Thermal Modeling In Support of Exposure Limits Above 6 GHz

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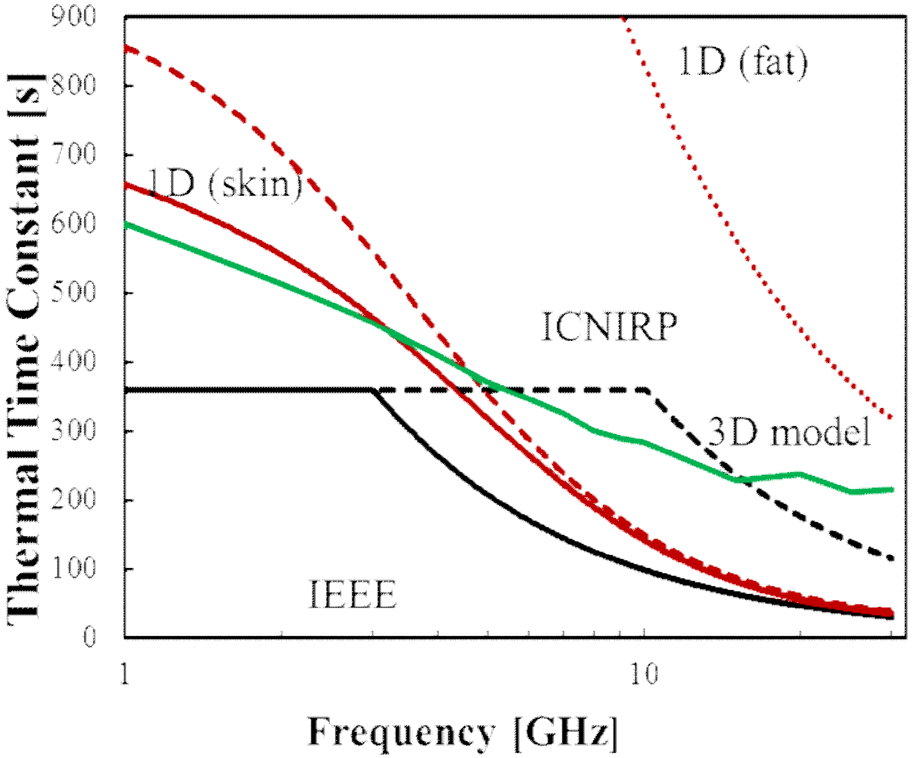
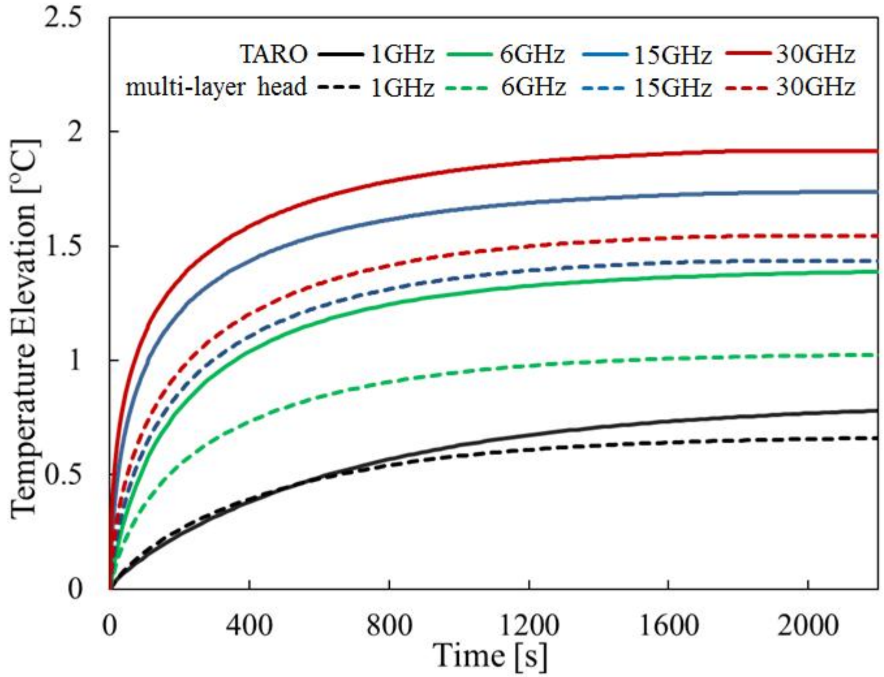
(presented by A. Hirata)

Results in Hirata Lab





Goal of Work:

- Estimate exposure conditions > “transition” that are below thresholds for thermal hazard
- Use simple theory to develop scaling relations
- Develop Green’s function approach to define averaging times and areas
- Complement more detailed thermal models (Hirata’s group)

Penne's Bioheat Equation

In simplified form, Pennes' bioheat equation (BHTE) can be written:

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

where

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

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 (1.767 $\cdot 10^{-6}$ m^3/(kg sec) or 106 ml/min/kg in the mixed units typically used in the physiology literature).

Scaling Properties of BHTE

$$\tau_1 = 1 / m_b\rho \approx 500 \text{ sec}$$

time constant for heat removal by blood flow

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

Thermal diffusion

$R_1 = \dfrac{\sqrt{k}}{r\sqrt{m_b c}}$ » 7 mm

Screening distance by blood flow

$R_2 = \sqrt{4at}$ » $0.5\sqrt{t}$ mm

By thermal diffusion

Approximation 1 – Pure Surface Heating

- Excellent approximation >30 GHz
- Decent approximation (conservative) 10-30 GHz
- Yields simple expression for rise in surface temperature:

$$T_{sur}(t) = \frac{I_0 T_{tr}}{r\sqrt{k m_b C}} \, erf\left(\sqrt{\frac{t}{t_1}}\right) = \frac{I_0 T_{tr} R_1}{k}$$

$$= 0.019\ I_0 T_{tr} \mathrm{erf}\left(\sqrt{t / t_1}\right)$$

(Takes » 500 sec to reach steady state, independent of frequency

Approximation 2 – Conduction Only Model

- Excellent approximation for small exposed areas and short times
- Yields simple expressions for transient rise in surface temperature and for small exposed areas :

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

where x=R_0/R_1.

Local heating – independent of blood flow

$$T_{sur}(t) \approx 10^{-3} IoT_{tr}\sqrt{t} \quad {}^{o}\mathrm{C}$$

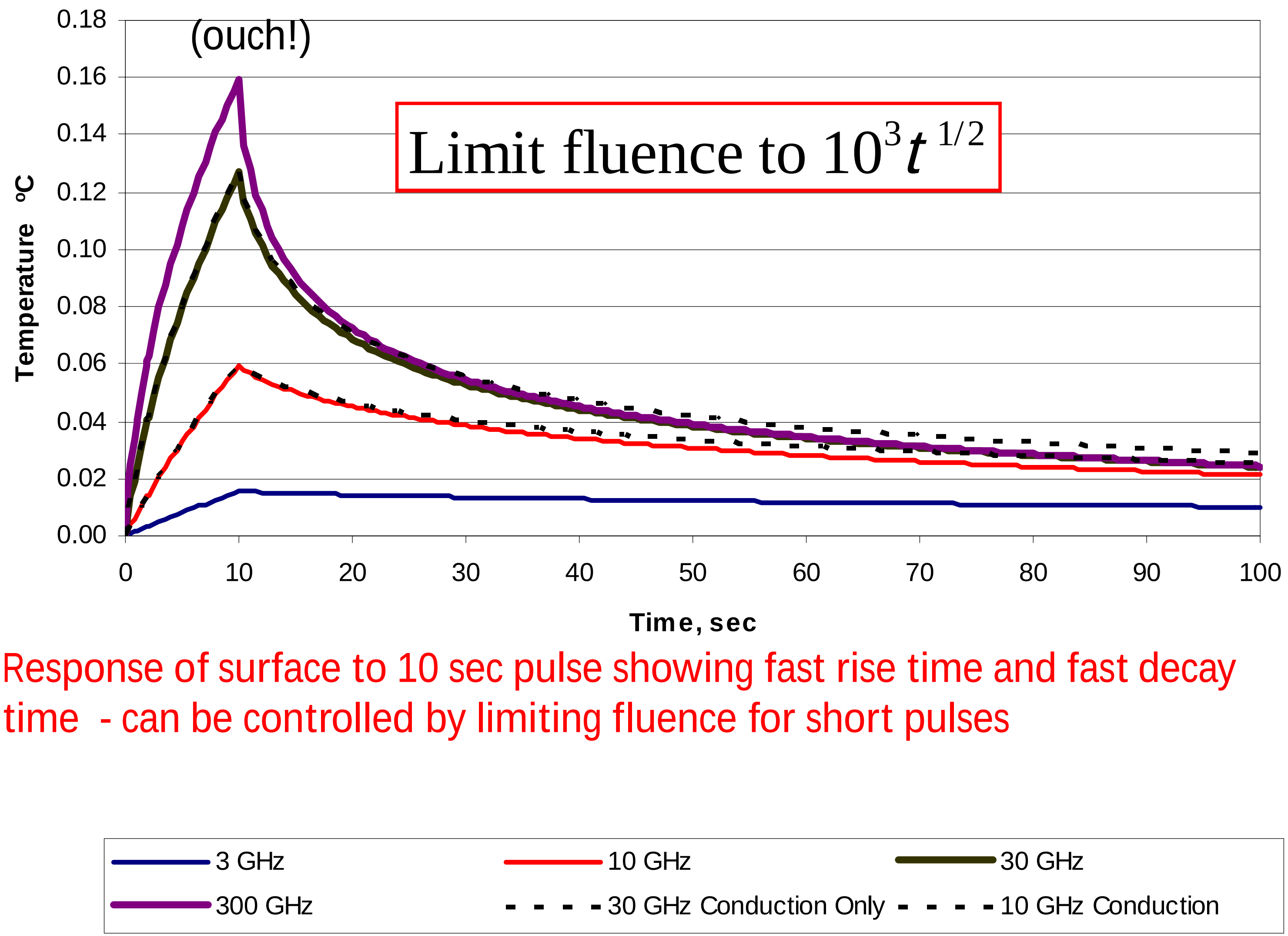
Transient heating proportional to $t^{1/2}$

Implications for Guidelines

- Present IEEE, ICNIRP guidelines are excessively conservative above transition frequency.

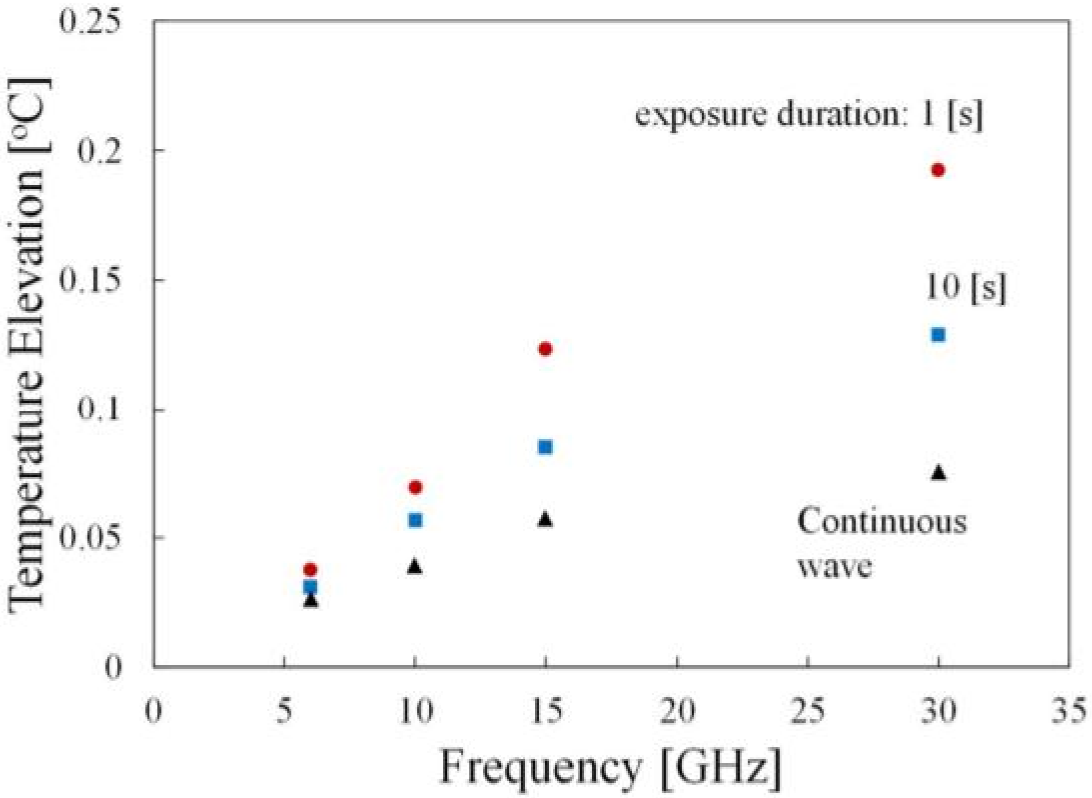
  Predicted skin temp. increases » 0.1 ^{o}C

- "Averaging times" are far too short at mm wave frequencies, should be several hundred seconds
- Need new provisions for short high intensity pulses that can create damage before victim can withdraw ("Active Denial type pulses")



Response of surface to 10 sec pulse showing fast rise time and fast decay time - can be controlled by limiting fluence for short pulses

Results in Hirata Lab



Other comments

- Emphasis on steady state temperature is not correct. Few people will sit motionless while their skin temperature creeps above threshold for pain then stay longer until burns occur
- Main prospective cause of thermal injury – high exposures that cause damage before victim can escape
- Second concern: vulnerable individuals with impaired thermal pain sensation

Personal electronic devices such as laptop computers and transmitters used near the body have similar risk profiles (for thermal hazards)

For such devices, might want to frame limits > 10 GHz as upper bound to skin temperature, not MPE.

This would avoid uncertainties in calculating temperature from incident power density – just measure skin temperature directly

e.g. IEC 60601-1:2015 specifies limits for "touch temperature"

for devices that will be in contact the body.

ERMAL RESPONSE OF HUMAN SKIN TO MICROWAVE ENEI
A CRITICAL REVIEW

Kenneth R. Foster,* Marvin C. Ziskin,† and Quirino Balzano‡

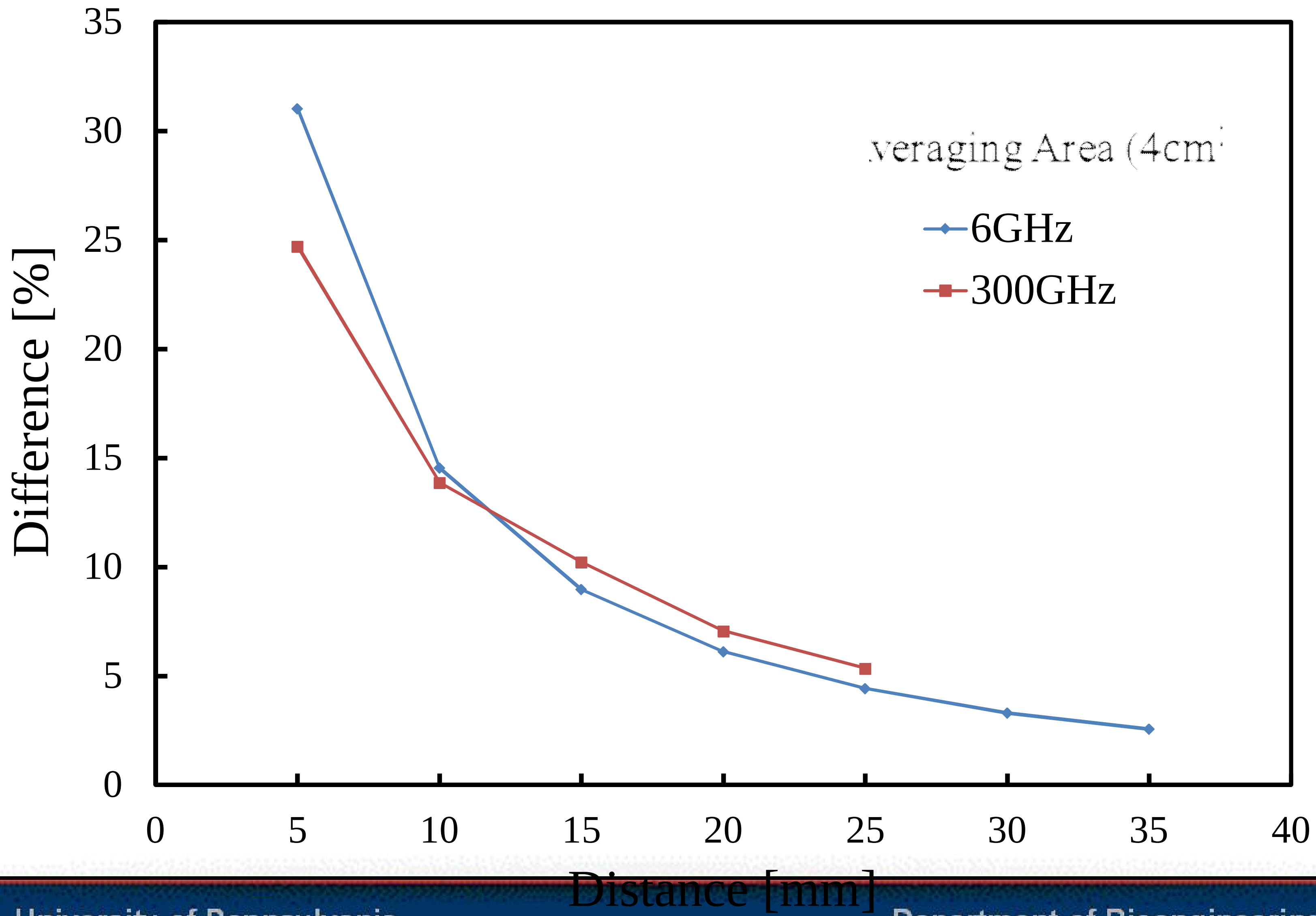
Health Phys. 111(6):528–541; 2016

hermal Modeling for the Next Generation of Radiofrequency Exposure Limits: Comment

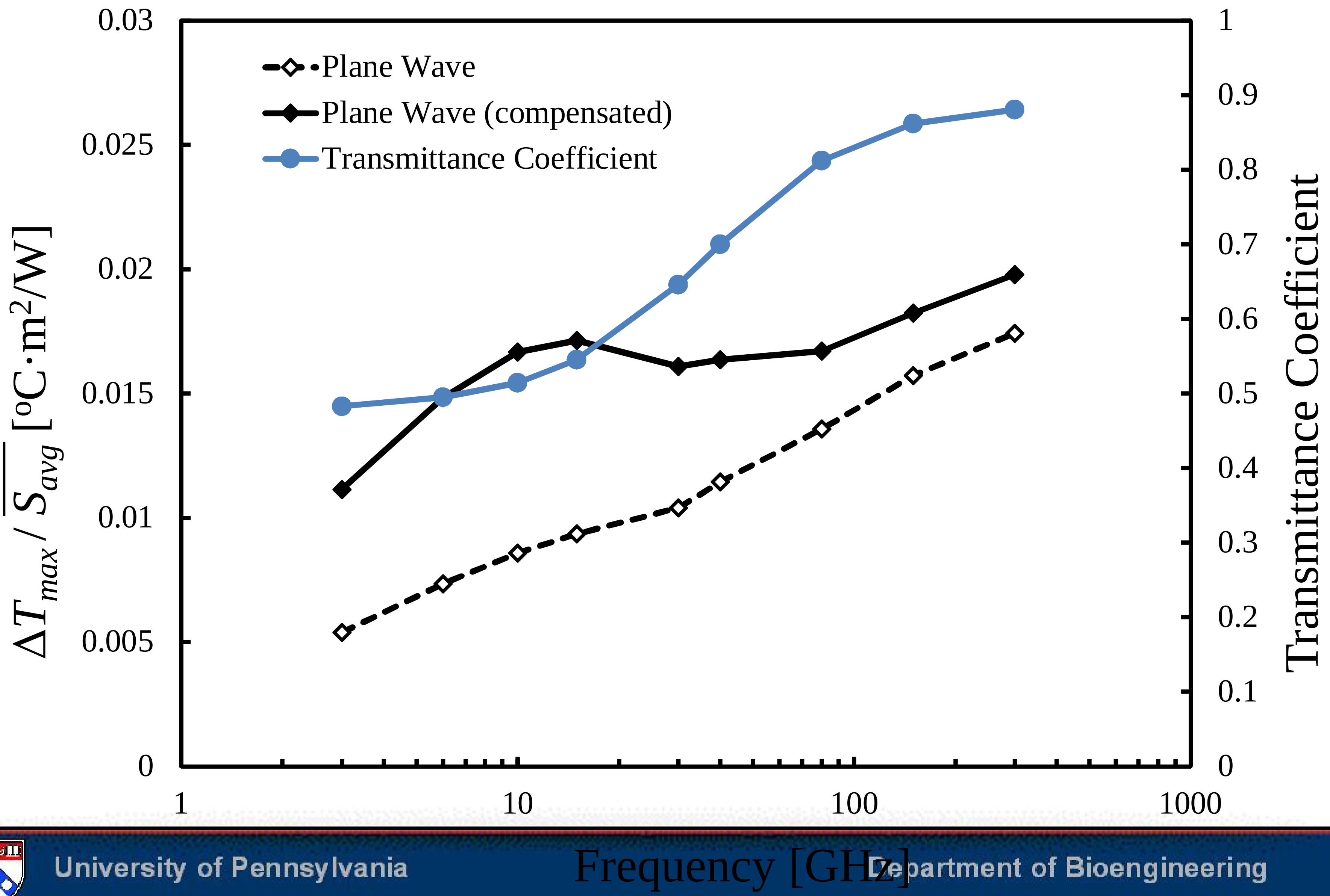
Kenneth R. Foster*, Marvin C. Ziskin+, and Quirino Balzano++

(under review with Health Physics

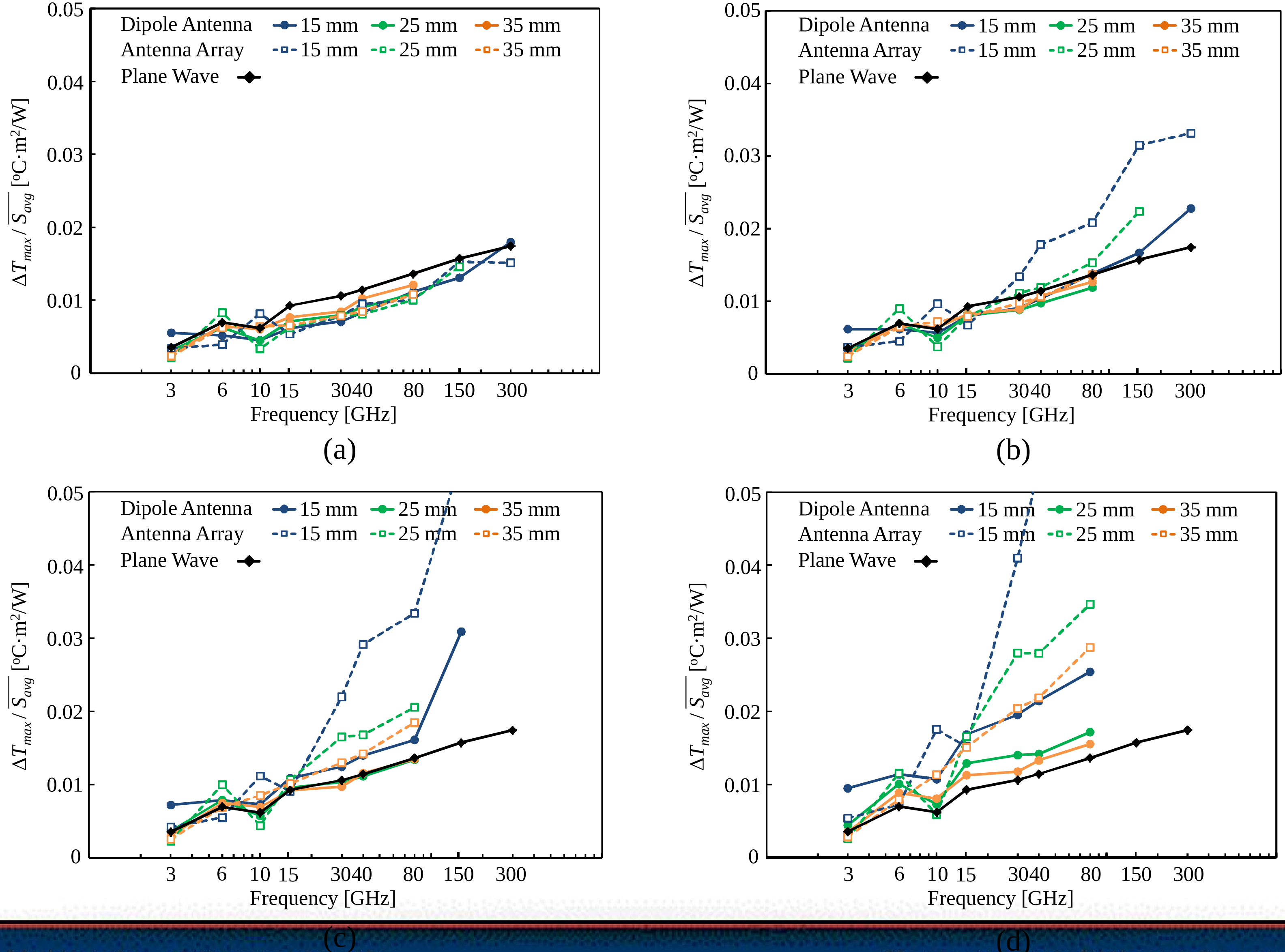
Difference rate between S_x and S_{xyz} due to Dipole Antenna $\frac{S_{xyz} - S_x}{S_{xyz}} \times 100$ (%)



Heating factor in the homogeneous model emitted from plane wave)



Heating Factor (Ratio of Max. Temperature elevation to Avg. Power Density)



Averaging area : (a) 100 mm^2 (b) 400 mm^2 (c) 900 mm^2 (d) 2000 mm^2