THERMAL MODELING FOR THE NEXT GENERATION OF RADIOFREQUENCY EXPOSURE LIMITS: COMMENTARY

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Abstract—**This commentary evaluates two sets of guidelines for human exposure to radiofrequency (RF) energy, focusing on the frequency range above the "transition" frequency at 3–10 GHz where the guidelines change their basic restrictions from specific absorption rate to incident power density, through the end of the RF band at 300 GHz. The analysis is based on a simple thermal model based on Pennes' bioheat equation (BHTE) (Pennes 1948) assuming purely surface heating; an Appendix provides more details about the model and its range of applicability. This analysis suggests that present limits are highly conservative relative to their stated goals of limiting temperature increase in tissue. As applied to transmitting devices used against the body, they are much more conservative than product safety standards for touch temperature for personal electronics equipment that are used in contact with the body. Provisions in the current guidelines for "averaging time" and "averaging area" are not consistent with scaling characteristics of the bioheat equation and should be refined. The authors suggest the need for additional limits on fluence for protection against brief, high intensity pulses at millimeter wave frequencies. This commentary considers only thermal hazards, which form the basis of the current guidelines, and excludes considerations of reported "non-thermal" effects of exposure that would have to be evaluated in the process of updating the guidelines.**
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INTRODUCTION

Exposure limits for radiofrequency (RF) energy have been in place for many years. The two major international guidelines are those of the International Commission on Nonionizing Radiation Protection (ICNIRP 1998) and the Institute of Electrical and Electronics Engineers (IEEE) (IEEE 2005). Most national limits [in the U.S., the limits of the Federal Communications Commission (FCC 2010)] are generally similar to IEEE and ICNIRP limits. All three sets of limits are in the process of revision and updating.

The frequency range above 3–10 GHz through the top of the RF band (300 GHz) has heretofore received relatively little attention by the committees that develop the guidelines, despite a large number of (generally low-powered) devices that already operate in this wide band (Fig. 1). Largely, this is because most devices operating in this frequency range have little potential for high-level exposure to humans, and partly because few consumer devices operate at present in this frequency range and there has been little controversy about the safety of such devices. However, this broad frequency band is about to gain much wider use with the introduction of a new generation (5 G) of wireless communications (Andrews et al. 2014) and the development of high-powered millimeter wave devices (30–300 GHz) for industrial and military applications.

The authors consider the present IEEE and ICNIRP limits and suggest potential improvements for the next generation of limits. This commentary considers scaling principles of heat transfer in tissue using analytical expressions that are obtained from relevant limiting approximations for RF exposure to tissue. The model assumes that incident RF energy on the body is absorbed exactly at the surface (surface heating approximation), which is an excellent approximation for millimeter waves (30–300 GHz) but overestimates temperature increases at lower frequencies. The model is described in more detail in the Appendix.

To avoid misinterpretation, the authors emphasize that they consider *only* thermal hazards and do not comment on the contentious issue of "non-thermal" effects, which would have to be evaluated by the expert panels that update the limits. Nor do they propose that the limits be based exclusively on the considerations presented here. Development of exposure guidelines is not an exact science but requires scientifically informed judgments regarding thresholds for effects and the magnitude of safety factors. However, the guidelines need to be valid over a wide range of exposure

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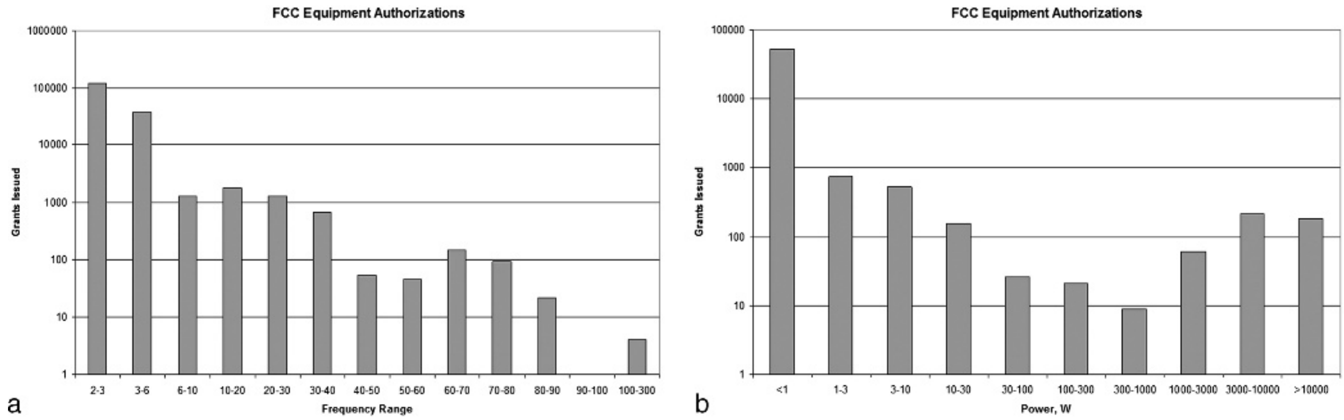

Fig. 1. FCC authorizations for devices > 2 GHz by frequency and power output. Each authorization (provided by FCC as a requirement to market a device in the U.S.) applies to a particular model of device. The number of authorizations does not indicate the number of devices that are actually in use for any particular model.

conditions, and this can only be assured by careful attention to the physics of interaction with the fields (or, for thermal hazards, to the thermal response of tissues to RF exposure).

Present IEEE and ICNIRP limits

Relevant parts of IEEE C95.1-2005 and ICNIRP (1998) are summarized in Table 1. At frequencies below 3–10 GHz (depending on the guideline), two sets of limits are provided: "basic restrictions" (in quantities that directly relate to hazards) and reference levels (in more easily measured quantities that will ensure compliance with the basic restrictions). Below 3–10 GHz (depending on the guideline), the basic restrictions are expressed in terms of specific absorption rate (SAR), which is the power deposited per unit mass of exposed tissue in W kg^{-1}, while reference levels are expressed in terms of incident power density (Wm^{-2}). Because of the technical difficulty of determining SAR at higher frequencies where the energy penetration depth is small, both guidelines have a "transition frequency" ranging from 3–10 GHz, above which the distinction between basic restrictions and reference levels is removed and the guidelines are stated in terms of incident power density only.

Thermal basis of limits

Both IEEE and ICNIRP limits are principally designed to avoid excessive heating to body tissues at microwave frequencies. While neither limit is framed explicitly in terms of temperature limits, both limits consider that increases of 1 °C in either core body temperature or local tissue temperature are acceptable:

- ICNIRP (1998): "Between 10 and 300 GHz, basic restrictions are provided on power density to prevent excessive heating in tissue at or near the body surface." (ICNIRP 1986)… "Established biological and health effects in the frequency range from 10 MHz to a few GHz are consistent with responses to a body temperature rise of more than 1°C."
- IEEE C95.1-2005 (quoting WHO 2003): "[A] 1°C rise in temperature, even in the most sensitive tissues and organs, is not adverse" (p. 78).

Both the IEEE and ICNIRP committees have recently sponsored workshops on thermal hazards that generally reaffirm these views (Foster and Morrissey 2011; Sienkiewicz et al. 2016). For near-surface heating, the most obvious thermal hazards (burns, thermal pain) require raising tissue temperature to levels of about 43–44 °C, which is about 10 °C above skin temperature in ordinary room environments. Thermal pain occurs very quickly after the threshold is reached, while thermal damage (burns) requires maintaining tissues above 43 °C for minutes or more, depending on the temperature elevation. Erythema ab igne (chronic reddening of skin due to thermal damage to microvasculature) is not mentioned in either the IEEE standard or ICNIRP limit but has been reported to occur after prolonged exposure to heat, including contact with warm laptop computer cases, at levels somewhat below the threshold for thermal pain (Corazza et al. 2016). Excessive whole-body heating, which drives the limits below 1 GHz, is not a significant issue at the frequencies presently considered because the shallow penetration depth into tissue results in excessive skin heating before sufficient total energy is deposited into the body to cause excessive thermal loads to the body.

Below are comments on the scaling properties of the BHTE as they relate to the design of the guidelines. The BHTE has an intrinsic distance scale R_1

$$R_1 = \frac{\sqrt{k}}{\rho\sqrt{m_b C}} \approx 7\,\text{mm}, \tag{1}$$

where ρ, k, and C are the density, thermal conductivity, and specific heat of the tissue, and m_b is the blood perfusion parameter in the BHTE (parameter values from Hasgall

Table 1. Comparison of ICNIRP, FCC, IEEE exposure limits above and below transition frequency.

1A. General public.

	ICNIRP	FCC	IEEE		
Range (GHz)	10–300	1.5–100	3–30	30–100	100–300
Transition frequency (GHz)	10	6		3	
Power density limit above transition frequency	10 (averaged over 20 cm^2)	10 (spatial peak limit)	10 (averaged over 100 λ^2), where λ is the free space wavelength	10 averaged over 100 cm^2	100 averaged over 100 cm^2
($W\ m^{-2}$);	200 (averaged over 1 cm^2)	(averaged over 1 cm^2)[a]	e.g., averaging area = 2,500 cm^2 at 6 GHz Spatial peak exposure $18.56\,f^{0.699}$	Spatial peak 1,000 $W\ m^{-2}$ in any 1 cm^2 Spatial peak exposure 200 $W\ m^{-2}$	(monotonic increase from 10 at 100 GHz to 100 at 300 GHz)
Averaging time (above transition)	Decreases from 6 min to 10 sec "to compensate for progressively shorter penetration depth as the frequency increases."		Decreases from 30 to 5 min over this frequency range	Decreases from 5 to 2.8 min	Decreases from 2.8 min to 10 s
SAR limit ($W\ kg^{-1}$) below the transition frequency, averaging mass of tissue	2 averaged over 10 g	1.6 averaged over 1 g	2 averaged over 10 g	2 averaged over 10 g	

1B. Occupational.

	ICNIRP	FCC	IEEE	
Frequency (GHz)	10–300	1.5–100	3–30	30–300
Transition frequency (GHz)	10	6	3	
Power density ($W\ m^{-2}$)	50 (averaged over 20 cm^2)	50	100 (averaged over 100 λ^2), where λ is the free space wavelength	100 averaged over 100 cm^2
	1,000 $W\ m^{-2}$ (averaged over 1 cm^2)	(averaged over 1 cm^2)[a]	e.g., averaging area = 2,500 cm^2 at 6 GHz	1000 $W\ m^{-2}$ averaged over 1 cm^2
			spatial peak exposure $200(f/3)^{0.2}$ between 3–96 GHz	Spatial peak exposure 400 $W\ m^{-2}$ above 96 GHz
Averaging time (above transition)			Decreases from 6 to 0.5 min	Decreases from 0.5 min to 10 s
Localized SAR limit ($W\ kg^{-1}$) below the transition frequency, averaging mass of tissue, head and trunk	2 averaged over 10 g	1.6 averaged over 1 g	2 averaged over 10 g	2 averaged over 10 g

[a]Proposed — Notice of proposed rulemaking (FCC 15-138).

et al. 2015). In addition, the BHTE has an intrinsic time scale τ_1

$$\tau_1 = \frac{1}{m_b \rho} \approx 500\,\text{s}, \qquad (2)$$

which is a measure of the amount of time needed for blood perfusion to remove heat from a given region of tissue.

Increase in skin temperature—steady state

Above the transition frequency, both IEEE and ICNIRP limits for the general public are 10 W m^{-2} (IEEE limits for the general public increase above 100 GHz) (Table 1). The thermal response of skin is estimated using a simple one-dimensional model based on a simplified form of the BHTE. One can assume an adiabatic half plane of tissue subject to surface heating at an absorbed power density of $I_o T_{tr}$ (W m^{-2}) (Appendix). This would approximate exposure to mm wave energy at an incident power density of I_o and energy transmission coefficient T_{tr}.

The step response of this model (i.e., the increase in surface temperature T_{sur} following sudden imposition of exposure at $t = 0$ with zero initial conditions) can be written [eqn (A9), Appendix]

$$\begin{aligned} T_{sur}(t) &= \frac{I_0 T_{tr} R_1}{k} erf\left(\sqrt{\frac{t}{\tau_1}}\right) {}^\circ\text{C} \\ &= 0.019\, I_0 T_{tr}\, erf\left(\sqrt{t/\tau_1}\right) {}^\circ\text{C} \end{aligned} \qquad (3\text{a, b})$$

where the second expression is obtained using parameter values given in the Appendix. Because of the surface heating approximation, this result is independent of frequency; the limits of this approximation are discussed in the Appendix.

At the guideline limits of 10 W m^{-2} and an energy transmission coefficient of 0.6–0.8, which is typical of that for mm wave radiation, eqn (3b) predicts a steady state increase in T_{sur} of 0.10–0.15 °C. The surface temperature will reach 90% of the steady state increase after approximately 1.4 $\tau_1 \approx 675$ s. This increase is roughly a factor of 7–10 below the "acceptable" temperature increase of 1°C stated in the guidelines, and 1.5–2 orders of magnitude below thresholds for burn or thermal pain under normal environmental conditions. This approximate calculation shows the high (and arguably excessive) level of conservatism in both the current IEEE and ICNIRP guidelines for protection against thermal hazards.

Spatial and temporal averaging times

Both IEEE and ICNIRP limits specify "averaging areas" and "averaging times" over which the exposure is to be averaged to assess compliance (Table 1). Such provisions are needed because of thermal inertia and effects of thermal conduction in RF-exposed tissue.

Averaging areas. Above the transition frequency, the guidelines specify "averaging areas" that range from 1 cm^2 (ICNIRP) to 2,500 cm^2 (IEEE). A model calculation gives some insight into the proper choice of these secondary, but still important, aspects of the limits. A circular area of radius R_0 is considered that is exposed to RF energy (surface heating model) at absorbed power density $I_o T_{tr}$. The maximum steady-state increase in temperature T^{ss} is [eqn (A11) Appendix]:

$$T^{ss} = \frac{I_O T_{tr} R_1}{k}(1 - e^{-x}), \qquad (4)$$

This takes on limiting values of $I_o T_{tr} R_0 k^{-1}$ and $I_o T_{tr} R_1 k^{-1}$ for small or large exposed areas, respectively, with a transition occurring at a radius of the irradiated area of about R_1.

For small exposed areas ($R_0 < R_1$), eqn (4) shows that the maximum increase in surface temperature scales as the lateral dimension of the exposed area, not its area, and it is reduced from that for a large exposed area by the factor $[1-\exp(-R_0 R_1^{-1})]$. This correction can be an order of magnitude or more in some previous human studies involving localized exposure to mm wave energy (Foster et al. 2016). Physically, when the exposed area of skin is small, heat diffuses in three dimensions away from the exposed area, while for larger exposed areas thermal diffusion is principally normal to the skin surface.

A more detailed perspective on spatial averaging is provided by the Green's function solution to the BHTE (Gao et al. 1995 and in the Appendix). The Green's function solution to the BHTE [eqns (A10, A11)] provides the temperature increase as a convolution of the Green's function (the thermal response to a point heat source) with the input power density. Spatial averaging, as provided in the exposure guidelines, results in a different expression [eqn (13)] that cannot be derived from the Green's function.

In the spatial frequency domain, the thermal response to a heat source can be written as the product of the spatial Laplace transform of the Green's function with that of the absorbed power density $I_o(s,t)T_{tr}$. In the steady state [eqn (A13), Appendix], the transfer function becomes:

$$T(s,t) = \frac{2}{k}\left(\frac{1}{s^2 + 1/R_1^2}\right) T_{tr} I_0(s,t), \qquad (5)$$

where s is the spatial frequency in m^{-1}. In engineering terms, this is a low-pass spatial filter with cutoff frequency R_1^{-1}. The filter removes spatial variations in the SAR pattern over distances smaller than $R_1 \approx 7$ mm, which again points to R_1 as a reasonable "averaging distance."

These scaling considerations suggest that a reasonable choice for an "averaging area" would be of the order of about 1–2 cm^2 for the parameters presently used. That is similar to the averaging area in the present ICNIRP guidelines but considerably below those specified in the IEEE standard. The Green's function (Appendix, eqn A7) suggests that the spatial averaging should employ an exponential windowing function, as opposed to a simple area average that is specified in the guidelines. However, the tradeoff between such refinements and need for a practical exposure limit would need to be evaluated. Also, the uncertainties, both in the thermal model and in the parameters within it, are sufficiently large that a range of choices could be made, particularly considering the high level of conservatism in the present and foreseeable guidelines against thermal hazards.

Averaging times. Both the IEEE and ICNIRP limits provide "averaging times" that range from 6–30 min at the lower end of the presently considered frequency range to 10 s at 300 GHz. ICNIRP explains this as necessary "to compensate for progressively shorter penetration depth as the frequency increases."

However, the theory suggests that these choices are not optimal. Even at mm-wave frequencies, considerable time (hundreds of seconds) is required for the steady state to develop after exposure has begun [eqn (2)]. Even at mm-wave frequencies, the rise in skin temperature is determined largely by heat transfer at deeper layers in tissue. Consequently, for most purposes, an appropriate averaging time would be of the order of several minutes to smooth out transient variations in incident power density. For small exposed areas where the thermal response time scales as the square of the diameter of the exposed area (Foster et al. 2016), a shorter averaging time might be appropriate.

Pulsed energy

Neither IEEE nor ICNIRP provide limits for brief, high intensity pulses that may cause transient increases in skin temperature to hazardous or painful levels. One military non-lethal weapons system (the U.S. Active Denial system) is explicitly designed to produce thermal pain using short pulses of mm waves at high intensity. Future sources of high intensity pulsed mm wave or terahertz radiation may produce such exposures in non-military settings (Benford et al. 2015; Giri 2004; Kumar et al. 2011). The RF exposure guidelines should be updated to include the possibility of such exposures.

The early transient response is obtained by expanding eqn (3a) in terms of $t\tau_1^{-1}$:

$$T_{sur}(t) = \frac{2I_0T_{tr}}{\rho\sqrt{\pi k m_b C}}\left[\sqrt{\frac{t}{\tau_1}} - \frac{1}{3}\left(\frac{t}{\tau_1}\right)^{3/2} + \cdots\right]. \quad (6)$$

Since $\tau_1 = (\rho m_b)^{-1}$, the leading term in eqn (6) is independent of blood flow (m_b), and the early transient response of skin temperature increases as $t^{1/2}$, assuming surface heating. For a short pulse of duration τ with the parameter values defined above, the incremental increase in surface temperature becomes

$$T_{sur}(\tau)\approx 10^{-3} IoT_{tr}\sqrt{\tau}\,^{\circ}\mathrm{C}. \quad (7)$$

To limit the increase in skin temperature to 1°C, this implies that the fluence (integral of the absorbed power density over the pulse duration) should be limited to about $10^3\tau^{1/2}$ J m^{-2}. The pulses must be far enough apart in time for the transient increases in skin temperature to decay, which implies a pulse separation of a few tens of seconds at mm wave frequencies. In addition, the duty cycles would need to be low enough that a sequence of pulses complies with provisions for time-averaged exposures. Equation (7) is a quite good approximation at mm wave frequencies and is conservative (i.e., overpredicts temperature increase) at lower frequencies.

There is limited experimental evidence in support of the suggested limit [eqn (7)]. Walters et al. (2000) determined the threshold for thermal pain in humans from exposures to 3-s pulses of RF energy at 94 GHz. This corresponds to a fluence of 38,000 J m^{-2} for each pulse (Walters et al. 2000), which is approximately 20 times higher that suggested in eqn (7). Dalzell et al. (2010) reported that 1-s pulses of 0.1–3 THz radiation with fluences of approximately 50,000 W m^{-2} were sufficient to cause thermal damage to cells in culture. Chalfin et al. (2002) reported that 1- to 5-s pulses of RF energy at 35 and 94 GHz with mean fluences of 75,000 and 50,000 J m^{-2}, respectively, were sufficient to produce "minimally detectable" lesions in the corneas of rhesus monkeys. In these latter two studies, the estimated transient increases in temperature in the exposed targets are above 20 °C. Consequently, the suggested limit on fluence given above will provide a safety margin of 10 or more relative to the threshold for thermal pain at mm wave frequencies and larger margins at lower frequencies.

Comments on surface heating model

The above discussion is based on a highly-simplified model assuming purely surface heating and that the surface is insulated from the environment. The authors comment on the approximations inherent in this approach.

1. Surface heating approximation. This approximation is excellent for mm waves (where the energy penetration depth is < 1 mm) but fails progressively at lower frequencies, over-predicting the surface temperature increase by 25% at 10 GHz (Table A1). However, the errors are all in a conservative direction;
2. The conduction-only model. This is an excellent approximation to the BHTE for small irradiated areas [eqn (4)] or for short times in the step response [eqn (6)]. It will fail progressively for longer exposure times (greater than tens of seconds at mm wave frequencies) or larger exposed areas (greater than a few cm^2). Again, the errors are in a conservative direction; and
3. Adiabatic surface approximation. The simple theory is based on the assumption that none of the RF-induced

heat in the skin is lost to the surrounding environment. If RF exposure produces a temperature increase ΔT_{sur} at the skin surface, the increase in heat flux ΔQ from the skin to the surrounding environment will be approximately

$$\Delta Q \approx h \Delta T_{sur}. \quad (8)$$

where h is the heat transfer coefficient. Typical values of h are of the order of 1-10 W m^{-2} C^{-1} depending on environmental conditions (Fiala et al. 1999). RF exposure at an incident power density of 100 W m^{-2} will raise skin temperature by about 1°C, which implies an increase in heat loss from the skin to the environment of 1-10 W m^{-2}. This suggests that the errors from assuming insulated boundary conditions for RF exposure calculations are modest, a few percent, and in a conservative direction. These heat fluxes occur in the presence of naturally occurring heat flows across the skin that typically exceed 100 W m^{-2} (Foster et al. 2016).

While more complex analytical models can be developed, they are mathematically complex. The best approach is to rely on simple analytical models such as described here to examine the scaling characteristics of bioheat transfer and estimate thermal responses, and supplement the model with more detailed numerical simulations (e.g., Hashimoto 2017 Morimoto 2017). All of these approaches rely on the same theoretical foundation, Pennes' BHTE. Attempting to use more realistic vessel-by-vessel models for bioheat transfer would introduce a far higher level of complexity and most likely would be unworkable for setting exposure limits that apply to a wide range of exposure conditions.

Comments on use of thermal modeling in setting exposure guidelines

The reluctance of the guideline committees to base limits on thermal modeling is explained by IEEE C95.1-2005 (p. 89): "Interpretation of the temperature data from modeling studies of the brain and eye must include consideration of the following limitations of the models: 1) the adequacy of physiological blood flow in many of the numerical model studies has not been verified, 2) none of the results for brain and eye have been validated in live animals and humans, and 3) the results from independent laboratories varied over a wide range. Until these limitations can be resolved, thermal models are useful but in and of themselves are not sufficient for safety standard development."

This is particularly true of the calculation of the steady state temperature, which is sensitive to the blood perfusion parameter m_b (eqn 1). By contrast, the transient response is dominated by heat conduction, which is a much simpler process to model. Moreover, the simple thermal model adequately describes available experimental data for heating of skin by mm wave radiation. That said, the relative dearth of experimental data for human thermal responses to RF exposure in the presently considered frequency range is a major limitation.

DISCUSSION

A fair question is what hazards are the guidelines protecting against? IEEE C95.1-2005 (pp. 81–82) summarizes "various considerations relevant to RF safety:"

"From the practical perspective of managing RF safety issues within industrial environments, the various considerations relevant to RF safety may be ranked as follows:

1. RF shocks and burns: These probably constitute the most harmful RF exposure hazard… A substantial proportion of shock and burn accidents are caused by contact with live, high-powered RF conductors…;
2. Localized RF heating effects: These are undeniably realistic hazards, but they occur much less commonly than RF shocks and burns…;
3. Surface heating effects: These are potentially hazardous, though hardly ever experienced in practice. Possibilities for significant exposures could include open waveguides for high powered GHz sources and the potential use of microwave-based non-lethal weapons for crowd control. The much lower exposure thresholds and exposure durations for sensory effects provide a very effective guidance for protecting against physical harm.
4. Whole body heating effects: Although RF absorption sufficient to cause whole-body heating is the most discussed interaction between RF fields and humans in this standard, it likely presents an even lower potential risk of adverse effects than any of the items mentioned above. In practice, significant whole-body heating very rarely occurs. Discomfort due to absorbed RF energy requires sustained application of high, (e.g., kW) RF power that is generally not associated with most exposure situations.
5. Low-level effects: Despite more than 50 years of RF research, low-level biological effects have not been established. No theoretical mechanism has been established that supports the existence of any effect characterized by trivial heating other than microwave hearing."

There are, in fact, few reported cases of serious injury from overexposure to RF energy despite the widespread use of RF technologies. Most reported injuries occur in occupational settings due to equipment failure or other mishap causing very high exposures leading to injury before the worker can withdraw from exposure. In most circumstances, thermal pain avoidance would cause an individual to withdraw from exposure before serious injury occurs.

Apart from occupational settings in which high powered RF equipment is in use, an individual in ordinary life has almost no possibility of encountering thermally hazardous levels of RF energy. There have been very few reported incidents of interlock failure in microwave ovens that could potentially expose the user to high levels of RF energy. Skin burns are a rare complication from medical procedures such as electrosurgery or catheter ablation for heart arrhythmias (Dhillon et al. 2013). Protecting against such hazards is more a matter of safe equipment design and use than exposure limits, and medical procedures are not covered by the IEEE and ICNIRP guidelines in any event.

However, there is an interesting analogous case of a consumer product that can, and infrequently does, cause thermal injury: personal electronics devices including laptop computers, whose cases can become quite warm during normal use. In important respects, the exposure characteristics of such devices resemble those for communications handsets used close to the body. In both cases, the user is aware of the presence of the device and ordinarily can terminate exposure in the event of excessive heating of the skin.

However, unlike the case of wireless handsets, there have been (rare) cases of thermal injury to users of personal electronics from excessive case temperature, typically to individuals with impaired pain sensation. For example, there are a few reported cases of serious burns to disabled individuals from use of laptop computers (e.g., Paprottka et al. 2012; Thaunat and Morelon 2010). Erythema ab igne (or EAI), a less serious thermal injury, has also been reported on rare occasions from prolonged use of laptop computers. [involved a young person who spent a lot of time playing games on a laptop (Arnold and Itin 2010)]. EAI has also been reported from use of other heat-producing devices including heated car seat heaters, space heaters, warming pads, and, in former times, wood burning stoves. The number of reported cases of EAI from use of personal electronics devices is very tiny (Corazza et al. 2016 listed 24 cases), but the true incidence of such problems is unknown.

The approach taken by regulatory agencies to manage such hazards is quite different than that used to regulate RF exposure from RF-emitting products such as mobile phone handsets. Moreover, the safety factors that are designed into the two kinds of regulation are quite different (referring to thermal hazards only.)

For personal electronics and other devices used against the body, product safety standards (IEC 60601-1:2015 for medical electronic equipment, IEC-60950:2005 for information technology equipment), including laptops, limit the touch temperature of their cases. The maximum touch temperatures are low enough that an individual who picks up a hot device will have time to put it down before thermal injury occurs; i.e., the limits are designed to protect against very short term thermal exposures, and they rely on pain avoidance to protect the user against injury. By contrast, IEEE and ICNIRP guidelines for RF exposure are designed to protect against "long term" heating (i.e., steady-state temperature increases, which require tens of minutes to develop).

In addition, the margins of safety in the product standards are far smaller than in the RF exposure guidelines. For example, the Third Edition of IEC 60601-1:2015 specifies a limit of 43 °C (close to the threshold for thermal pain) for touch temperatures of devices that will be in contact with patients' bodies for more than 10 min, and a limit of 48 °C (well above the threshold for pain) for devices used by nonpatients for contact times greater than 1 min. As discussed above, the present IEEE or ICNIRP exposure guidelines offer safety margins of 1.5–2 orders of magnitude under normal ambient conditions. In part, this may be due to uncertainties inherent in thermal modeling, particularly as related to calculating thermal responses from "long term" exposures where the steady state temperature increase is achieved.

T or delta T?

In limiting touch temperature, the product safety standards explicitly recognize that the threshold for thermal hazard is related to skin temperature (as well as exposure time). By contrast, the IEEE and ICNIRP guidelines for RF energy are designed to limit *increases* in tissue temperature produced by exposure. In principle, RF exposure guidelines could take a similar approach to those of product safety standards by limiting skin temperature (not *increase* in skin temperature) in the user.

Under this approach, manufacturers of RF-emitting devices would be required to show that the devices in ordinary use will not raise skin temperature above a specified limit, considering both the temperature increase from contact with the case as well as RF energy exposure. Compliance could be verified by simply measuring skin temperature beneath an operating device (as opposed to calculations of MPE or SAR). While this approach may be difficult for a number of reasons, it would remove many of the uncertainties inherent in thermal modeling and exposure assessment and be simple and direct to apply. Product safety standards for electronics products that can be hazardous under real-world conditions of use offer precedent for such an approach.

Recommendations

1. Considered from the perspective of thermal analysis, the two international limits (ICNIRP, IEEE) as well as the U.S. limits (FCC) are very conservative with respect to achieving their goal of limiting temperature increases of tissue to 1°C. Thermal analysis, combining the simple model described here, with more detailed analysis using anatomically detailed 3D anatomical models (Morimoto et al. in press; Hashimoto et al. in press) can help ensure that desired levels of protection of the limits are achieved. The simple model (as well as more detailed analysis) suggests that MPE limits of about

100 W m^{-2} would limit increases in skin temperature to about 1 °C for exposures to large areas of the body;

2. The thermal averaging times and averaging areas defined in both IEEE and ICNIRP guidelines need to be reconsidered in light of the scaling properties of the BHTE. Both guidelines provide averaging times that are far shorter than the thermal response time of skin to RF exposure in the frequency range considered here. The two guidelines define different averaging areas (Table 1) in terms of simple area averages (which implies use of a rectangular window). By contrast, the Green's function for the BHTE suggests the use of an exponential windowing function; however, that refinement may not be needed in view of the high level of conservatism in current exposure limits. The "averaging area" specified in the ICNIRP guidelines is roughly similar to that suggested by the Green's function analysis, while that defined by the current IEEE guidelines is considerably larger;
3. Future editions of the guidelines need provisions for exposures to brief, high intensity RF pulses that are capable of raising skin temperature to harmful or painful levels within short times. Such exposures are presently possible with the military "Active Denial" system (although the guidelines would not apply to the use of weapons). However, the rapid development of high power mm wave and THz sources will raise the possibility of such exposures in some occupational settings in the future. The thermal model discussed above provides a simple way to implement such limits by limiting the fluence of pulses (eqn 7); and
4. The technology for exposure assessment needs to be improved, particularly at frequencies between the transition (10 GHz for ICNIRP) and the beginning of the mm wave band (30 GHz) where the energy penetration depth in skin ranges from about 2 mm (10 GHz) to less than 1 mm (30 GHz) (Table A1, Appendix). The transition between use of SAR as the dosimetric quantity below the transition frequency to incident power density above it is not reflected in the physics of electromagnetic waves, which obey the same propagation laws at all frequencies.

In particular, the computational problem in assessing exposure from devices in close proximity to the skin needs to be studied. The current ICNIRP limits are expressed above the transition frequency in terms of MPE, which is defined in terms of far field exposure. In fact, when devices are used in close proximity to the body, a near field exposure condition exists and calculations of absorbed power (SAR) at and near the surface may be needed to assess compliance, which may create computational issues in view of the short energy penetration depths. This may be accomplished by direct temperature measurements, but the transient increases in temperature at exposure levels within existing guidelines may be difficult to measure reliably.

Moreover, thermal modeling remains problematic, particularly for long-term (several minutes or more) exposures. The applicability and accuracy of the BHTE for calculating skin temperature increases for general exposure situations (arbitrary exposed areas of skin, steady state temperatures) have been subjected to *almost no* experimental tests for RF exposures at any frequency. Absent experimental validation of a generally useful thermal model, this calls for caution in setting limits based on thermal modeling.

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APPENDIX

Simplified models of heating of skin by millimeter wave energy

The main paper cites several approximate solutions to the bioheat equation (BHTE). This Appendix provides some mathematical details to expand the analysis.

Thermal model

Simple one- and two-dimensional models give insight into the heating characteristics of tissue in response to RF exposure. This discussion is based on a simplified form of the BHTE as presented in Foster et al. (2016). In simplified form, the BHTE can be written:

$$K\nabla^2 T - \rho^2 C m_b T + \rho SAR = \rho C \frac{dT}{dT}, \qquad \text{(A1)}$$

where

T = the temperature rise of the tissue (°C) above the baseline temperature (i.e., temperature above that previous to RF exposure);

k = the thermal conductivity of tissue (0.37 W m^{-1} °C);

SAR = the microwave power deposition rate (W kg^{-1});

C = the heat capacity of the tissue (3,390 W s kg^{-1} °C);

ρ = the tissue density (1,109 kg m^{-3}); and

m_b = the volumetric perfusion rate of blood [1.8×10^{-6} m^3 (kg s)$^{-1}$ or 106 mL min^{-1} kg^{-1} in the mixed units typically used in the physiology literature].

These parameter values are from Hasgall et al. (2015) as used in a commercial finite difference time domain/thermal analysis program and are used without further modification. A semi-infinite plane of tissue with adiabatic boundary conditions is assumed, exposed to RF energy with absorbed power density (near the surface) given by

$$SAR = \frac{I_o T_{tr}}{\rho L} e^{-z/L}, \qquad \text{(A2)}$$

where I_o is the incident power density, T_{tr} is the energy transmission coefficient into the tissue, and L is the energy penetration depth into tissue, which is defined as the distance beneath the surface at which the SAR has fallen to a factor of e^{-1} below that at the surface. Table A1 summarizes the energy penetration depth and transmission coefficient over the frequency range that is presently considered, calculated from electrical and thermal parameters for dry skin (from Foster et al. 2016).

Equation (A1) has two intrinsic time scales representing heat transport by blood perfusion and thermal conduction, respectively:

$$\begin{aligned} \tau_1 &= 1/m_b\rho \approx 500\, s \\ \tau_2 &= L^2/\alpha, \end{aligned} \qquad \text{(A3a, b)}$$

where $\alpha = k(\rho C)^{-1}$ is the thermal diffusivity (≈10^{-7} m^2 s^{-1} for soft tissue) and L is a measure of the spatial extent of the SAR pattern (e.g., the energy penetration depth in eqn A2). The corresponding distance scales are

$$\begin{aligned} R_1 &= \frac{\sqrt{k}}{\rho\sqrt{m_b C}} \approx 7\,\text{mm} \\ R_2 &= \sqrt{4\alpha t} \approx 0.5\sqrt{t}\,\text{mm}. \end{aligned} \qquad \text{(A4a, b)}$$

Analytical solutions to the BHTE model are available for simple geometries (e.g., Foster et al. 1978), and a Green's function solution is also available (e.g., Gao 1995), but they are mathematically cumbersome and not repeated here. This appendix summarizes limiting cases in the BHTE that are referred to in the accompanying paper. The following results were obtained by computer algebra (Maple, Waterloo Maple) or numerically using the finite element method (PDEase, Macsyma, Arlington MA; currently sold as FlexPDE, PDE Solutions, Spokane Valley WA).

The simplified cases discussed in the main paper are as follows.

Uniformly irradiated plane, no blood perfusion, finite energy penetration depth (m_b = 0, L>0). In the limit $m_b \to 0$, eqn (A1) becomes the simple heat conduction equation. For the 1D problem with adiabatic boundary conditions, the surface temperature $T_{sur}(t)$ can be written

$$\begin{aligned} T_{sur}(t) &= C_1\sqrt{t} - C_2\left(1 - e^{t/\tau} erfc\sqrt{t/\tau_2}\right), \\ C_1 &= \frac{2 I_o T_{tr}}{\sqrt{\pi k \rho C}} = 9.54 \times 10^{-4} I_o T_{tr}\,^\circ\text{C}\,\text{s}^{-1/2}. \\ C_2 &= \frac{I_o T_{tr} L}{k} = 2.7 \times I_o T_{tr} L\,^\circ\text{C} \end{aligned} \qquad \text{(A5a, b, c)}$$

The first term in eqn (A5a) shows the characteristic t$^{1/2}$ response characteristic for surface heating, while the second transient term arises from diffusion of heat within the energy penetration depth L. The second transient decays to a constant (C_2) as $t > \tau_2$. Numerical solution of the BHTE (Fig. A1) shows that eqn (A5) provides an accurate approximation for the increase in surface temperature for times shorter than ≈ 100 s; i.e., effects of blood perfusion are small at early times in the transient response. In the absence of blood perfusion, the heat conduction equation for the uniformly irradiated adiabatic plane does not have a finite steady state solution (Fig. A1).

Uniformly irradiated plane, surface heating (L=0), finite blood perfusion (m_b>0). In this case, the steady-state increase in surface temperature T_{sur}^{ss} is

$$\begin{aligned} T_{sur}^{ss} &= \frac{I_o T_{tr} R_1}{k} = \frac{I_o T_{tr}}{\rho\sqrt{k m_b C}} \\ &= .019\, I_o T_{tr}\,^\circ\text{C}\,\text{m}^2\text{W}^{-1}, \end{aligned} \qquad \text{(A6)}$$

with the present choice of thermal parameters. Equation (A6) is independent of frequency because of the approximation of purely surface heating. Numerical simulations show

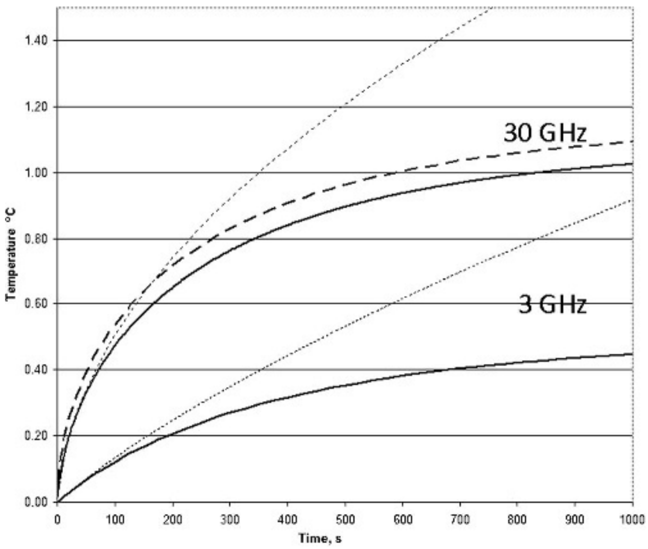

Fig. A1. Step response for the 1D (adiabatic plane) problem at two frequencies (3 and 30 GHz), with $I_o = 100$ W m^{-2}, $T_{tr} = 0.6$ for each case). The solid lines are numerical solutions to the BHTE (eqn A1), the dotted lines are the solutions to the conduction-only problem (eqn A5a) and the heavy broken line is the solution to the surface heating only problem (which is independent of frequency) (eqn A9).

that eqn (A6) is an excellent approximation at mm-wave frequencies (30–300 GHz) and results in a 25% overestimate at 10 GHz (Table A1).

Finite exposed areas

The scaling properties of the BHTE for finite irradiated areas of skin can be explored using the Green's function solution for the BHTE (Gao et al. 1995), simplified for the case of surface heating only. Gao et al. (1995) provide the Green's function for the BHTE for an infinite space (i.e. do not include effects of boundary conditions). By symmetry, the same solution applies for an exposed half space with adiabatic boundary conditions, provided the surface temperature is multiplied by a factor of 2 to take into account the unidirectional flow of heat into the surface.

It is assumed that the surface is uniformly exposed to RF energy over a circular area of radius R_0 with an absorbed power density $I_o T_{tr}$ (W m^{-2}), assuming surface heating only. In cylindrical coordinates (r,z), the Green's function solution (Gao et al. 1995) as applied to the center of the exposed area simplifies to

$$T(0,0,t) = \frac{I_o T_{tr}}{\rho c_p (4\pi\alpha)^{\frac{3}{2}}} \int_0^t \frac{e^{\frac{t'}{\tau_1}}}{t'^{\frac{3}{2}}} \iint_{R_0} 2\pi r' e^{\frac{r'^2}{4\alpha t'}} dr' d\varphi' dt', \tag{A7}$$

which evaluates to

$$T(0,0,t) = \frac{2 I_o T_{tr}}{\rho c_p (4\pi\alpha)^{\frac{1}{2}}} \int_0^t \frac{e^{\frac{t'}{\tau_1}}}{\sqrt{t'}} \left(1 - e^{\frac{R_0^2}{4\alpha t'}}\right) dt'. \tag{A8}$$

The integral (eqn A8) can be evaluated in closed form when $R_0^2 >> 4\alpha t$:

$$\begin{aligned} T(0,0,t) &= \frac{I_o T_{tr}}{\rho\sqrt{k m_b C}} erf\left(\sqrt{\frac{t}{\tau_1}}\right), \\ T(0,0,t) &= 0.019\, I_o T_{tr} erf\left(\sqrt{t/\tau_1}\right) {}^\circ\mathrm{C\,m^2W^{-1}}, \end{aligned} \tag{A9}$$

with the present choice of parameter values. For short times ($t << \tau_1$), this asymptotically approaches the first term in eqn (A5a). As $R_o \rightarrow \infty$, eqn A9 becomes valid for all time and provides the steady-state solution for the plane.

Steady-state solution for irradiated disk

The steady-state temperature increase T_{sur}^{ss} (x,y,0) for a finite irradiated area can be obtained from eqn (14) of Gao et al. (1995):

$$T_{sur}^{ss}(x,y,0) = \frac{1}{2\pi k} \iint_D \frac{e^{-\sqrt{\frac{1}{R_1^2}\left[(x-x')^2 + (y-y')^2\right]}}}{\sqrt{x'^2 + y'^2}} T_{tr} I_0(x',y') dx' dy', \tag{A10}$$

where the integral extends over the entire irradiated area. For a radially symmetric exposure pattern centered at $r = 0$, eqn (A10) becomes

$$T_{sur}^{ss}(r,0) = \frac{1}{k} \int_{r=0}^{\infty} e^{\frac{r'}{R_1}} T_{tr} I_0(r') dr'. \tag{A11}$$

For the case of the uniformly irradiated disk of radius R_o, the temperature increase at the center evaluates to

Table A1. Model results, assuming $I_o = 100$ W m^{-2}.

Frequency, GHz	Energy transmission coefficient into skin T_{tr}[a]	Energy penetration depth L (mm)[a]	Steady state temperature increase, °C[b]	Steady state temperature increase, °C [analytical approximation, from eqn. (A6) using T_{tr} from this table]	Time to reach 90% of steady state temperature increase, s[b]	Temperature increase after 10 s of exposure, °C[b]	Time at which the response to a 10 s pulse has fallen to 1/e of its peak value, s [b]
3	0.47	9.4	0.39	0.89	925	0.012	>100
10	0.49	1.9	0.74	0.93	775	0.05	86
30	0.54	0.43	0.98	1.0	800	0.13	26
100	0.70	0.18	1.31	1.33	650	0.18	18
300	0.84	0.14	1.58	1.60	650	0.22	18

[a]Calculated from thermal properties of dry skin from Hasgall et al. (2015) and dielectric properties for dry skin from Gabriel et al. (1996).[b] Calculated numerically from BHTE assuming an adiabatic half plane of tissue assuming thermal properties of dry skin (Hasgall et al. 2015).

$$T_{sur}^{ss} = \frac{I_o T_{tr} R_1}{k}\left(1-e^{-x}\right), \tag{A12}$$

where $x = R_0\,R_1^{-1}$ and R_1 is defined in eqn (A4a). This has the limiting cases

$$\begin{aligned} T_{surface}^{ss} &= \frac{I_o T_{tr} R_1}{k}, \frac{R_0}{R_1} \to \infty (\text{large disk}) \\ &= \frac{I_o T_{tr} R_o}{k}, \frac{R_o}{R_1} \to 0\,(\text{small disk}). \end{aligned} \tag{A12a, b}$$

The transition between these limiting cases occurs at $R_0 \approx R_1 \approx 7$ mm. Consequently, for small disks, the maximum temperature at the surface is reduced from that in a large disk by the factor $R_0 R_1^{-1}$.

The guidelines specify maximum exposures ($I_{max,avg}$) to be averaged over specified areas if the exposure is non-uniform. The spatial average of an exposure over a disk of radius R_{av} can be written

$$I_{o,avg} = \frac{1}{\pi R_{av}^2}\int_{r=0}^{R_{av}} 2\pi r' I_0\left(r'\right) dr'. \tag{A13}$$

The problem is how to choose R_{av} to maintain the temperature increase at the surface within the limits imposed by the guidelines for an arbitrary exposure pattern. If the averaging area is too large, excessive exposures might be allowed to a small area by the guidelines if the exposure pattern is sufficiently non-uniform, while a too small averaging area will make the guideline overly conservative. There is no general solution to this problem, but limiting cases can be found.

For large exposed areas, the Green's function [eqn (A11)] shows that the temperature increase at any point on the surface is influenced mostly by exposures within a distance of R_1 from that point, suggesting that an appropriate averaging area should have lateral dimensions of about R_1. For small exposed areas, a simple approximation can be found for the special case of a small disk with R_0 that is uniformly exposed at a level $I_o(r')$ such that the exposure, when averaged over the "averaging area" πR_{av}^2, complies with the guideline limit $I_{max,avg}$. The exposure can be written

$$\mathrm{I}_0\left(r'\right) = I_{max,avg}\frac{R_{av}^2}{R_0^2} u\left(R_0 - r'\right) \tag{A14}$$

where $u(r)$ is the unit step function and $R_o << R_1$ is assumed. Inserting eqn (A14) in eqn (A11) to find the steady-state temperature increase at the center of the disk yields

$$\begin{aligned} T_{sur}^{ss}(r,0) &= \frac{1}{k} T_{tr} I_{max,avg} \frac{R_{avg}^2}{R_0} \\ &= \frac{T_{tr} I_{max,avg} R_1}{k}, \end{aligned} \tag{A15}$$

where the second equation above [eqn (A15a,b)] gives the steady state temperature increase for a large exposed area at the guideline limit. This implies that

$$R_{av} = \sqrt{R_0 R_1}. \tag{A16}$$

In other words, the average of the exposure [eqn (A14)] over an "averaging area" of πR_{av}^2 is an appropriate test of compliance with the guideline limit, in the sense that the maximum temperature increase in the disk will be no more than that in a large area of skin exposed at the guideline limit. This is not very satisfactory, since it shows that the "averaging area" in the guidelines will depend somewhat on the exposure pattern. The Green's function for the problem [eqns (A10, A11)] does not provide an analytic expression for an "averaging area" as used in the guidelines.

Frequency domain analysis

Additional insight into the heating behavior is gained from the Green's function in the (spatial) frequency domain. Consider a uniformly irradiated plane, with an exponentially decreasing SAR pattern given by eqn (A2). From eqn (9) of Gao (1995), the response of an adiabatic half plane of tissue to a suddenly imposed exposure $I_o(s)$ with zero initial conditions (step response) is given by

$$T(s,t) = \frac{2}{k}\left(\frac{1}{s^2 + 1/R_1^2}\right)\left\{1 - \exp\left[-\left(1 + s^2 R_1^2\right)\frac{t}{\tau_1}\right]\right\} T_{tr} I_0(s,t), \tag{A17}$$

where $T(s,t)$ and $I_o(s,t)$ are the spatial Laplace transforms of the temperature and exposure, and s is the spatial frequency. If the input is exponentially decreasing with distance (eqn A2) we have (ignoring constant factors)

$$I_0(s) = \frac{I_0}{s + 1/L}. \tag{A18}$$

The steady-state temperature is (ignoring constant factors)

$$\begin{aligned} T(s) &= \left(\frac{1}{s^2 + 1/R_1^2}\right) I_0(s) \\ I_o(s) &= \frac{I_0}{s + \frac{1}{L}}. \end{aligned} \tag{A19}$$

In engineering terms, this is an expression for a low-pass filter with cutoff frequency in the spatial domain of R_1^{-1}. Over the RF frequency range of present interest, R_1 (about 7 mm) > L (≈1 mm) and the spatial frequency content of the input $I_o(s)$ is generally higher than the cutoff frequency of the filter, smoothing out the temperature profile.

The increase in surface temperature with a suddenly imposed input (step response) is determined by the exponential term in eqn (A17). That term has two factors. The first (e^{-t/τ_1}) is independent of spatial frequency, and decays exponentially with time. The second factor

$$\left(e^{-s^2 R_1^2 \frac{t}{\tau_1}}\right)$$

provides additional attenuation for high spatial frequencies (or thermal gradients over distance scales less than R_1).

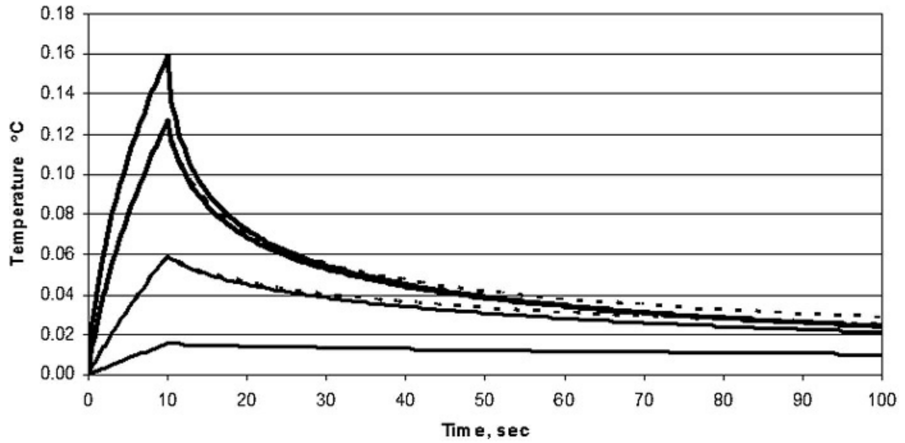

Fig. A2. Surface of a semiinfinite adiabatic plane exposed to a 10-s RF pulse at an absorbed power density of 60 W m^{-2} at indicated frequencies, from a numerical solution to the BHTE. The times required for the surface temperature to fall to e^{-1} of its peak temperature at the respective frequencies (in order of increasing maximum temperature) are 18 s (300 GHz), 26 s (30 GHz), 86 s (10 GHz), and > 100 s (1, 3 GHz). The results for exposures at 100 and 300 GHz are not distinguishable on the plot, and only the response at 300 GHz is shown.

Consequently, the step response is then dominated by the exponential factor (e^{-t/τ_1}) and approaches the steady state on a time scale of τ_1. This is shown in Fig. A2. In simpler terms, it requires times of the order of τ_1 (hundreds of s) for the surface temperature to approach the steady state, notwithstanding the fact that the energy is deposited very close to the surface.

Consider now the response to a brief pulse of energy (thermal washout) (Fig. A2). One defines $T_o(s)$ as the temperature distribution immediately after the end of the pulse and assumes that the input remains zero after that time. If the pulse is very brief, $T_o(s)$ at the end of the pulse will be proportional to the Laplace transform of the SAR pattern (eqn A2). Consequently $T_o(s) = (s{+}L^{-1})^{-1}$ at the end of the pulse, ignoring constant factors. The washout function then becomes

$$\begin{aligned} T(s) &= \exp\left[-\left(1+s^2R_1^2\right)\frac{t}{\tau_1}\right]T_0(s) \\ T_0(s) &\approx \frac{T_0}{s+\dfrac{1}{L}}. \end{aligned} \qquad \text{(A20a, b)}$$

One is now concerned with times $t << \tau_1$. Equation (A20) lacks the low-pass filter in eqn (A17), and the high spatial frequencies in $T_0(s)$ are retained. These high frequency components will decay at a much faster rate due to the second term in the exponential in eqn (A20), as shown in Fig. A2. The transient response after the pulse will also contain a much slower component as the absorbed energy is carried away by blood perfusion.

Fig. A2 shows numerical solutions to the BHTE for exposures to 10 sec pulses of RF energy at several frequencies (uniformly illuminated plane, finite depth of penetration, finite blood perfusion parameter). During the pulse, the surface temperature increases following eqn (A5). After the pulse ends, the surface temperature decays to baseline on two different time scales. The most apparent component of the response occurs over the first few seconds after the pulse ends, as heat diffuses away from the exposed region. In addition, there is a much slower component to the response, of the order of τ_1 (500 s), reflecting the time for blood to remove the heat added by the pulse.

Table A1 provides a numerical summary of the results in this Appendix, comparing numerical solutions of the BHTE for the step and pulse responses and different approximations discussed here to estimate the response. When appropriately pieced together, the simple approximations to the solution to the full BHTE discussed above provide an excellent view of the thermal response of the model.

■■