SYSTEMATIC DERIVATION OF SAFETY LIMITS FOR TIME-VARYING 5G RADIOFREQUENCY EXPOSURE BASED ON ANALYTICAL MODELS AND THERMAL DOSE

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***Abstract*—Extreme broadband wireless devices operating above 10 GHz may transmit data in bursts of a few milliseconds to seconds. Even though the time- and area-averaged power density values remain within the acceptable safety limits for continuous exposure, these bursts may lead to short temperature spikes in the skin of exposed people. In this paper, a novel analytical approach to pulsed heating is developed and applied to assess the peak-to-average temperature ratio as a function of the pulse fraction α (relative to the averaging time ΔT; it corresponds to the inverse of the peak-to-average ratio). This has been analyzed for two different perfusion-related thermal time constants (τ_1 = 100 s and 500 s) corresponding to plane-wave and localized exposures. To allow for peak temperatures that considerably exceed the 1 K increase, the CEM43 tissue damage model, with an experimental-data-based damage threshold for human skin of 600 min, is used to allow large temperature oscillations that remain below the level at which tissue damage occurs. To stay consistent with the current safety guidelines, safety factors of 10 for occupational exposure and 50 for the general public were applied. The model assumptions and limitations (e.g., employed thermal and tissue damage models, homogeneous skin, consideration of localized exposure by a modified time constant) are discussed in detail. The results demonstrate that the maximum averaging time, based on the assumption of a thermal time constant of 100 s, is 240 s if the maximum local temperature increase for continuous-wave exposure is limited to 1 K and α ≥ 0.1. For a very low peak-to-average ratio of 100 (α ≥ 0.01), it decreases to only 30 s. The results also show that the peak-to-average ratio of 1,000 tolerated by the International Council on Non-Ionizing Radiation Protection guidelines may lead to permanent tissue damage after even short exposures, highlighting the importance of revisiting existing exposure guidelines.**
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Key words: dosimetry; electromagnetic fields; exposure, radiofrequency; radiofrequency

INTRODUCTION

THE FIFTH generation of wireless communication technology (5G) promises to facilitate transmission at data rates up to a factor of 100 times higher than 4G. For that purpose, higher frequencies (including millimeter-wave bands), broadband modulation schemes, and thus faster signals with steeper rise and fall times will be employed, potentially in combination with pulsed operation for time domain multiple access. 5G is designed as a ubiquitous communication system spanning applications such as high-bandwidth mobile data and telephony, real-time machine-to-machine communication (e.g., autonomous mobility), and the Internet of Things (IoT). Exposure to radiofrequency (RF) radiation from wireless devices to large radar installations and medical equipment can result in increases in body core temperature or cause localized temperature rises, with the potential for adverse health effects. The thresholds for frequencies above 10 MHz set in current exposure guidelines (ICNIRP 1998; IEEE 2005, 2010) are intended to limit tissue heating. As exposure is frequently transient and pulsed, rather than continuous, limits are expressed in terms of time-averaged quantities. The International Council on Non-Ionizing Radiation Protection (ICNIRP) defines an averaging time of $68 f_G^{-1.05}$ min (where f_G is the frequency in GHz), while IEEE specifies $19.63 f_G^{-1.079}$ min for frequencies below 30 GHz and $2.524 f_G^{-0.476}$ min for those above. The averaging durations have been derived considering the time constant of in vivo temperature evolution. However, short pulses can lead to important temperature oscillations, which may be further exacerbated at high frequencies (>10 GHz, fundamental to 5G), where the shallow penetration depth leads to intense surface heating and a steep, rapid rise in temperature (e.g., proportional to $\sqrt{t}$ for plane-wave exposure [Foster et al. 2016]). The recommendations in the ICNIRP guidelines limit the power density during short pulses to 1,000 times the limit for the time-averaged incident power density. The IEEE standard limits the radiant exposure (energy absorption per unit area) during any 100 ms to one-fifth of the total radiant exposure for the whole averaging time. The physical or biological rationales for these limits, however, are not provided.

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Laakso et al. (2017) investigated the mean and maximal temperature of such oscillations by simulating the exposure of anatomical models to a single pulse of plane-wave exposure, with varying pulse durations and frequencies in the range of 6–100 GHz. The authors conclude that the current guidelines do not adequately prevent excessive heating from pulsed exposure, as peak temperatures can easily exceed the mean temperature by more than a factor of 3 and suggest that radiant exposure limits be introduced. Morimoto et al. (2017) studied the time constants for temperature elevation in simplified models, as well as in anatomical models fitted with detailed skin, for exposure to dipole antennas and beams. They conclude that the thermal time constants can be as short as 30 s for narrow-beam exposures and that short pulses can carry enough energy to cause injuries; the appendix includes a qualitative discussion based on step-response functions and their Fourier transforms, providing insight into the time constants of the temperature rise and fall, respectively. Both publications focus on single pulses, and there is no discussion of the quasistatic worst-case scenario of an extended pulse train, in which previous pulses have created a background temperature increase through diffusion on which freshly arriving pulses superimpose rapid, localized heating. Furthermore, none of the papers provides a closed-form analytical treatment of pulsed exposure with objective criteria for safe transient exposures.

In view of the revision of safety standards currently ongoing, the aim of this study is to:

- Analytically derive a model for worst-case transient heating and a simple approximation formula for short pulses;
- Introduce objective criteria to derive safety limits (based on relative oscillation magnitudes and a thermal dose concept previously employed to derive magnetic resonance imaging [MRI] exposure safety guidelines);
- Apply the approach to plane-wave exposure and to situations with smaller thermal time constants that are relevant for localized exposure; and
- Discuss the underlying assumptions and resulting conclusions with regard to standardization.

THEORY

Oscillation magnitude

General solution. The largest temperature oscillations occur when the entire deliverable power over one time-averaging interval is deposited during a small fraction α of the averaging period Δt at an intensity I_0/α, where I_0 is the threshold for the time-averaged intensity over the entire averaging period Δt. For prolonged exposure over multiple averaging periods, this corresponds to a pulse train. Assuming a linear differential equation for the transient temperature evolution, a step-response function $S(t)$ (i.e., the transient temperature evolution as a result of activating exposure at one intensity unit; the system response to a Heaviside step function) can be defined. In the extreme case of energy delivery during the first fraction of the averaging period, the oscillation minimum temperature in the quasi-steady-state regime becomes $T_{\min} = lim_{n\to\infty}\sum_{i=1}^{n}(I_0/\alpha)\{S(i\Delta t)-S([i-\alpha]\Delta t)\}$, while the oscillation maximum temperature is $T_{max} = (I_0/\alpha)\,S(\alpha\Delta t) + lim_{n\to\infty}\sum_{i=1}^{n}(I_0/\alpha)\{S([i+\alpha]\Delta t) - S(i\Delta t)\}$. Provided that the step-response function monotonically increases but remains finite, these infinite sums converge, as they are alternating series with monotonically decreasing and ultimately vanishing absolute values of the summands. Thus, the oscillation magnitude $\Delta T(\alpha)$ is:

$$(I_0/a)\times S(\alpha\Delta t) + (I_0/\alpha) \times lim_{n\to\infty}\sum_{i=1}^{n}\{S([i-\alpha]\Delta t) - 2S(i\Delta t) + S([i+\alpha]\Delta t)\}. \quad (1)$$

For $\alpha = 1$ (continuous exposure), eqn (1) becomes $\Delta T(1) = lim_{n\to\infty} I_0 \times \{S(0) - S(n\Delta t) + S([n+1]\Delta t)\}$. $S(0)$ must be zero and assuming that $lim_{n\to\infty} S(t) = S_{\max}$ (the step-response function asymptotically reaches a maximal temperature), $\Delta T(1) = I_0[0°C/(W\ m^{-2}) - S_{\max} + S_{\max}] = 0°C$; there are no oscillations for continuous exposure, as expected. In the limit of extremely small α, the term under the infinite sum in eqn (1) can be seen as a finite difference approximation of $\alpha^2\frac{d^2S(i\Delta t)}{dt^2}$ and

$$\Delta T(\alpha) \approx (I_0/\alpha)\,S(\alpha\Delta t) + I_0\alpha\, lim_{n\to\infty}\sum_{i=1}^{n} S''(i\Delta t). \quad (2)$$

As α becomes smaller, the first term in eqn (2) dominates and approaches $I_0\,\Delta t \times S'(\alpha\Delta T/2)$, while the second term vanishes.

Superficial plane-wave heating, PBE. The transient surface temperature step-response function for the Pennes bioheat equation (PBE) in the limit of plane-wave exposure of a homogeneous half space with negligible wave penetration depth is: $S_{\mathrm{PBE}}(t) = \frac{F_T}{\rho\sqrt{Km_bC}} \times erf\left(\sqrt{\frac{t}{\tau_1}}\right)$ (Foster et al. 2016), where *erf* is the error function, $\tau_1 = 1/(m_b\,\rho)$ is the perfusion-related thermal time constant, and F_T is the power transfer factor from air to skin. This is a suitable approximation for far-field exposure (distances greater than a few centimeters) for most of the 5G frequency range. The extremely rapid initial rise of the Green's function is a result of the small penetration depth. In fact, $I_0\,\Delta t \times S'_{\mathrm{PBE}}(0) = \infty$. $I_0\alpha\, lim_{n\to\infty}\sum_{i=1}^{n} S''(i\Delta t)$ is equal to:

$$(I_0\alpha)\times\frac{F_T}{\rho\sqrt{Km_bC}}\times\left(-\frac{2\Delta t Li_{1/2}\left(e^{-\Delta t/\tau_1}\right) + \tau_1 Li_{3/2}\left(e^{-\Delta t/\tau_1}\right)}{2(\tau_1\Delta t)^{3/2}\sqrt{\pi}}\right) \quad (3)$$

(Mathematica 9.0, Wolfram Research, Inc., Champaign, Illinois, U.S.), where Li_s is the polylogarithm of order s. Eqn (3) is

finite for $\Delta t > 0$ and hence can be neglected when α is sufficiently small in comparison to $I_0 \frac{S(\alpha \Delta t)}{\alpha}$.

For sufficiently small α (see Results section), the relative oscillation is:

$$\frac{\Delta T(\alpha)}{I_0\, S_{\mathrm{PBE}}(\infty)} \approx \frac{erf\left(\sqrt{\frac{\alpha \Delta t}{\tau_1}}\right)}{\alpha}. \quad (4)$$

From this relationship, a maximal averaging time Δt that maintains the oscillation below a certain percentage level can be found for any given α and τ_1.

Superficial localized heating, PBE. A similar approach can be applied for localized exposures (e.g., transmitter, such as a cell phone, in body vicinity). Assuming a Gaussian power-density beam of width w, $I(R) = I_0 \times e^{-R^2/(2w^2)}$, and utilizing the four-dimensional, spherically symmetric Green's function from Yeung et al. (2016) multiplied by a factor of 2 to be applicable to the heating of a half space with isolating boundary conditions, one obtains for the step function:

$$S_{\mathrm{PBE}}(t, w) = \frac{F_T \sqrt{\rho C}}{4(K\pi)^{3/2}} \int_0^t \int_0^\infty e^{-R^2 \rho C/4Kt'} \times e^{-t'/\tau_1} \times e^{-R^2/(2w^2)} / t'^{3/2} \times (2\pi R)\, dR\, dt'. \quad (5)$$

While the integral over R can be evaluated analytically, $\int_0^\infty e^{-R2/4Kt'} \times e^{-R^2/(2w^2)} \times (2\pi R) dR = 4\pi K t' w^2/(2Kt' + w^2 \rho C)$, no closed form for the integral over t' could be found. Only when the beam width is much larger than the thermal diffusion length, $4\pi K t' w^2/(2Kt' + w^2 \rho C) \approx 4\pi K t/(\rho C)$, can both integrals be solved analytically. In that case, the plane-wave $S_{\mathrm{PBE}}(t)$ is recovered.

Thermal dose (CEM43)

CEM43 is a thermal dose concept (Sapareto and Dewey 1984) that permits the effect of transient heating to be translated to an equivalent (in terms of effect) number of minutes of heating at 43°C. CEM43 thresholds for a wide range of tissues have been extracted from a comprehensive literature review for the purpose of establishing MRI safety guidelines (Van Rhoon et al. 2013). For skin, damage has been observed in humans at 600 min CEM43 and in animals (mice) at 240 min CEM43. The CEM43 dose can be computed by evaluating $\int R^{T(t)\,-\,43} dt$, where $T(t)$ is the temperature in °C and $R = 2$ for $T > 43$°C or $R = 4$ for $T \leq 43$°C.

In the quasi-steady-state, $T(t) = T_0 + I_0/\alpha \times \left(S(t) + \sum_{i=1}^{\infty} \{S(t + i\Delta t) - S(t + [i-\alpha]\Delta t)\}\right)$ during the pulse period $0 \leq t < \alpha \Delta t$, and $T(t) = T_0 + I_0/\alpha \times \sum_{i=0}^{\infty} \{S(t + i\Delta t) - S(t + [i-\alpha]\Delta t)\}$ during the interval $\alpha \Delta t \leq t < \Delta t$ before the next pulse, where T_0 is the skin temperature in the absence of exposure. Based on these formulas, the CEM43 density per time interval $\left(\overline{\mathrm{CEM43}}(\alpha, \Delta t) = \int_0^{\Delta t} R^{T(t)-43} dt/\Delta t\right)$ can be evaluated numerically by averaging $R^{T(t)-43}$ over one oscillation (Δt) period. The maximum exposure duration as a function of α and Δt is then obtained as $t_{\max} = L_{\mathrm{CEM43}} / \overline{\mathrm{CEM43}}(\alpha, \Delta t)$, where L_{CEM43} is the thermal dose limit, and by inversion a limit on the minimal α as a function of maximal exposure time can be determined [$\alpha_{\min} = f(t_{\max}, \Delta t)$]. Typically, this cannot be performed analytically but rather, requires numerical solving.

Tissue properties

For the subsequent applied analysis, the following tissue properties are required:

- Skin base temperature (T_0): To obtain conservative limits, realistic worst-case skin temperature values are required. While the skin temperature under indoor conditions is on the order of 34°C, hot and humid environments lead to increases in skin temperature (Gonzalez-Alonso et al. 1999; Wyndham et al. 1976; Eichna et al. 1950) to a value of T_0 = 37°C (and even higher during initial exposure, i.e., before acclimatization). The subsequent analysis can easily be transferred to other T_0 values, as lowering it by 1° simply results in a 4-fold increase of the CEM43-constrained exposure time;
- Thermal time constant (τ_1): Foster et al. (2016) specifies τ_1 = 500 s, based on a perfusion value of 106 mL min^{-1} kg^{-1}. The effective perfusion of 30 mL min^{-1} kg^{-1} observed by Carrasco et al. (2018) at frequencies >30 GHz, where the penetration is shallow and the principal heating occurs in poorly or unperfused skin layers, results in $\tau_1 \approx 2000$ s. A change of τ_1 in the subsequent results simply corresponds to a proportional change in Δt, as the plane-wave exposure equations' dependence on these two variables is always of the form $\Delta t/\tau_1$; and
- Thermal dose limit (L_{CEM43}): The results below were computed assuming L_{CEM43} = 12 min and L_{CEM43} = 60 min, which is based on the lowest thermal dose (600 min) where adverse thermal effects have been observed in human skin according to Van Rhoon et al. (2013), divided by the same safety factors as used in current safety guidelines (50 and 10) for exposure of the general public and occupational exposure, respectively. The results can easily be scaled to other thermal dose limits.

RESULTS

The core of the results presented were computed based on the assumption that τ_1 = 500 s (Foster et al. 2016). In addition, some of the thermal-dose-related results are also presented for τ_1 = 100 s, which is the time-constant order observed for localized exposures at high frequencies (Morimoto et al. 2017). It must be noted that

the plane-wave step-response function with modified τ_1 is only approximately applicable to the localized exposure case, as described above under Theory: Oscillation magnitude. However, it is a good approximation that is amenable to analytical treatment. As previously discussed, rescaling τ_1 is equivalent to rescaling Δt in the plane-wave exposure case.

Oscillation magnitude

An example of the transient temperature during a single oscillation period is shown in Fig. 1.

Fig. 2 shows the relative oscillation magnitude according to eqn (2), as well as the normalized oscillation minimum and maximum temperatures as a function of α for different values of $\Delta t/\tau_1$. It also shows the relative oscillation magnitude according to eqn (2) as a function of $\Delta t/\tau_1$ for different values of α.

In view of transmission bursts on very short timescales, the relative oscillation magnitude was also computed assuming an averaging time of 10 and 100 ms and a burst duration of 1–100 μs (Fig. 3).

To verify the approximation (derived for the limit of small α) of the relative oscillation magnitude in eqn (4), Fig. 4 shows a comparison with the numerically solved exact formula derived from eqn (2). Good agreement is found for α below 40%. For increased accuracy, all results in the remainder of this paper have been computed without resorting to the small α approximation.

CEM43. Based on $\overline{\text{CEM43}}$ as a function of α for different values of Δt, Fig. 5 illustrates the relationship between t_{max} and α. Results are provided for averaged intensities leading to 1 K and 4 K temperature increases at continuous exposure and for two values of τ_1 (500 s and 100 s) to mimic plane-wave and localized exposure.

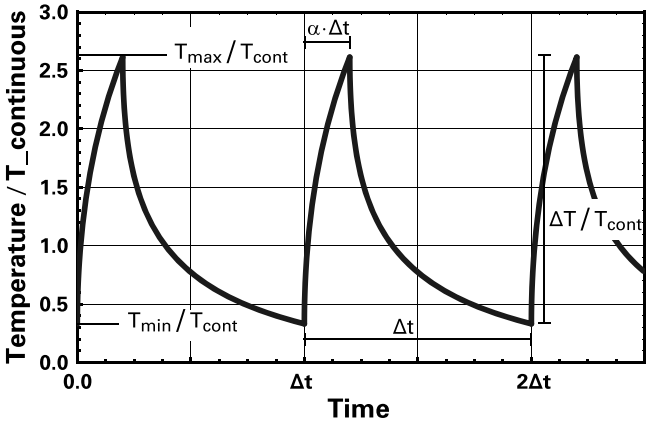

Fig. 1. Transient temperature oscillations resulting from a pulse train, computed for $\Delta t = \tau_1$ and $\alpha = 20\%$ at an intensity resulting in a temperature increase of 1 K at continuous exposure. T_{min}: minimum temperature; T_{max}: maximum temperature; T_{cont}: temperature at continuous exposure.

DISCUSSION

Assumptions

The presented theory and results are generally valid provided the following assumptions are satisfied:

- The underlying partial differential equation that describes heating is linear, such that a step function can be defined. This assumption is reasonable, provided the heating remains sufficiently small for thermoregulation to not significantly affect the tissue properties, especially perfusion. Continuous exposure at an intensity resulting in a temperature increase of 1° certainly satisfies that condition. When the temperature increase becomes important, thermoregulation sets in and perfusion increases, resulting in a shorter τ_1, and the relative oscillations become more prominent;
- The location of peak temperature is also the location with the highest CEM43 per time density. While this condition is satisfied for the step functions investigated in this study, it is not necessarily correct, e.g., in inhomogeneous models where the time constant is variable. In such cases, the theory is still applicable, provided the step function of the location with the highest CEM43 is used instead; and
- The CEM43 dose concept is suitable for setting safety thresholds. CEM43 has proven to be a valuable metric for prediction of tissue damage across a wide variety of tissues and exposure conditions, including therapeutic applications. Still, there are open issues regarding, e.g., suitable recovery periods or translation of some experimental data from animal to human tissues. Furthermore, although the CEM43 concept has not yet been experimentally established for very short pulses, the CEM43 thermal dose model is applied here for oscillations on all timescales.

The application of the presented theory in conjunction with the PBE step or Green's functions introduces a range of additional assumptions and approximations:

- All investigated step functions have been derived under simplified conditions of (1) homogeneous tissue (skin is layered and inhomogeneous [Christ et al. 2018]), (2) isolating boundary conditions (conservative), and (3) surface energy deposition (negligible penetration depth—an assumption well satisfied at least for frequencies above 30 GHz [Carrasco et al. 2018]); and
- The PBE itself is an approximative model (Arkin et al. 1994; Bhowmik et al. 2013).

The analysis has been performed with regard to skin heating, which is the relevant safety concern at high frequencies. However, the presented approach is also suitable for the general assessment of (deep) tissue heating. In this

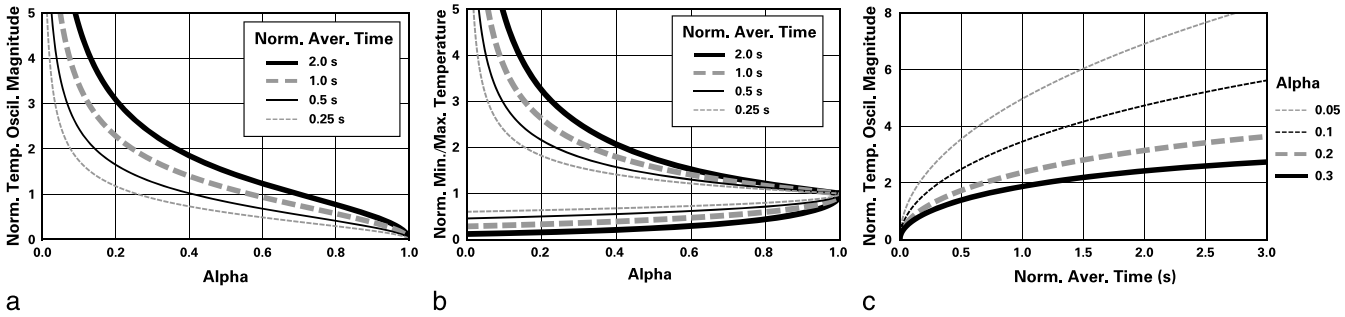

Fig. 2. (a) The oscillation magnitude according to eqn (2). (b) Maximum/minimum temperature during the oscillation period as a function of α for $\Delta t/\tau_1$ ranging from 0.25–2 (normalized to the temperature increase for continuous exposure, α = 100%). For a time constant τ_1 = 500 s (typical for plane-wave exposure), this corresponds to an averaging time range of 125–1,000 s, while for a time constant τ_1 = 100 s (relevant for localized exposure), this corresponds to an averaging time range of 25–200 s. (c) The normalized oscillation magnitude according to eqn (2) as a function of $\Delta t/\tau_1$ for α ranging from 0.05–0.3. For a time constant τ_1 = 500 s (respectively 100 s), the range up to $\Delta t/\tau_1$ = 3 corresponds to an averaging time of up to 1,500 s (respectively 300 s). Norm. Temp. Oscil. Magnitude: normalized temperature oscillation magnitude; Norm. Aver. Time: normalized averaging time; Norm. Min./Max. Temperature: normalized minimum/maximum temperature.

case, the thermal dose limits must be adapted accordingly, e.g., based on Van Rhoon et al. (2013), and suitable step-response functions must be determined (e.g., through four-dimensional electromagnetic and thermal simulations involving detailed anatomical models).

Standardization

As apparent from the presented results, the temperature oscillations become very large (≫10) (Fig. 2) when α is on the order of 0.001—i.e., within the duty-cycle limit of 1,000 suggested by ICNIRP guidelines (similarly for the limitation to energy delivery within 500 ms implied by the IEEE standard)—resulting in high thermal-dose-accumulation rates and short-exposure-duration constraints (≪1 s for localized exposure) (Fig. 5) that are unacceptable for regulatory purposes. Similarly, imposing limits on fluence or radiant exposure, as recommended (Morimoto et al. 2017; Laakso et al. 2017), without restricting the PAR, is not suitable. The thermal dose also escalates when the continuous exposure temperature increase (CETI) is on the order of 4 K (Fig. 5). Hence, the following recommendations are made:

- Limitation of CETI: A CETI limit of 1 K should be established;
- Introduction of two averaging times: A short averaging time that allows for bursts short enough to not significantly affect the temperature is introduced. Fig. 3 shows that for bursts longer than 30 μs, an averaging time of 10 ms produces a relative oscillation magnitude below 20%. In addition, a longer averaging time similar to the one used in current standards is maintained; and
- Derivation of limits from thermal dose considerations: Limits on averaging time and PAR can be derived from thermal dose considerations, as illustrated below.

The use of CEM43 thresholds of 12 min for the general public and 60 min for occupational exposure, in combination with maximal exposure durations of 18 h for the general public and 8 h for occupational exposure, allows limits on averaging time and PAR to be derived as a function

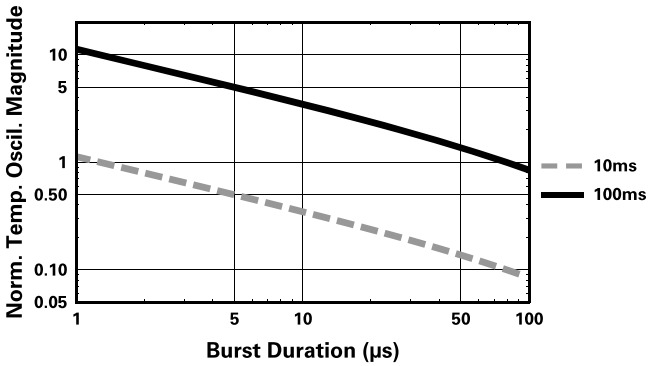

Fig. 3. Relative temperature oscillation magnitude as a function of burst duration for an averaging time of 10 or 100 ms. Norm. Temp. Oscil. Magnitude: normalized temperature oscillation magnitude.

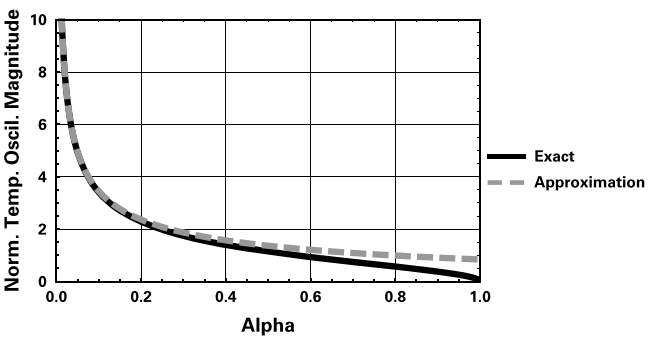

Fig. 4. Comparison of the exact formula for the relative oscillation magnitude derived from eqn (2) with the approximation in eqn (4), as a function of α (shown here for $\Delta t = \tau_1$). Norm. Temp. Oscil. Magnitude: normalized temperature oscillation magnitude.

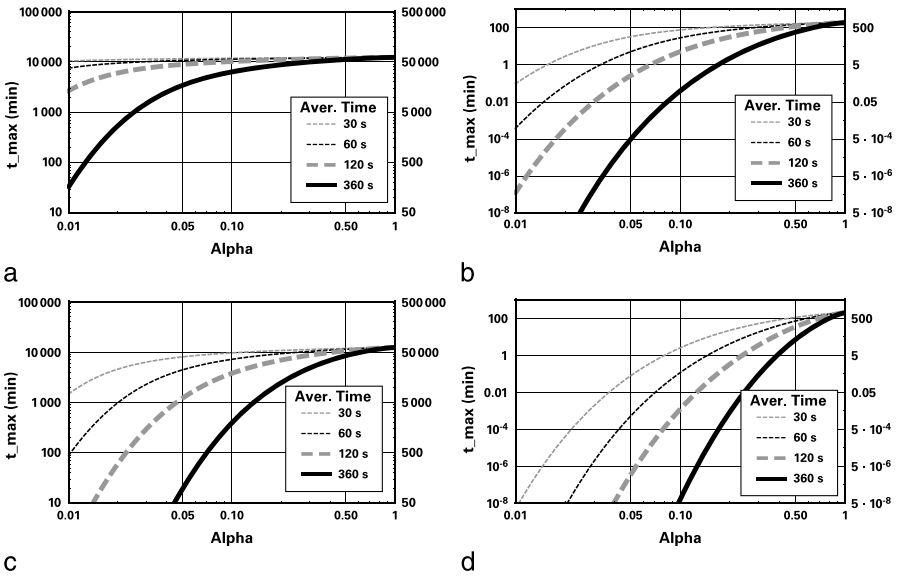

Fig. 5. t_{max} (t_max) as a function of α for different values of Δt and different thresholds of L_{CEM43} (left scale: general public; right scale: occupational exposure). Shown for averaged intensities leading to temperature increases of 1 K (a,c) and 4 K (b,d) under conditions of continuous exposure. Assuming two values of τ_1, 500 s (a,b) and 100 s (c,d), to mimic plane-wave and localized exposure, respectively. Aver. Time: averaging time.

of α (respectively PAR), as shown in Fig. 6. For example, when a CETI of 1 K and α ≥ 0.01 is assumed, the maximal averaging time for the general public would be around 30 s; for α ≥ 0.1, it increases to 4 min; and for α ≥ 0.001 (the PAR of 1,000 tolerated by ICNIRP), it decreases to 5 s. A CETI of 4 K, as currently contemplated by standardization bodies, is not feasible, as any temperature above 39.8°C would result in the general public CEM43 limit of 12 min before 18 h of exposure being exceeded. At a 2.8 K CETI, modulation would be prohibited (α = 100%), and the allowable maximum PAR increases (minimum α decreases) with decreasing CETI (Fig. 6).

CONCLUSION

Transient exposure with high PAR can lead to large temperature oscillations, with peak temperature increases in the skin reaching tens of degrees, thus exceeding tissue damage thresholds after short exposure durations. Thresholds for fluence alone do not guarantee safety. In this paper, a novel analytical approach to assessing the temperature oscillation magnitude for transient exposure in the quasi-steady-state regime has been developed and applied to plane-wave and localized exposures. Application of thermal dose considerations and limits derived from experimental data on thermal skin damage allow derivation of maximal averaging times as a function of the pulse duty cycle for occupational exposure and the general public. It is concluded that the CETI should be limited to 1 K in order to ensure safety when applying reasonably long averaging times (30–240 s) for devices that transmit data in bursts, as is typical for modern wireless communication systems. This becomes possible by imposing limits on PAR, while introducing a second averaging timescale on the order of

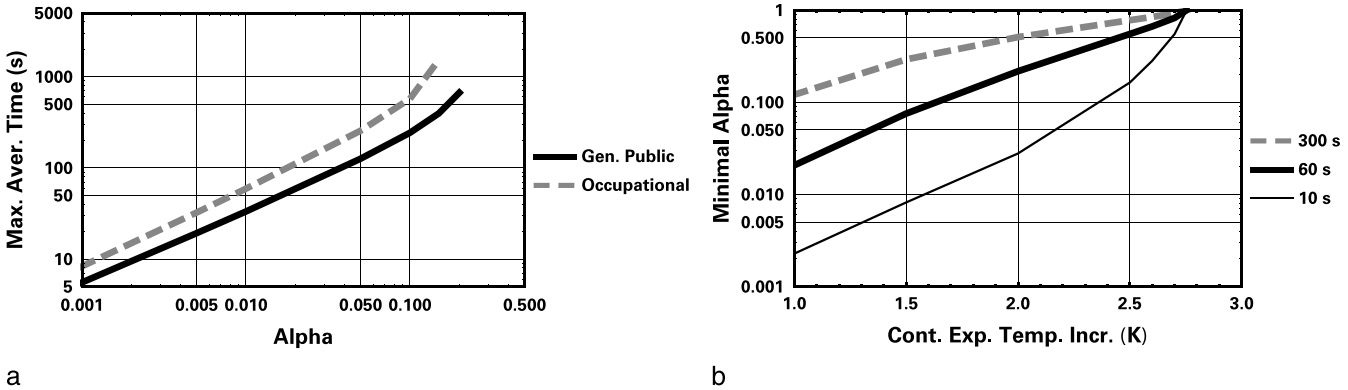

Fig. 6. (a) Maximum averaging time (Max. Aver. Time) as a function of α for the general (Gen.) public and occupational exposure, for a continuous exposure temperature increase of 1 K and for a time constant τ_1 = 100 s. (b) Minimum α as a function of the continuous exposure temperature increase (Cont. Exp. Temp. Incr.) to keep CEM43 below 12 min for an exposure of 18 h (suggested limit for the general public), computed with τ_1 = 100 s and three different averaging times (10, 30, and 60 s).

10 ms to allow for rapidly modulated signals. Another conclusion of this study is that the current ICNIRP (1998) and IEEE (2005, 2010) guidelines urgently need to be revised, as the duty cycle of 1,000 currently tolerated can produce unacceptable temperature increases that may result in permanent tissue damage.

The assumptions underlying the model and its limitations have been discussed. In view of standardization, which must be applicable globally, the computations are based on a skin base temperature of 37°C. A reduction by 1°C would increase the exposure time permitted by a factor of 4 and allow the averaging times or PAR constraints to be relaxed.

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