field strengths required to meet the NS-based Controlled Environment basic restrictions in SC6 (2015) for different PNS dosimetric analyses under worst-case conditions.

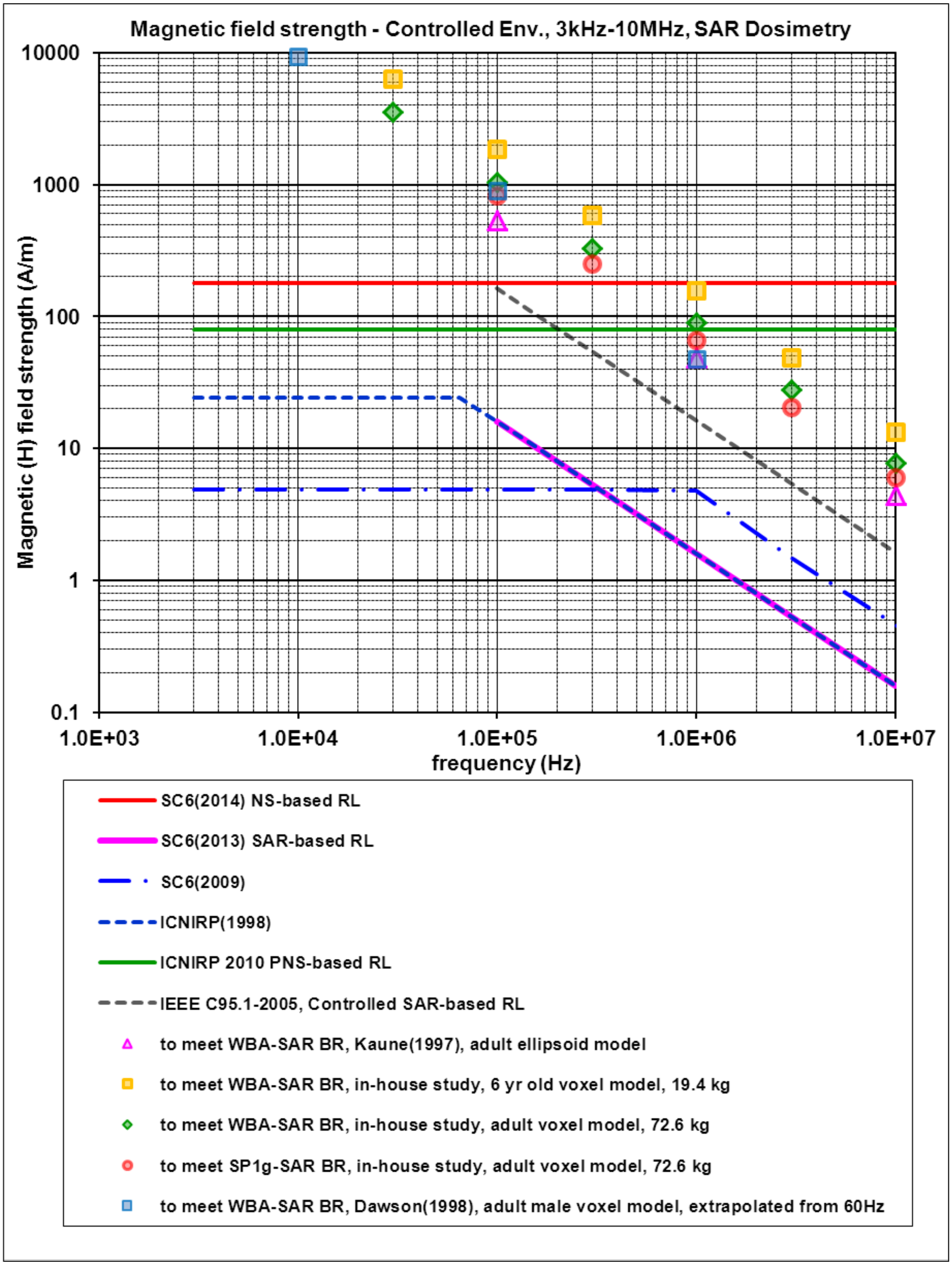

Figure 2(b). Magnetic field strength reference levels for Controlled Environments in SC6 (2015) and other standards. Also shown are magnetic field strengths required to meet the SAR-based Controlled Environment basic restrictions in SC6 (2015) for different SAR dosimetric analyses under worst-case conditions.

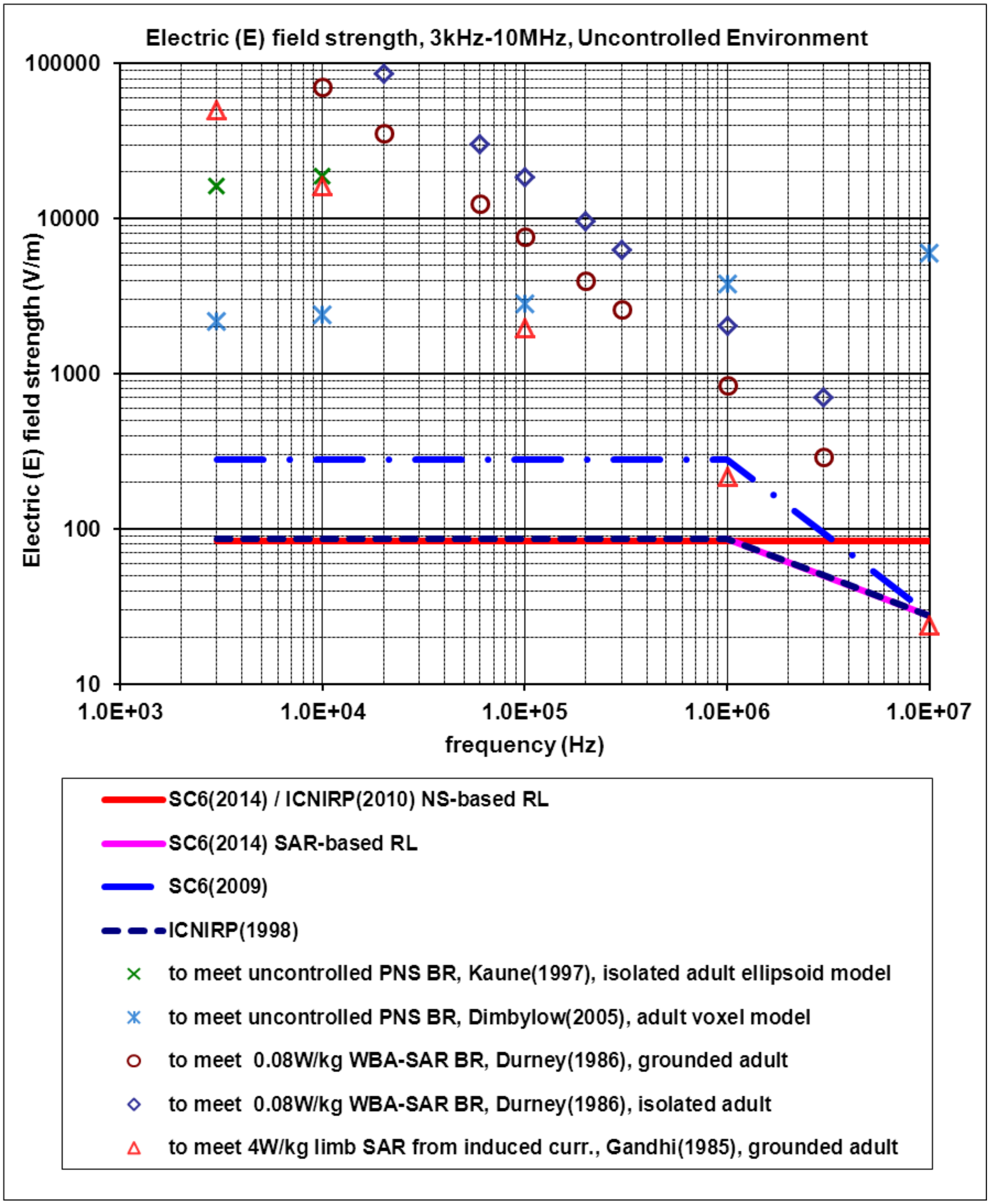

Figure 3. Electric field strength reference levels for Uncontrolled Environments in SC6 (2015) and electric field strengths required to meet the NS- and/or SAR-based Uncontrolled Environment basic restrictions in SC6 (2015) (in various numerical models exposed under worst-case conditions).

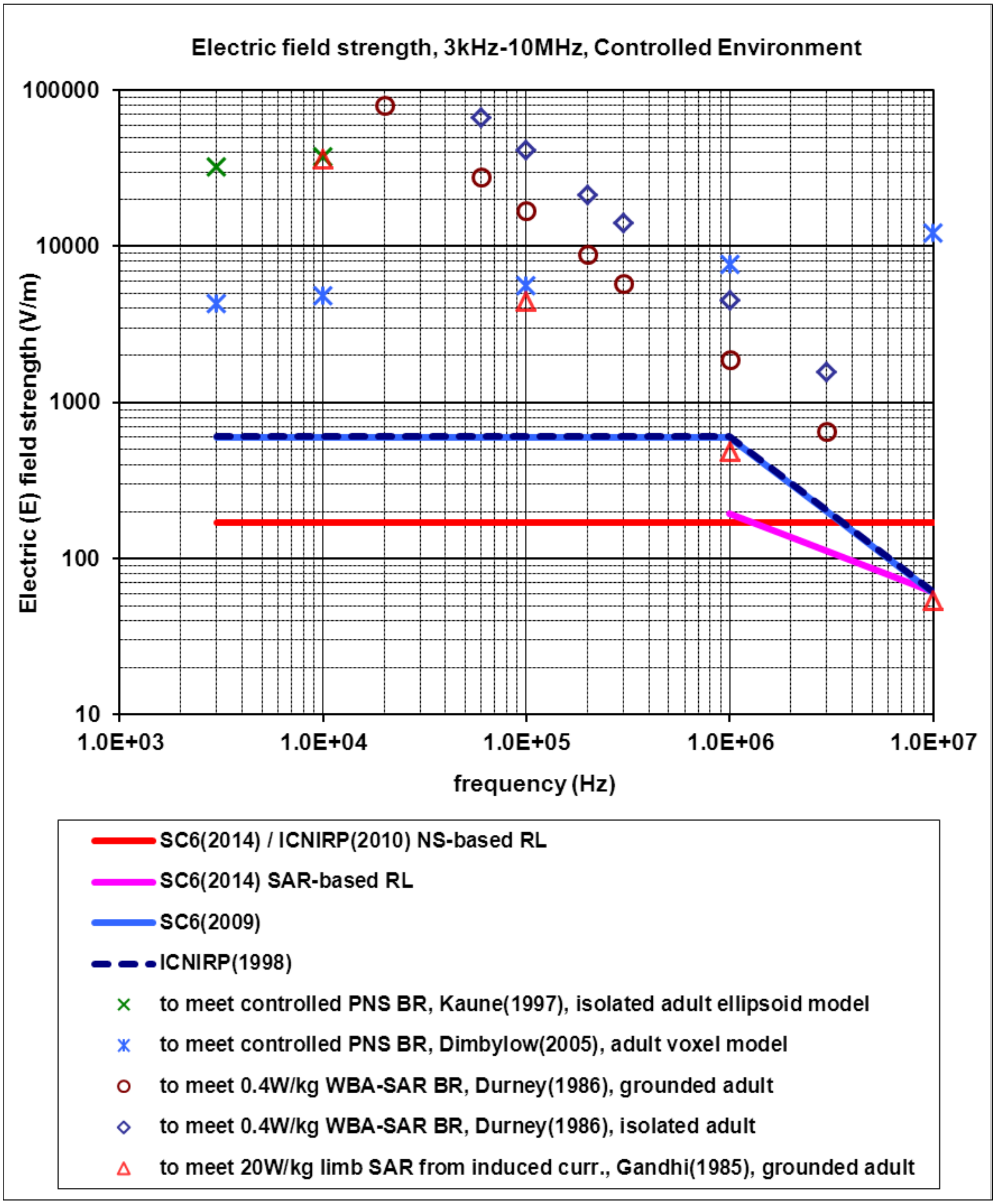

Figure 4. Electric field strength reference levels for Controlled Environments in SC6 (2015) and electric field strengths required to meet the NS- and/or SAR-based Controlled Environment basic restrictions in SC6 (2015) (in various numerical models exposed under worst-case conditions).

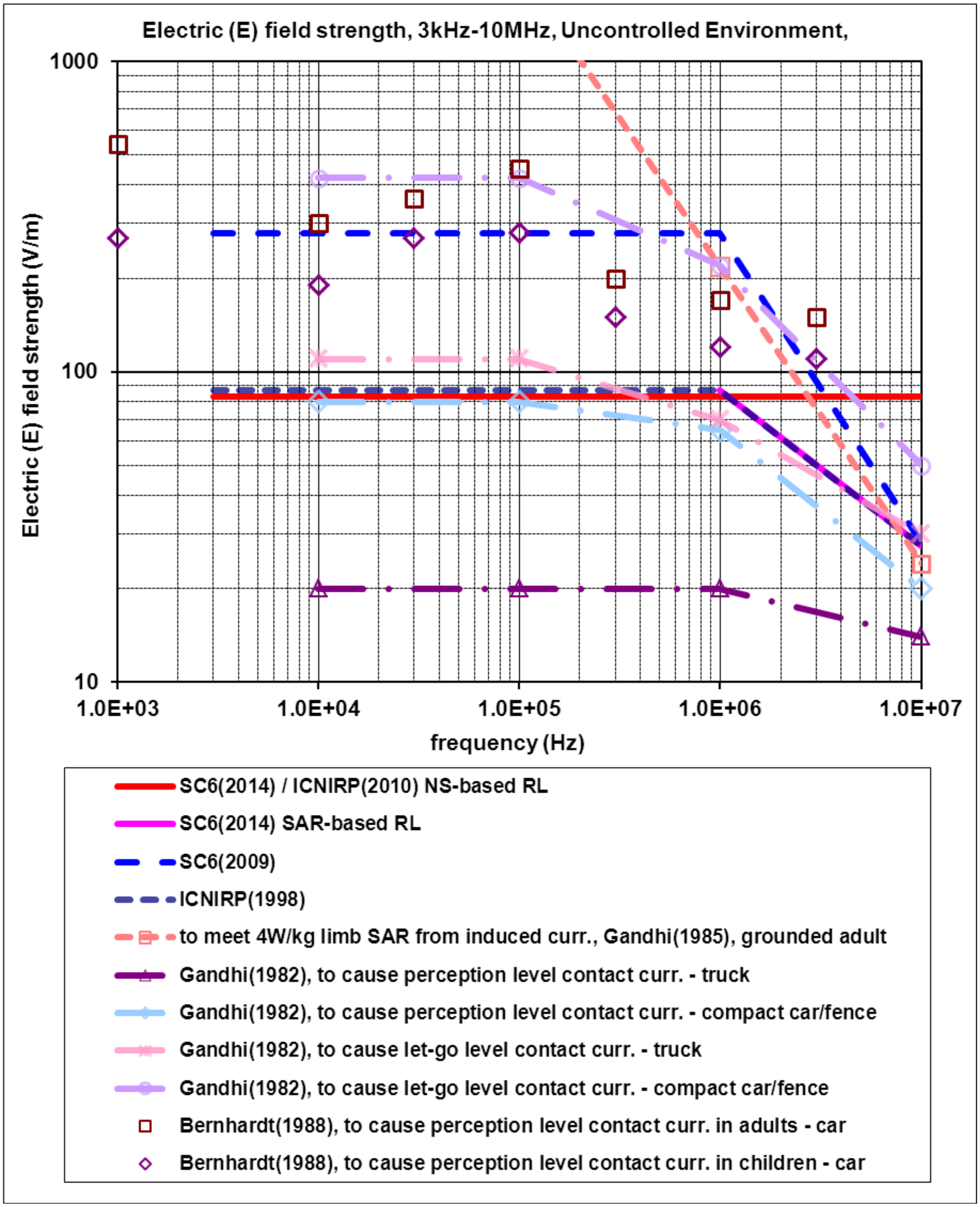

Figure 5. Electric field strength reference levels for Uncontrolled Environments in SC6 (2015) and electric field strengths of sufficient intensity to cause perception-level and let-go level contact currents for different objects under worst-case conditions.

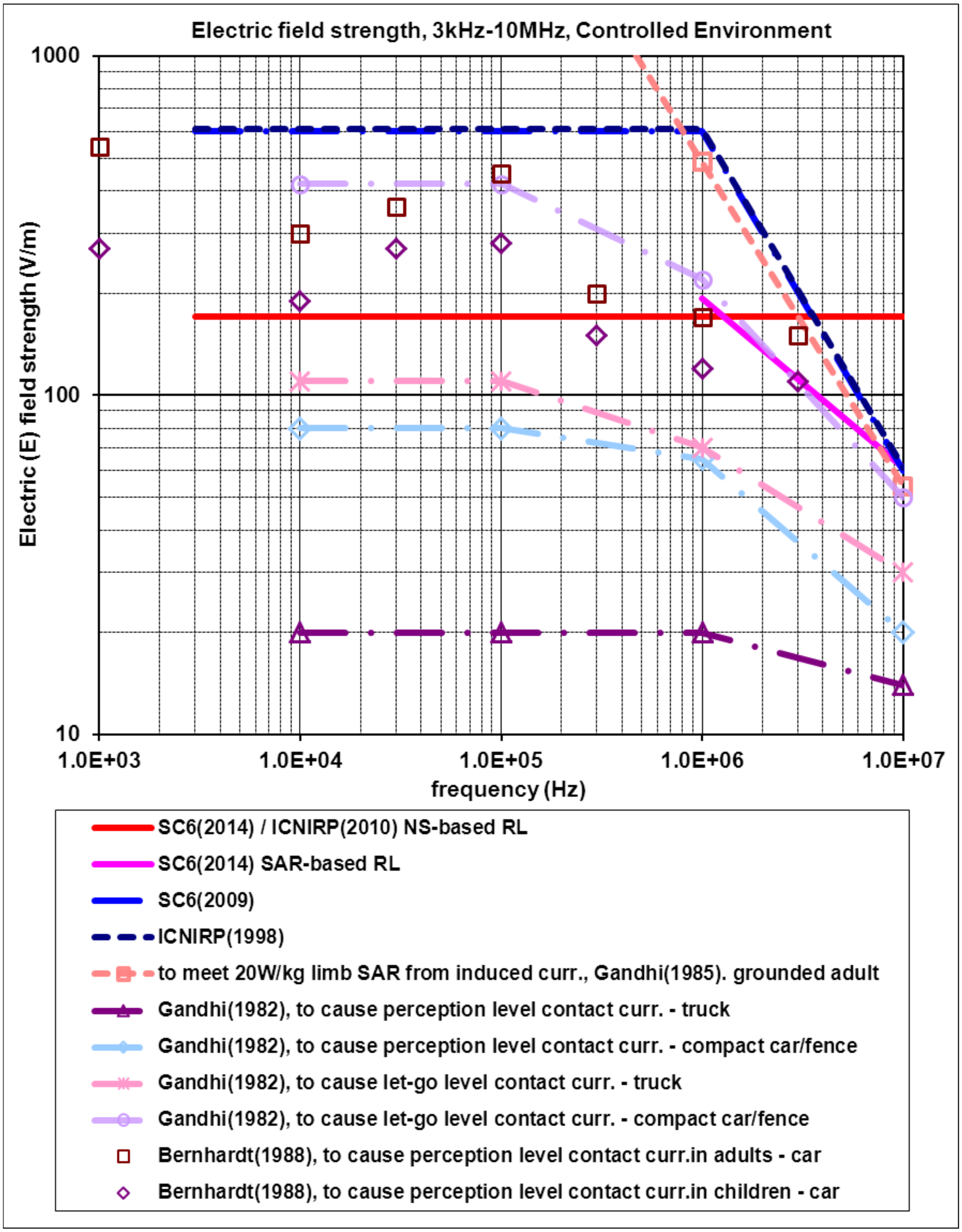

Figure 6. Electric field strength reference levels for Controlled Environments in SC6 (2015) and electric field strengths of sufficient intensity to cause perception-level and let-go level contact currents for different objects under worst-case conditions.

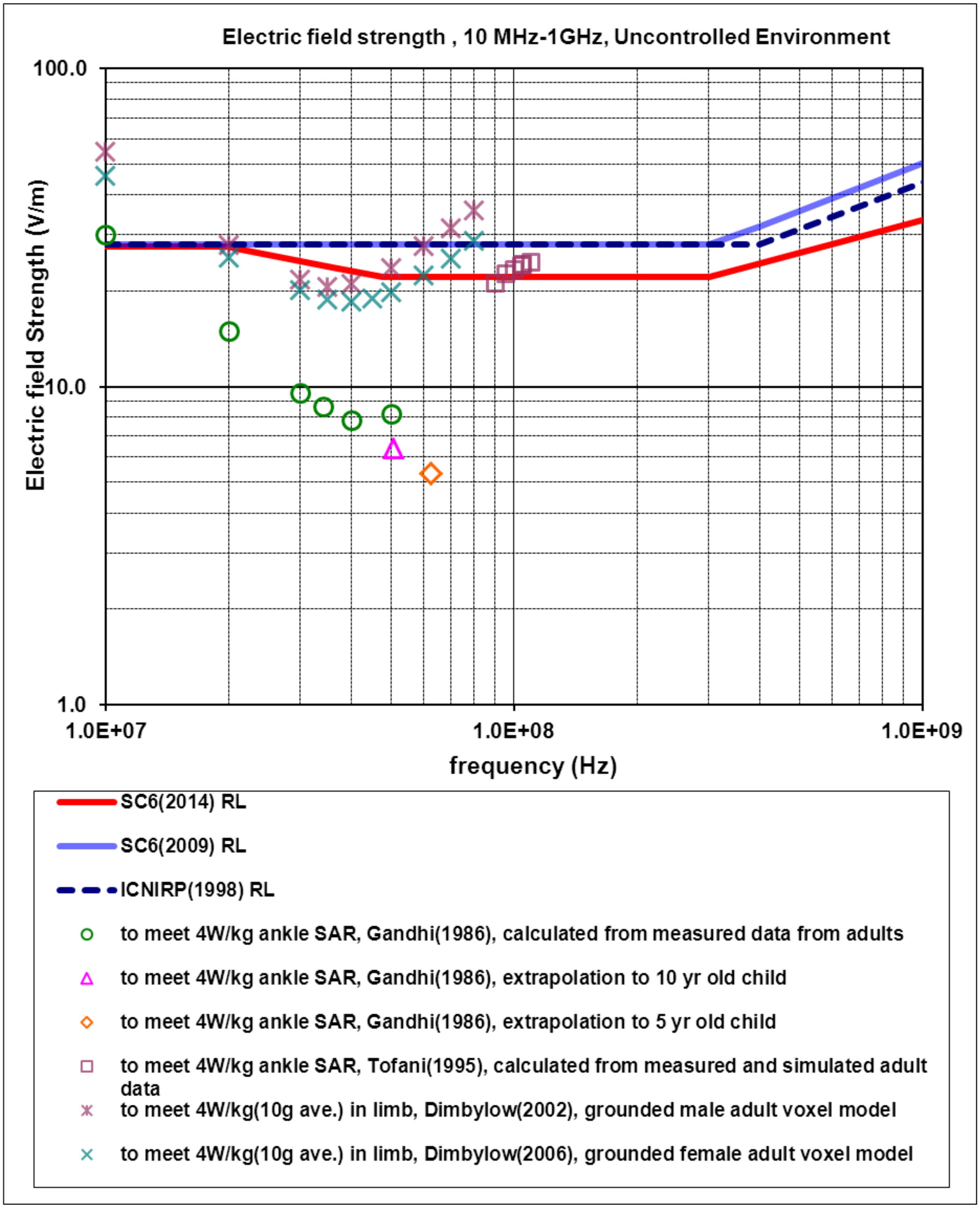

Figure 7. Uncontrolled Environment electric field strength reference levels and electric field strengths (vertically polarized, plane-wave) of sufficient intensity to produce limb SAR that meet the Uncontrolled Environment basic restriction of 4 W/kg in SC6 (2015).

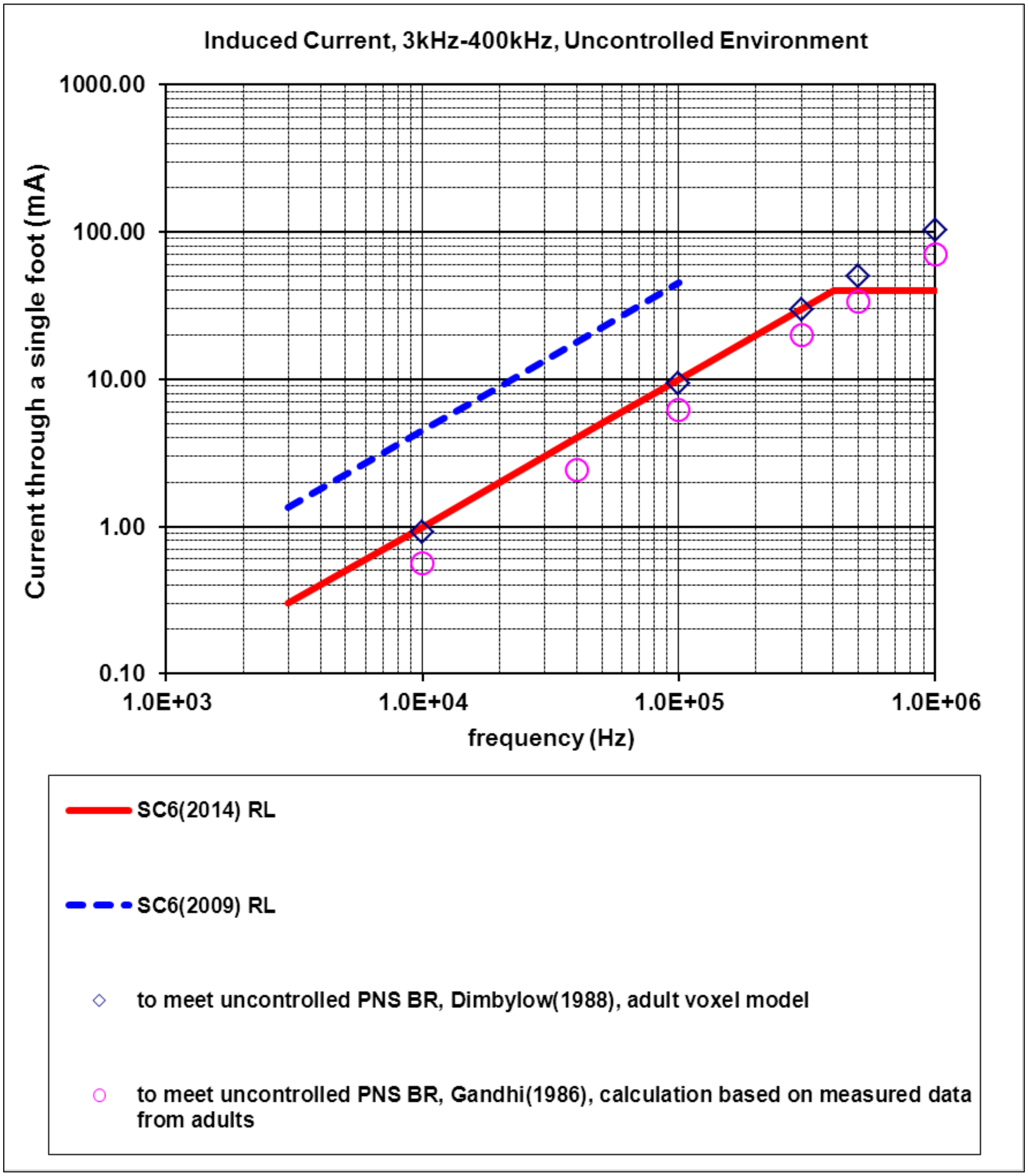

Figure 8. Induced current reference levels for Uncontrolled Environments for the frequency range 3 kHz to 1 MHz in SC6 (2015). Also shown are estimates of induced current required to meet the Uncontrolled Environment basic restriction for induced electric field.

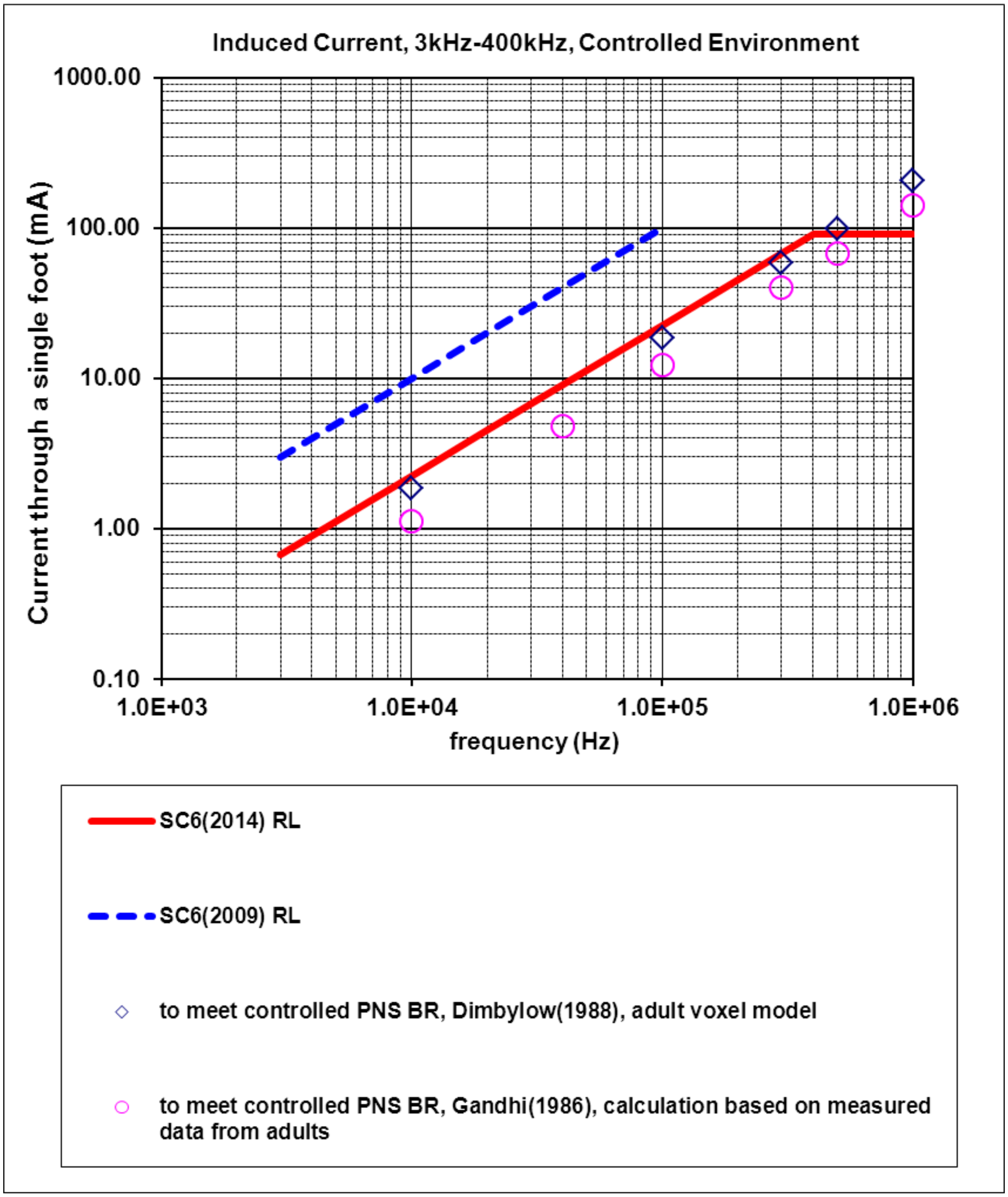

Figure 9. Induced current reference levels for Controlled Environments for the frequency range 3 kHz to 1 MHz in SC6 (2015). Also shown are estimates of induced current required to meet the Controlled Environment basic restriction for induced electric field.

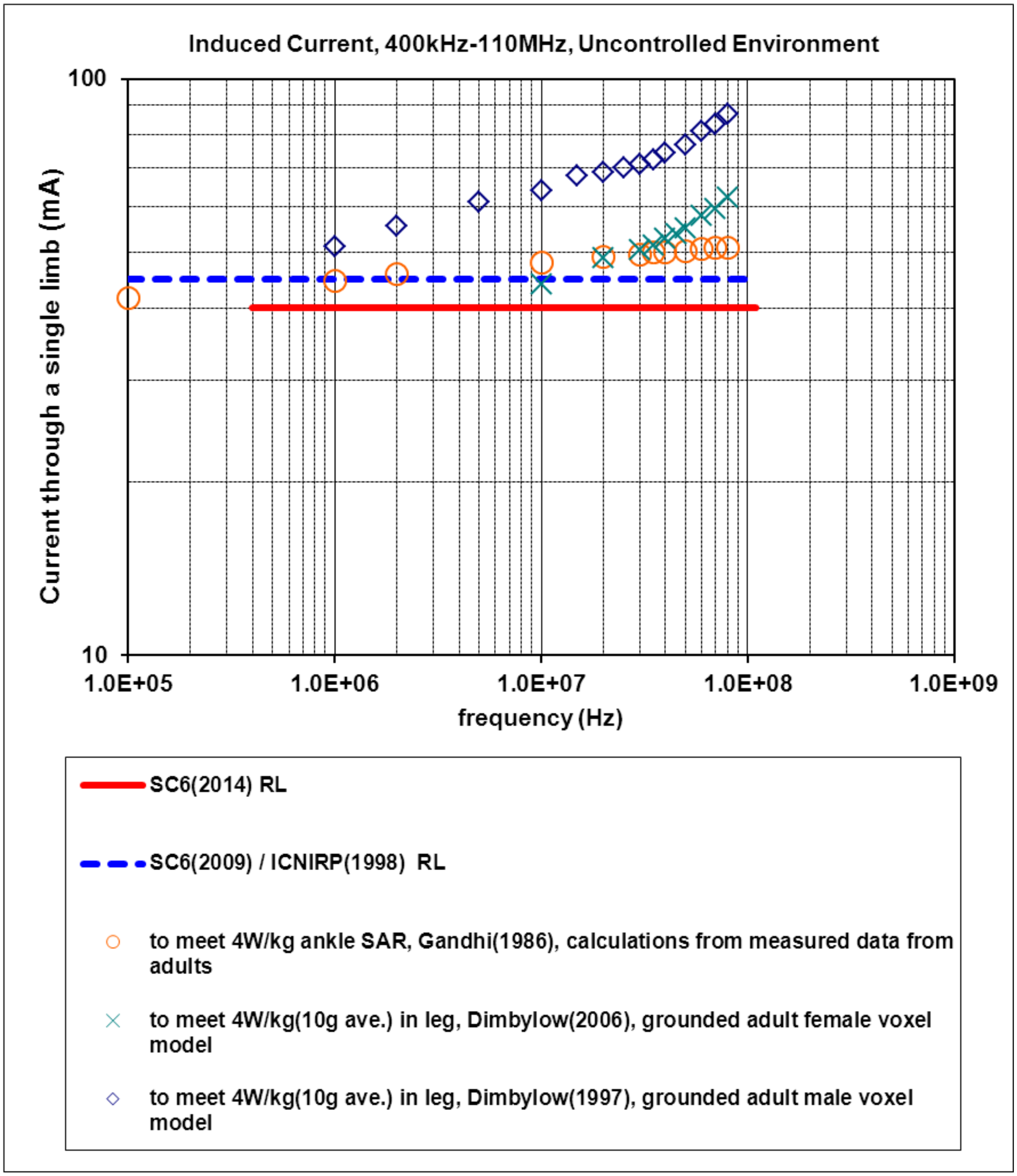

Figure 10. Induced current reference levels for Uncontrolled Environments for the frequency range 400 kHz to 10 MHz in SC6 (2015). Also shown are estimates of induced current required to meet the Uncontrolled Environment basic restriction for peak spatially-averaged SAR in the limbs (4 W/kg averaged over 10 g).

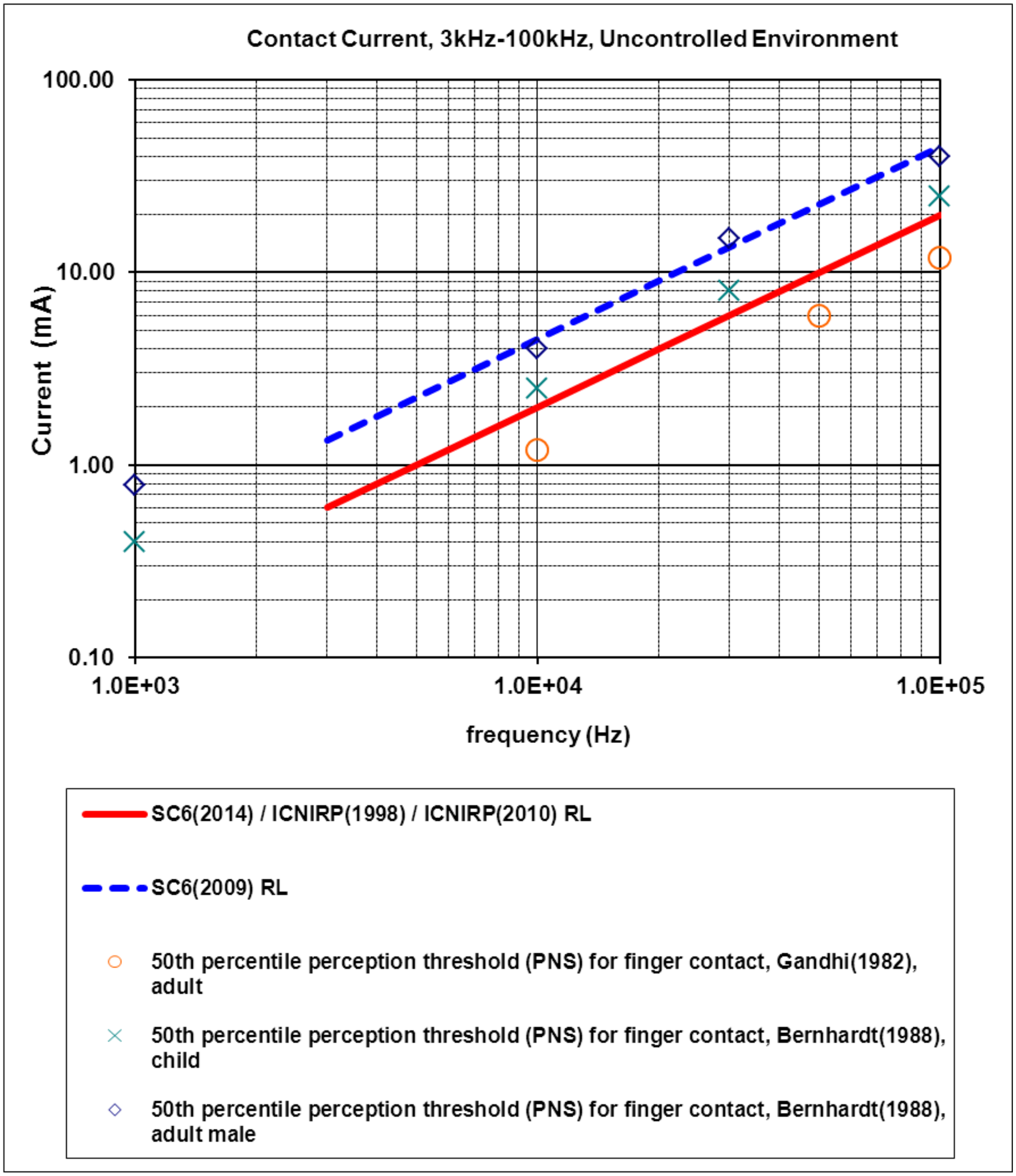

Figure 11. Uncontrolled-Environment contact current reference levels for the 3 - 100 kHz frequency range in SC6 (2015). Also depicted are the 50th percentile perception threshold currents (adult and children) for finger contact.

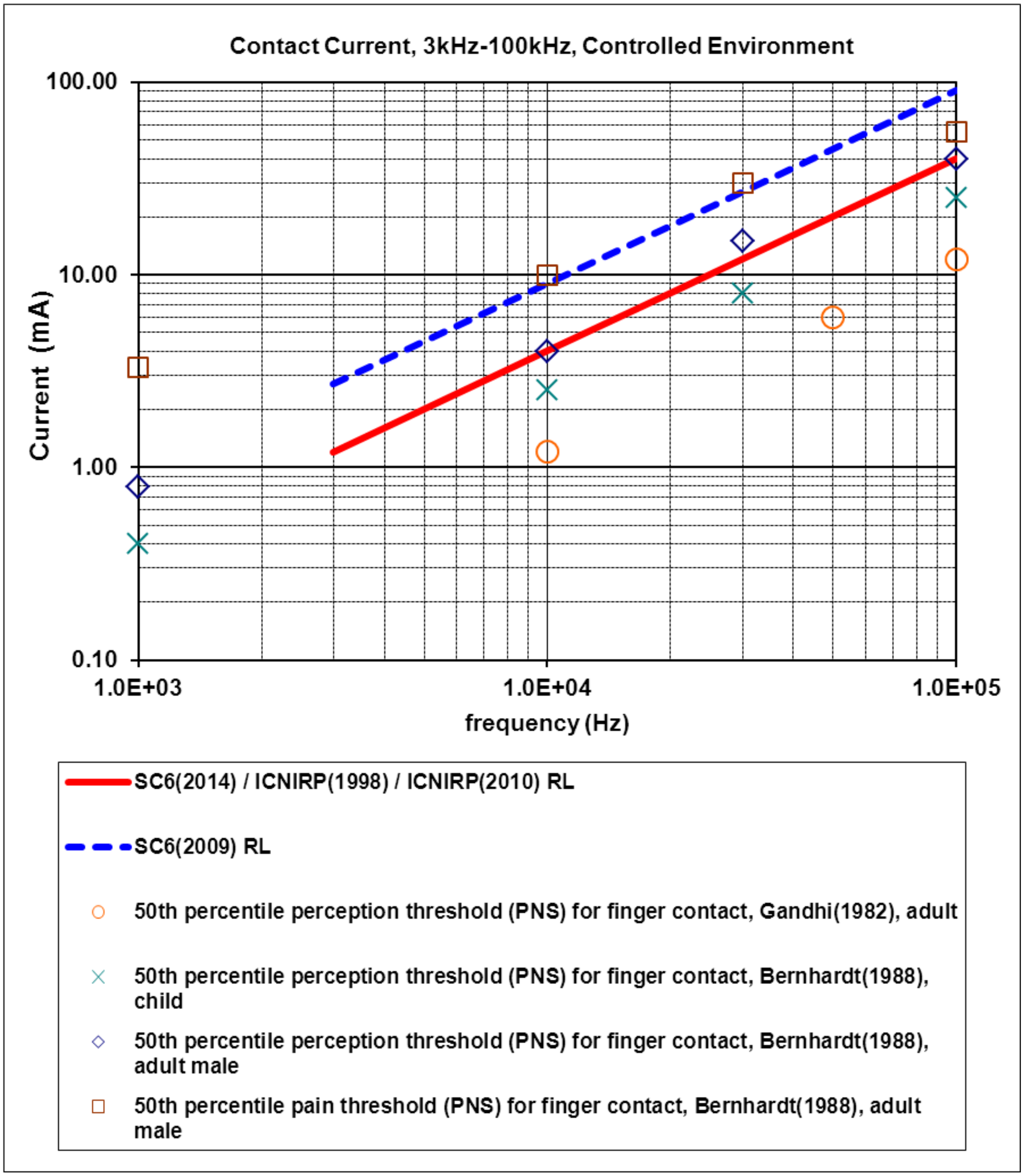

Figure 12. Controlled-Environment contact current reference levels for the 3 - 100 kHz frequency range in SC6 (2015). Also depicted are the 50th percentile perception threshold currents (adult and children) for finger contact.

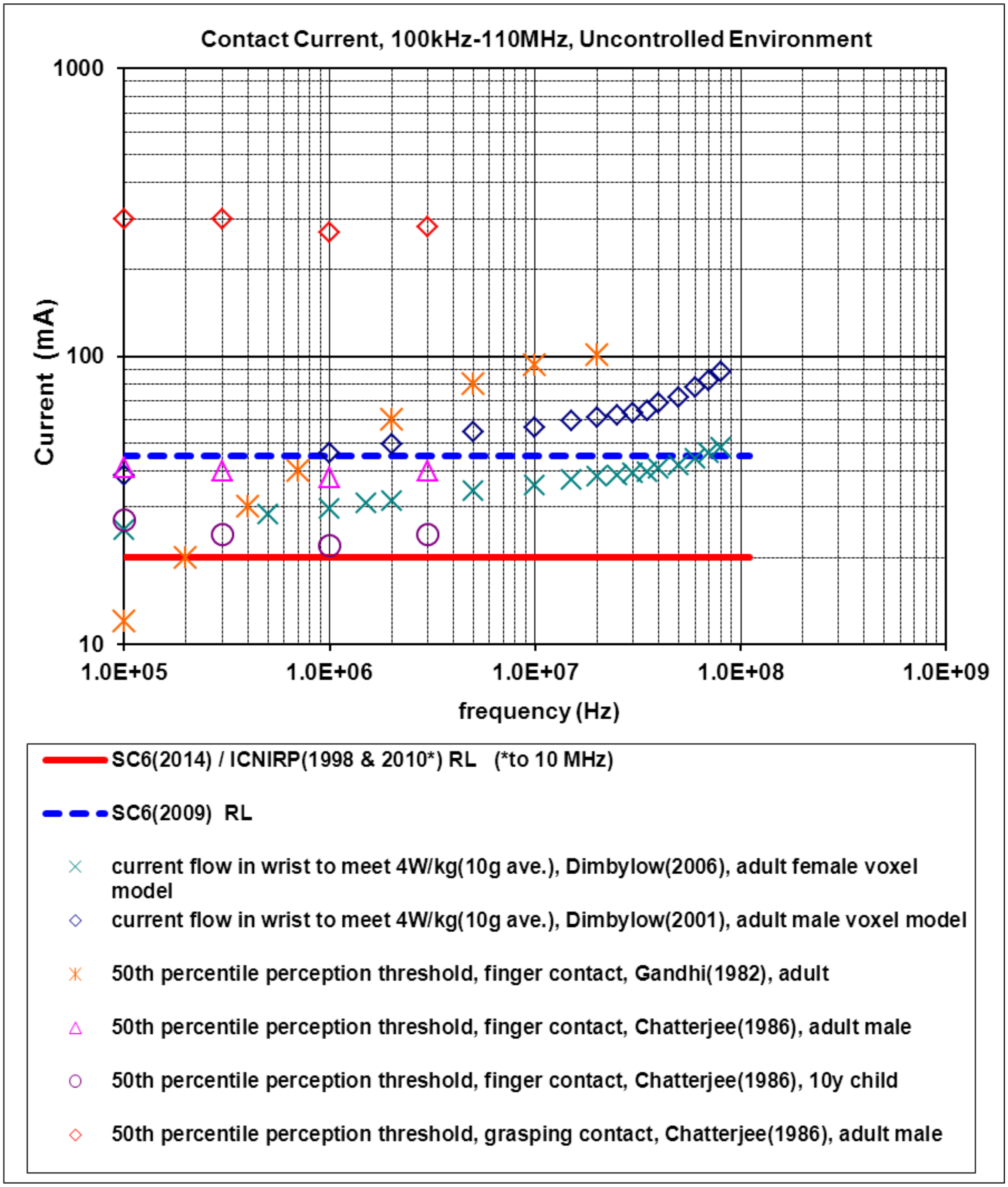

Figure 13. Uncontrolled-Environment contact current reference levels in SC6 (2015) in the 100 kHz – 110 MHz frequency range. Also plotted are the 50th percentile perception currents for finger-contact for adults and children, and the contact currents flowing in the wrist required to meet the basic restriction on peak spatially-averaged SAR in the limbs of 4 W/kg averaged over 10 g.

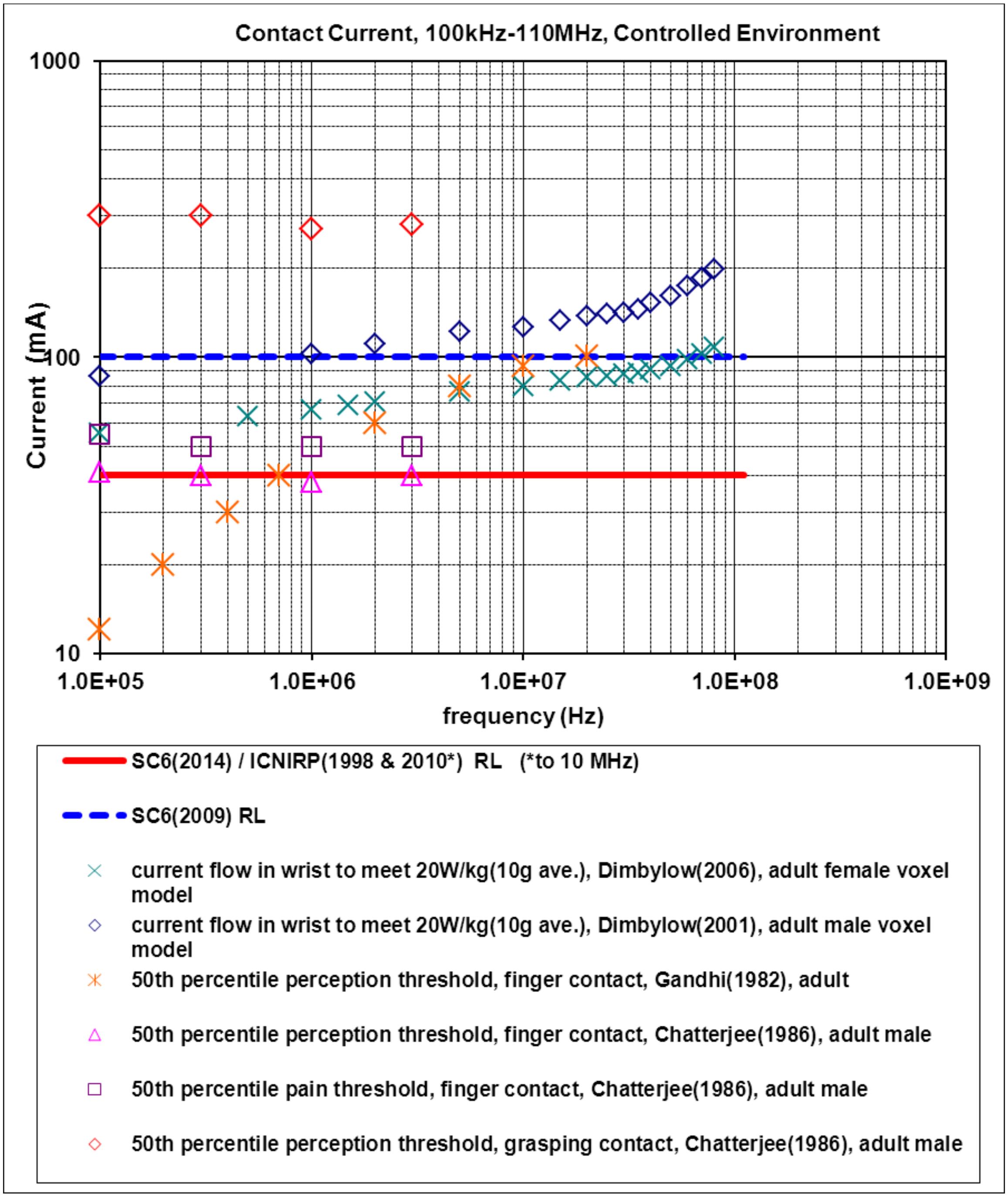

Figure 14. Controlled-Environment contact current reference levels in SC6 (2015) in the 100 kHz – 110 MHz frequency range. Also plotted are the 50th percentile perception currents for finger-contact for adults and children, the pain threshold for adults for finger contact, and the contact currents flowing 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.

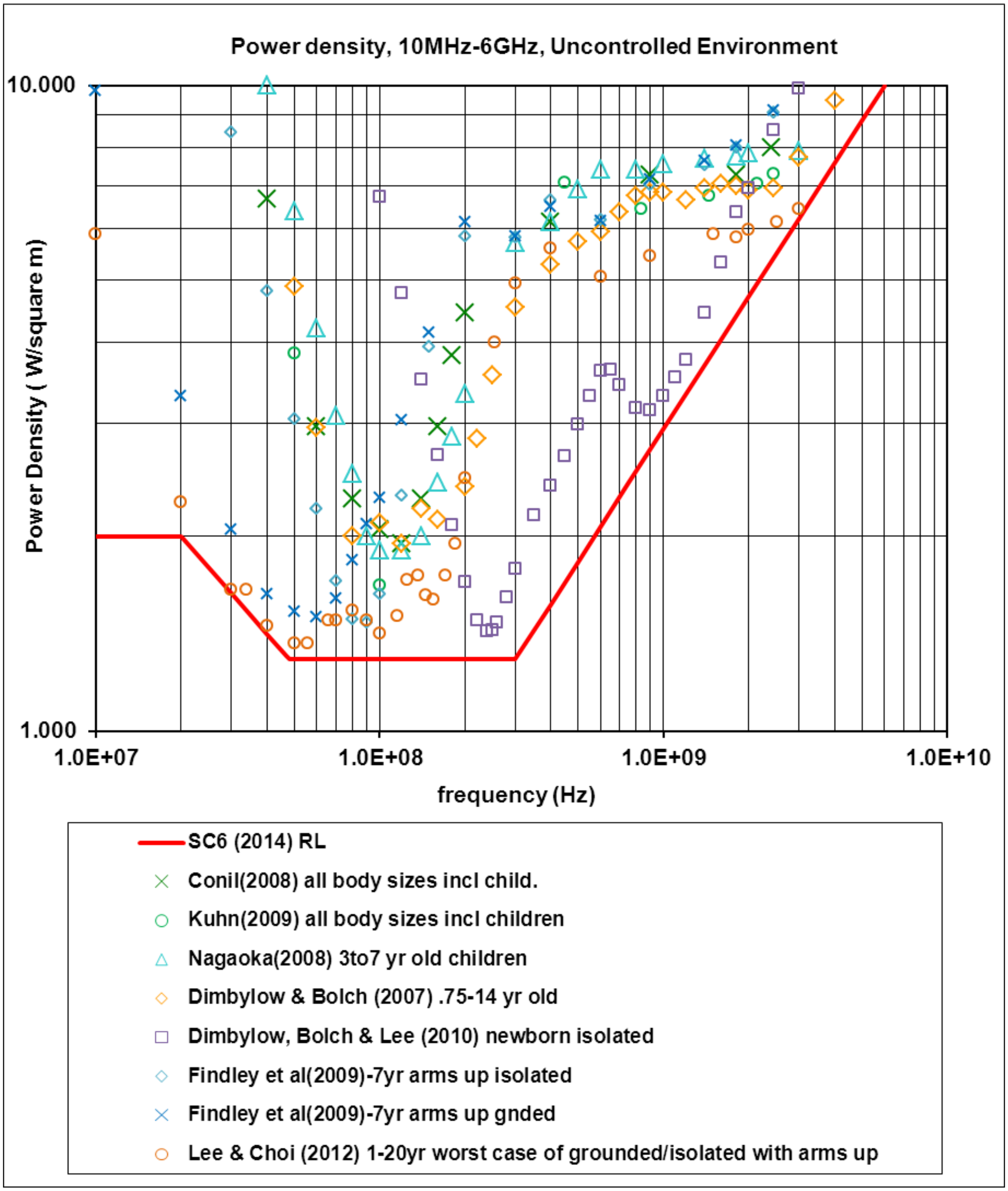

Figure 15. Plane–wave power densities necessary to produce the WBA-SAR basic restriction of 0.08 W/kg in different voxel models under various exposure conditions. Also plotted are the SC6 (2015) Uncontrolled Environment power density reference levels (red line).

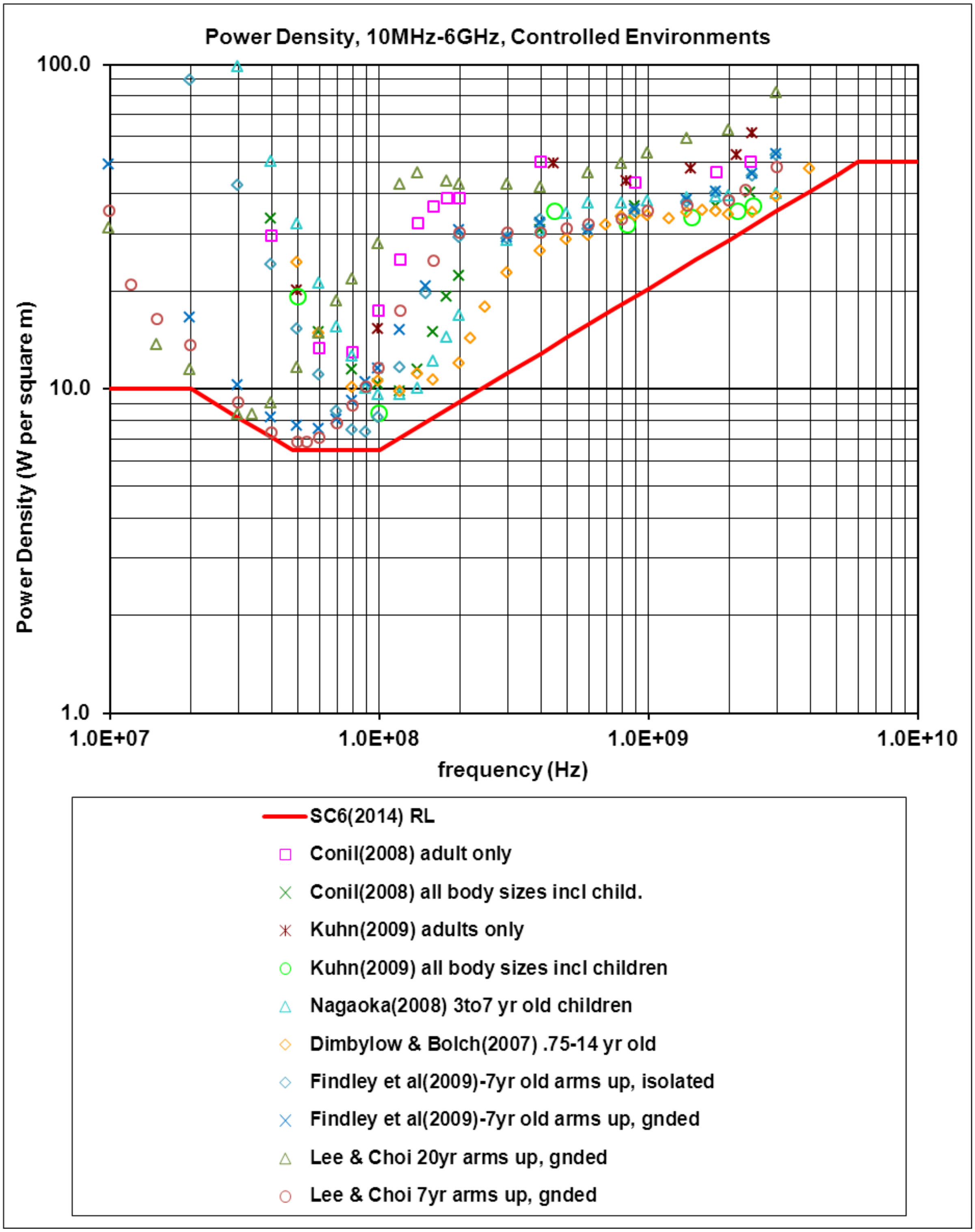

Figure 16. Plane–wave power densities necessary to produce the WBA-SAR basic restriction of 0.4 W/kg in different voxel models under various exposure conditions. Also plotted are the SC6 (2015; red line) Controlled Environment power density reference levels.

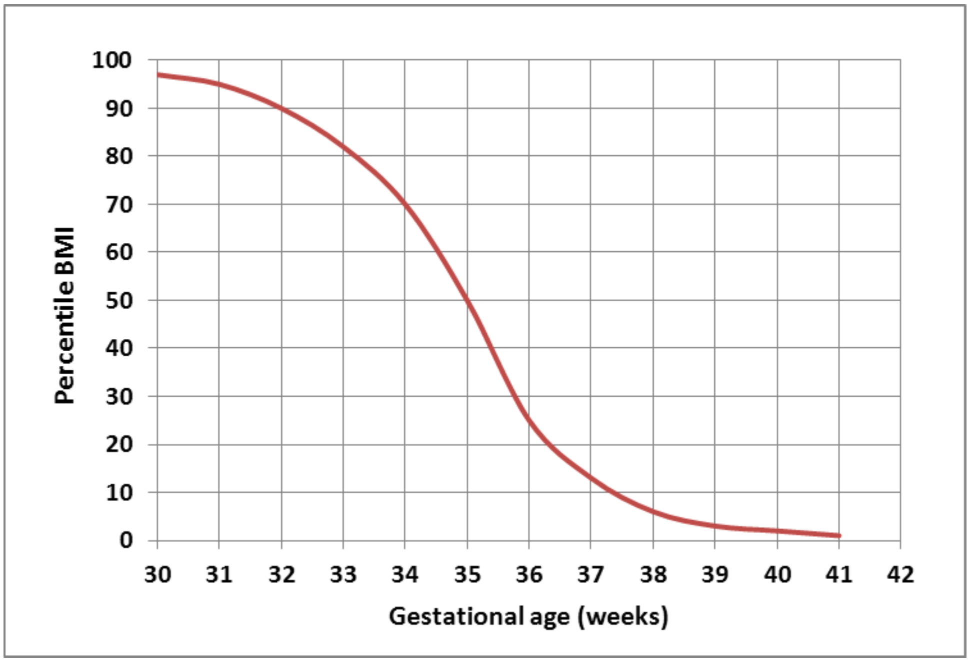

Figure 17. Percentile BMI versus gestational age for which the power density reference level of 1.29 W/m^2 is compliant with the 0.08 W/kg basic restriction, based on the isolated, whole-body resonance formula in Hirata (2010).