On the averaging time of human exposure at frequencies above 6 GHz

Kenneth R. Foster
Department of Bioengineering
University of Pennsylvania
Philadelphia PA 19104 USA
kfoster@seas.upenn.edu

supported in part by Mobile and Wireless Forum

Collaborators

Marvin C. Ziskin
Temple University Medical School,
Philadelphia PA 19140 USA

Quirino Balzano
Department of Electrical and Computer Engineering, University of Maryland, College Park MD 20742 USA

Akimasa Hirata
Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Japan

Tom Ely (1996): when developing the first US RF exposure limits (USAS C95.1; 1966]) he wrote that he "**was trying to come up with a number with as few significant figures as I could, considering the precision of what we were dealing with. A minute was too short — an hour was too long**" .

His committee settled on an averaging time of 0.1 hours. This became the 6 minutes in later standards.

Foster, Kenneth R., et al. "Heating of tissues by microwaves: A model analysis." Bioelectromagnetics: Journal of the Bioelectromagnetics Society, The Society for Physical Regulation in Biology and Medicine, The European Bioelectromagnetics Association 19.7 (1998): 420-428.

Current Situation

Table 1. Averaging times in exposure limits

Standard/guideline	Averaging time, minutes General public/lower tier	Occupational/upper tier
FCC 1998	30 min (mobile devices or far field exposure) 30 min (portable devices)	6 min (mobile devices or far field exposure) 6 min (portable devices)
IEEE C95.1-2005 Maximum permissible exposure (MPE) and basic restrictions for thermal hazards	6 min 0.1-3 MHz $0.0636\ f_M^{1.33}$ 30-100 MHz 30 0.1-5 GHz $150/\ f_G$ 5-30 GHz $25.24/\ f_G^{0.476}$ 30-100 GHz $5048/[(9\ f_G - 700) f_G^{0.476}]$ 100-300 GHz	6 min 0.1-3 MHz $19.63/f_G^{1.079}$ 3-30 GHz $2.524/f_G^{0.476}$ 30-300 GHz
ICNIRP (1998) Basic restrictions and reference levels (thermal hazards)	6 min (<10 GHz) $68/f_G^{1.05}$ (10-300 GHz)	6 min (<10 GHz) $68/f_G^{1.05}$ (10-300 GHz)

(f_M frequency in MHz, f_G frequency in GHz)

Averaging Time Needs Reexamination because

1. Presently revising/refining exposure limits > 6 GHz; new communications signals
2. Advent of technology for producing high peak power MM wave pulses

Averaging Time Should Correspond to Thermal Response Time of Tissue

1. If it is too long, then limits will conceivably allow high fluence pulses will that will cause excessive temperature increases
2. If it is too short, then the limits become excessively conservative by excluding thermally innocuous fluctuations in power.

Considering thermal hazards only!

Approach

1. Simple baseline model (Pennes' BHTE, 1D planar model) – uniform plane exposed to plane waves
   also surface heating approximation
   2 D model (finite exposure area)
2. Find step response to heat input then impulse and frequency responses
3. Compare with more precise image-based models
4. Relevance to standards

Pennes' Bioheat Equation

$$k\nabla^2 T - \rho^2 C m_b T + \rho SAR = \rho C \frac{dT}{dt} \tag{1}$$

where

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

$$SAR = \frac{I_o(t)\mathrm{T}_{tr}}{\rho L} e^{-z/L}$$

k is the thermal conductivity of tissue (0.37 W/m °C)

SAR is the microwave power deposition rate (W/kg)

C is the heat capacity of the tissue (3390 W sec/kg°C)

ρ is the tissue density (1109 kg/m^3)

and m_b is the volumetric perfusion rate of blood (1.8 ·10^{-6} m^3/(kg sec) or 106 ml/min/kg in the mixed units typically used in the physiology literature). Parameter values are from Hasgall et al. (2015) as used in a commercial finite difference time domain /thermal analysis program.

Calculate Step Response of Surface Temperature

Solution in Laplace Domain

$$T_{sur} = \frac{I_0 T_{tr} L}{ks} \frac{(\sqrt{R + s\tau_2} - 1)}{(R - 1 + s\tau_2)\sqrt{R + s\tau_2}}$$

where R is the ratio of time constants

$$R = \frac{\tau_2}{\tau_1}$$

$$\tau_1 = 1 / m_b \rho$$

$$\tau_2 = L^2 / \alpha$$

T_{sur} is surface temperature
L is the energy penetration depth in tissue
$I_o T_{tr}$ is the absorbed power density at the surface
mb is blood perfusion, ρ tissue density

Calculate Impulse Response

Solution in Laplace Domain

$$T_{sur,impulse,normalized} = \frac{1}{\tau_1}\left(1+\frac{1}{\sqrt{R}}\right)e^{\left(\frac{1}{\tau_2}-\frac{1}{\tau_1}\right)t}\, erfc\left[\sqrt{\frac{t}{\tau_2}}\right]$$

Calculate Frequency Response

Solution in Laplace Domain

$$\frac{T_{sur}(s)}{I_0(s)T_{ss}} = \frac{(R+\sqrt{R})(\sqrt{R}\sqrt{1+s\tau_1}-1)}{\sqrt{R}\sqrt{1+s\tau_1}(R+s\tau_1 R-1)}$$

$$\rightarrow \frac{1+\frac{1}{R}}{s\tau_1}, \mathrm{s} >> 1/\tau_1$$

Surface Heating Approximation

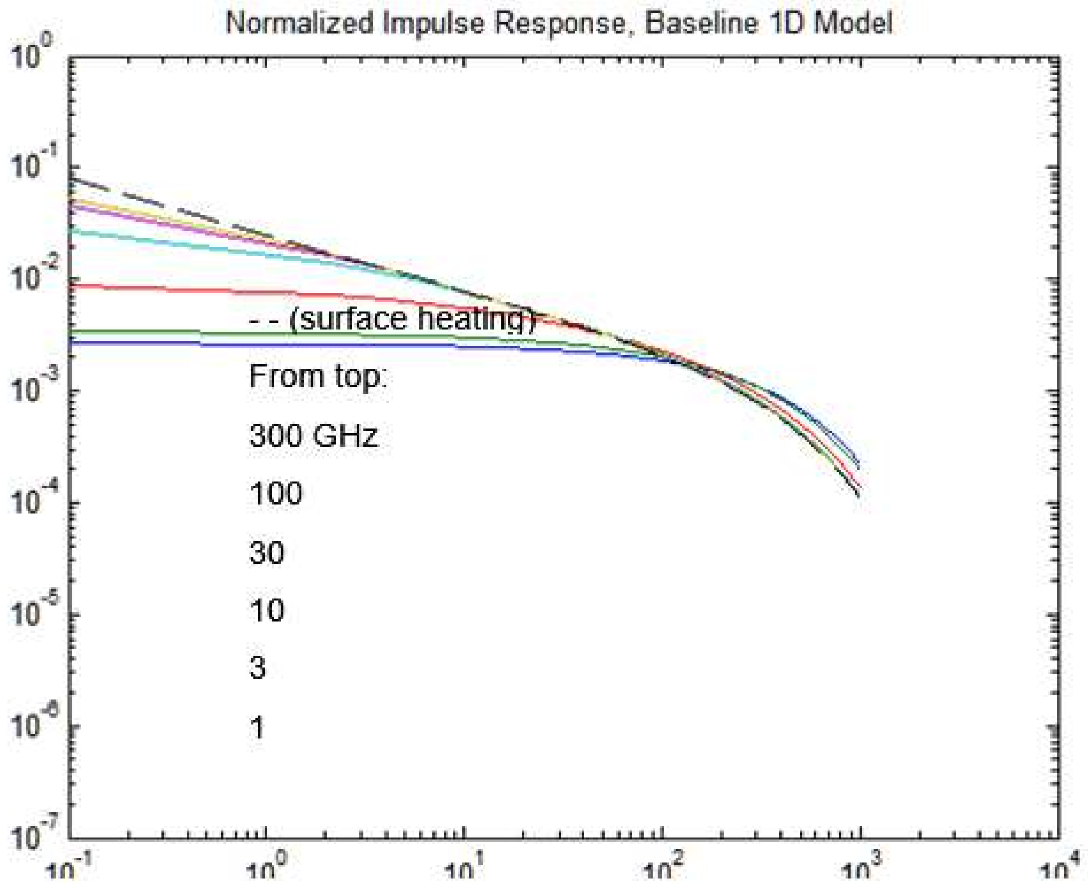
$$T_{sur,L=0}(t) = \frac{I_0 T_{tr}}{\rho\sqrt{k m_b C}}\, erf\left(\sqrt{\frac{t}{\tau_1}}\right)$$

Step response

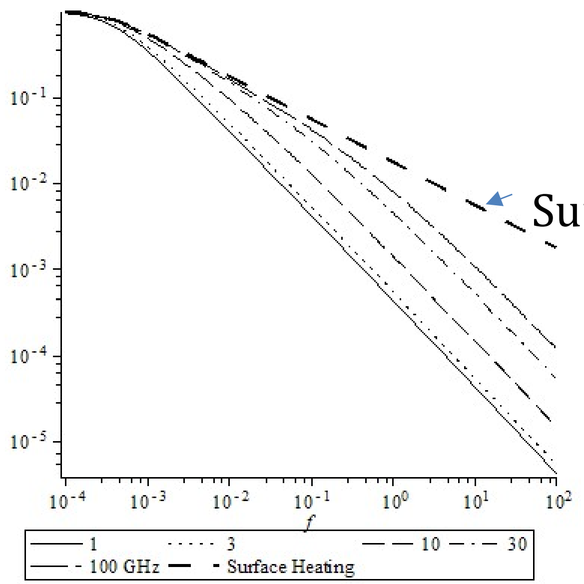
$$\mathrm{T}_{sur,L=0}(\mathrm{s}) = \frac{I_0 T_{tr}}{\rho\sqrt{k m_b C}} \frac{1}{s\sqrt{s\tau_1 + 1}}$$

Frequency response

Impulse Response - Baseline model



Frequency response – Baseline model



Surface heating approx.

Note very low amplitude of response above 0.02 Hz. Due mostly to thermal conduction (not blood perfusion)

Step Response – 2D model

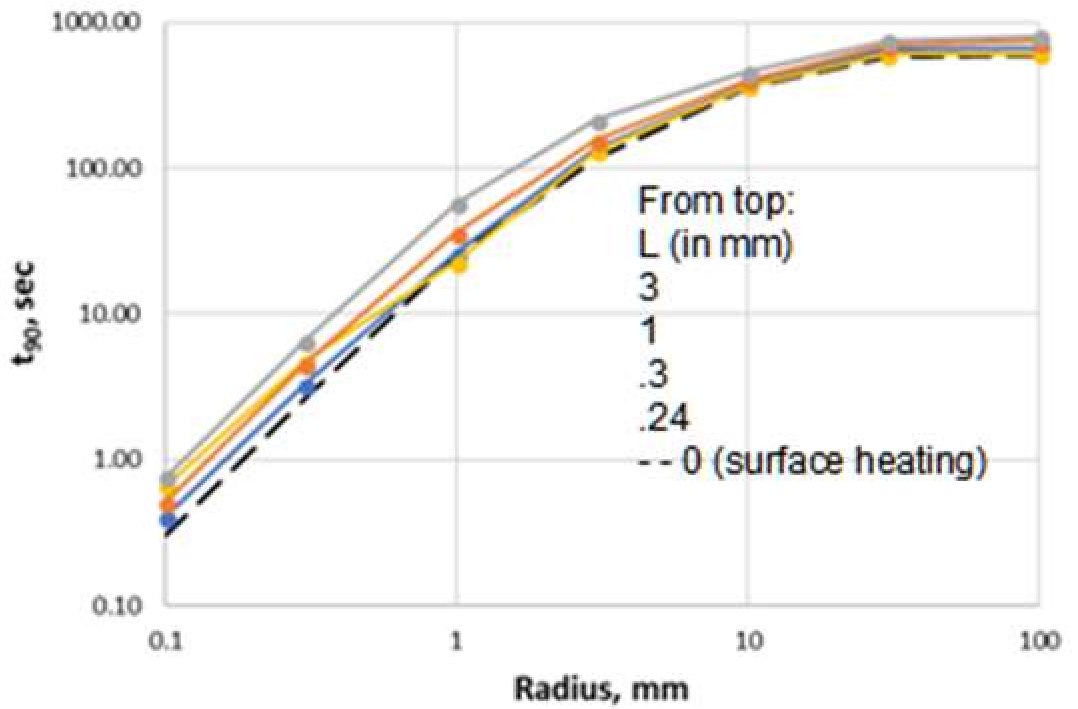
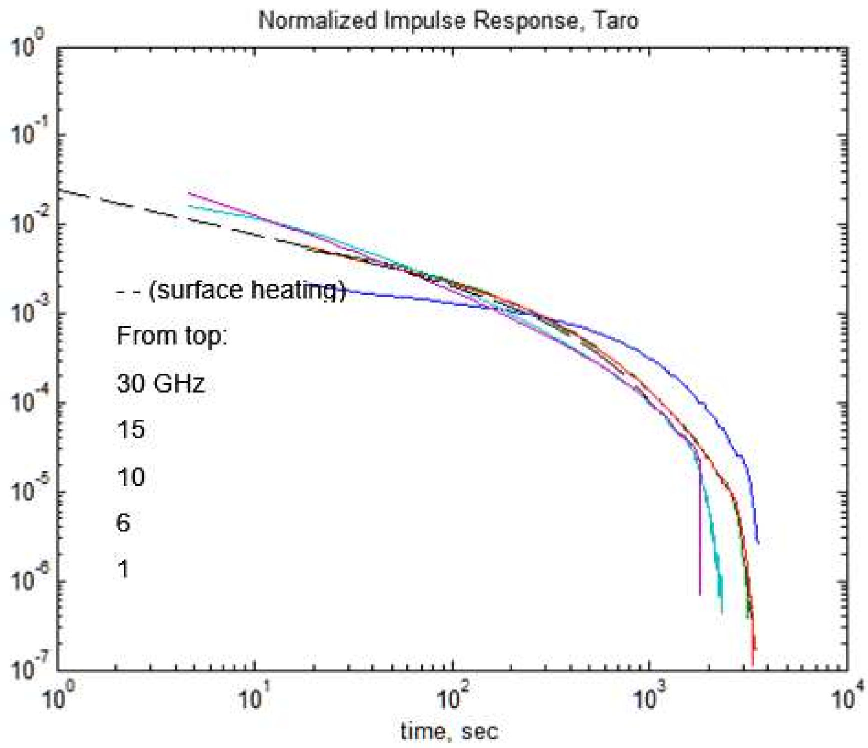
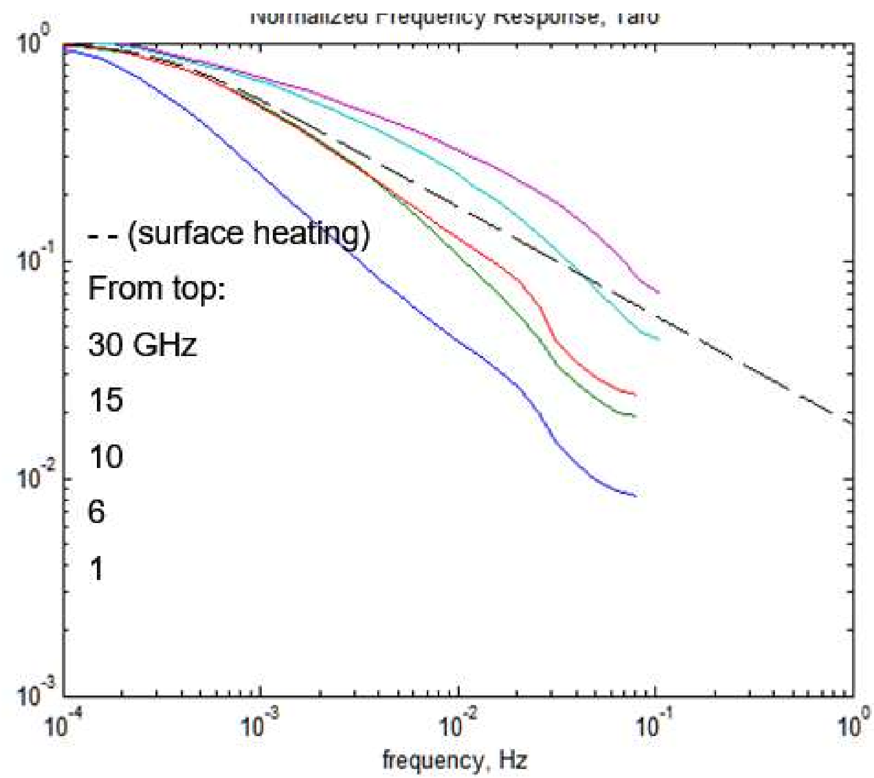


Figure 1. Response time of disk shaped exposed area with varying energy penetration depth L.

Impulse and Step Responses – Image-Based Model (Taro)

(From Morimoto et al 2017)





Big Bang Pulses

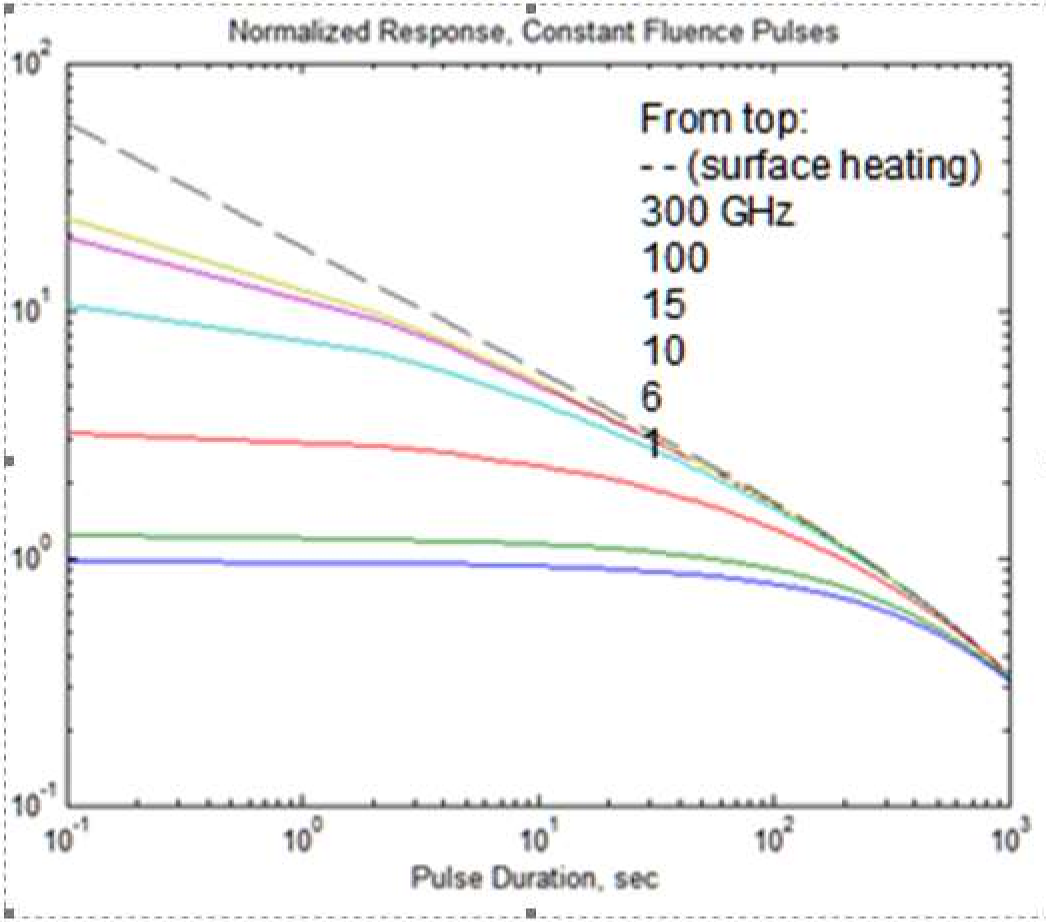


Figure 4. Response to pulses of varying duration but constant fluence, normalized to the steady state temperature for continuous exposure.

Response to Communications Waveform (GSM)

Response of tissue surface temperature to a continuous waveform, and to a GSM waveform. In both cases the time-averaged exposure was constant at 100 W/m^2, assuming an energy transmission coefficient of 0.47.

Conclusions

- BHTE is a *very* lowpass filter
- Responses of “baseline” 1D model agree well with more detailed models
- Modulation at typical communications waveforms is completely irrelevant to thermal response – the DC component of the waveform is essentially all that counts
- At mm wave frequencies, intense brief pulses might cause objectionable heating but still comply with 6 min averaging time
  - We suggest several alternative ways to extend present guidelines to improve suggested temporal averaging. Probably not important for communications signals and for any signals below mm range.