Review of studies of thermal response to skin above 6 GHz

Kenneth R. Foster
Department of Bioengineering
University of Pennsylvania
kfoster@seas.upenn.edu

Thermal Response of Human Skin to Microwave Energy: A Critical Review

Kenneth R. Foster*, Marvin Ziskin+, and Quirino Balzano++
Department of Bioengineering University of Pennsylvania

Address for correspondence:
*Department of Bioengineering
University of Pennsylvania
240 Skirkanich Hall
210 S. 33rd Street
Philadelphia PA 19104
kfoster@seas.upenn.edu

+Temple University Medical School
3420 N. Broad Street
Philadelphia, PA
ziskin@temple.edu

***

++Department of Electrical Engineering
University of Maryland
College Park MD
qbfree01@aol.com

Available Studies

- Several studies – acute exposures at *high power densities*, mostly 96 GHz (Brooks AFB group)
- Several studies at mm waves, mostly small area exposure from waveguide
- Miscellaneous other studies (mm wave exposure to eye, a few older studies at 10 GHz)
- Few if any studies involving large area heating, long times

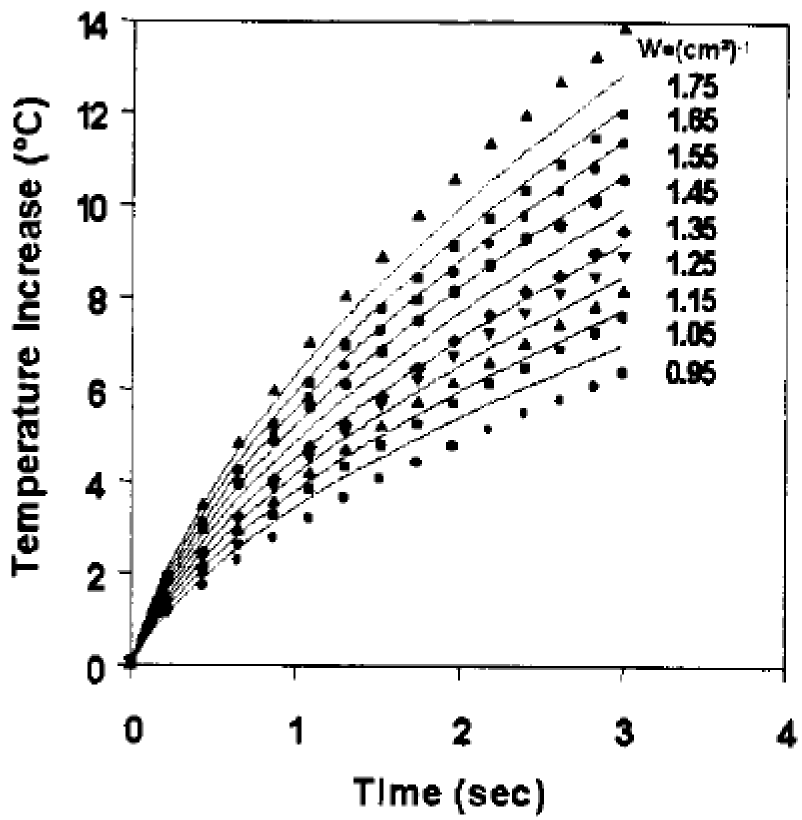


Fig. 4. The mean increase in skin temperature (markers) vs. fitted functions (curves) for a range of power densities (eqn 3).

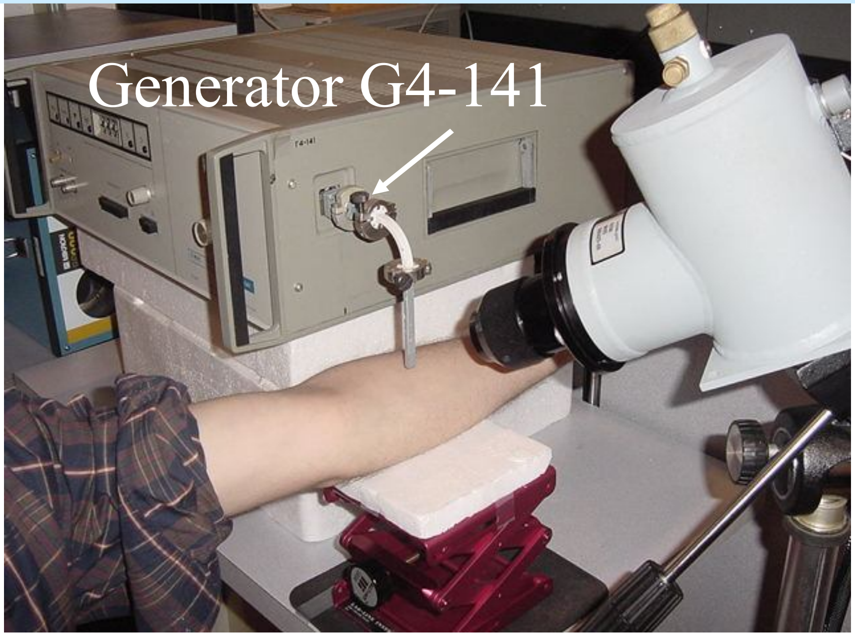
Volume 78(3), March 2000, pp 259-267

HEATING AND PAIN SENSATION PRODUCED IN HUMAN SKIN BY MILLIMETER WAVES: COMPARISON TO A SIMPLE THERMAL MODEL
[Papers]

Walters, Thomas J.*; Blick, Dennis W.*; Johnson, Leland R.†; Adair, Eleanor R.†; Foster, Kenneth R.‡

Temperature measurements in the skin during mm-wave exposure with WG opening

Lower forearm

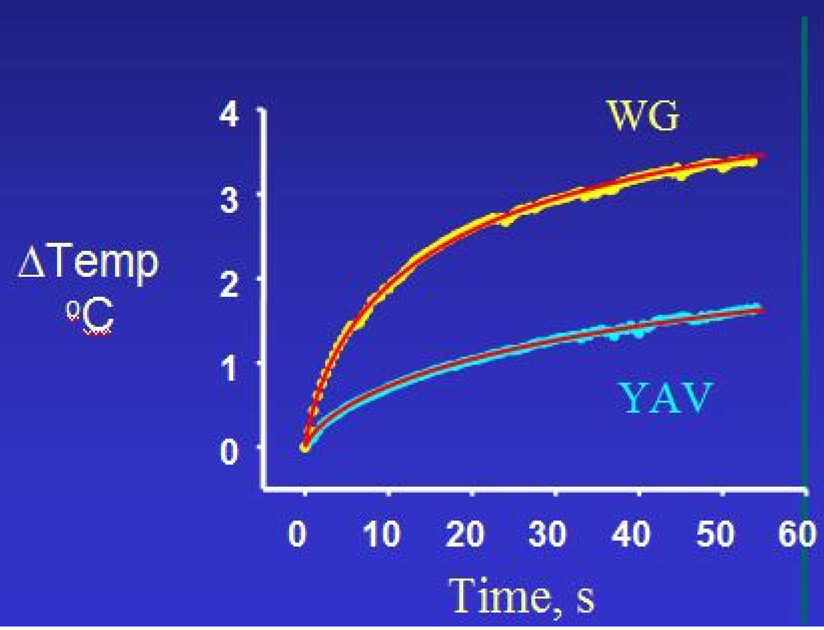


Index finger

Frequency: 42.25 GHz   Ziskin + Alekseev

Output power: 52 mW

Temperature rise kinetics measured at the skin surface during mm-wave exposure with YAV device (I_o=54.9 mW/cm^2) or waveguide opening (I_o=208 mW/cm^2) and fitting to model



(Ziskin + Alekseev)

Table 1. Summary of studies reporting temperature increases to skin from RF exposure

Study	Frequency, power density	Radius of heated region, mm)	Exposure time t, sec	Measured skin temperature increase, C	Max temperature increase after time t (numerical solution to BHTE, using parameters given in Eq. 1)	Steady State Temperature increase (from shape factor approximation, Eq. 13b) using parameters below Eq. 1)
Hendler et al. (1963)	10 GHz 2500 W/m^2 (quoted as power absorbed in skin)	(unspecified)	60	1	0.96	n/a
Alekseev and Ziskin (2005)	42.25 GHz, human forearm and finger, 2080 or 549 W/m^2	forearm 2.4 (2080 W/m^2)	600	4.5 (forearm)	4.9	4.9
		5.3 mm (549 W/m^2)		3.0	2.45	2.85
		Finger 2.4 (2080 W/m^2)	600	2.5	4.9	4.9
Nelson et al. (2002)	94 GHz, 1750 W/m^2	5 mm	180	8.4	8.8	10.2
Hu et al. (2011)	33.5 GHz, up to 8530 W/m^2, mouse abdomen	3 mm	240	≈8	21	24

Gustrau and Bahr (2002)	77 GHz, 100 W/m^2 (human forearm)	Not stated	Not stated (tens of minutes?)	0.7	1.2	n/a
Sasaki et al. (2014	data at 40, 75 GHz, 2000 W/m^2 rabbit eye	6.5 mm (radius of cornea)	180 sec	10.7 (40 GHz) (cornea) 13.2 (75 GHz) (cornea)	9.2 11.0 (calculations assume m_b=0)	12.6 14.5
Walters et al. (2000)	94 GHz Back of 8 human subjects up to 18000 W/m^2 3 sec	2 cm	3 sec	Up to 14 C	Up to 14 C (good agreement with 1D conduction model for 3 sec exposures)	
Walters et al. (2004)	94 GHz, forearms of 6 human subjects “low power” 1750 W/m^2 (180 or 480 sec) “high power” 10^4 W/m^2 (4 sec) or	1.65 cm	180 or 480 sec (low power) 4 sec (high power)	Low power: 9 C after 3 min (normal skin blood flow) 11 C after 5 min (blood flow from times 180-300 sec reduced to approximately baseline (pre-exposure) value High power: 8 C (small effect	BHTE simulations: 12.2 (with m_b given in Eq. 1 11.1 ($2m_b$) 10.2	n/a

Goal: simple thermal model

- Need simple model (no anatomical details)
- Use fixed parameters
- Need to evaluate model using independent data

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)

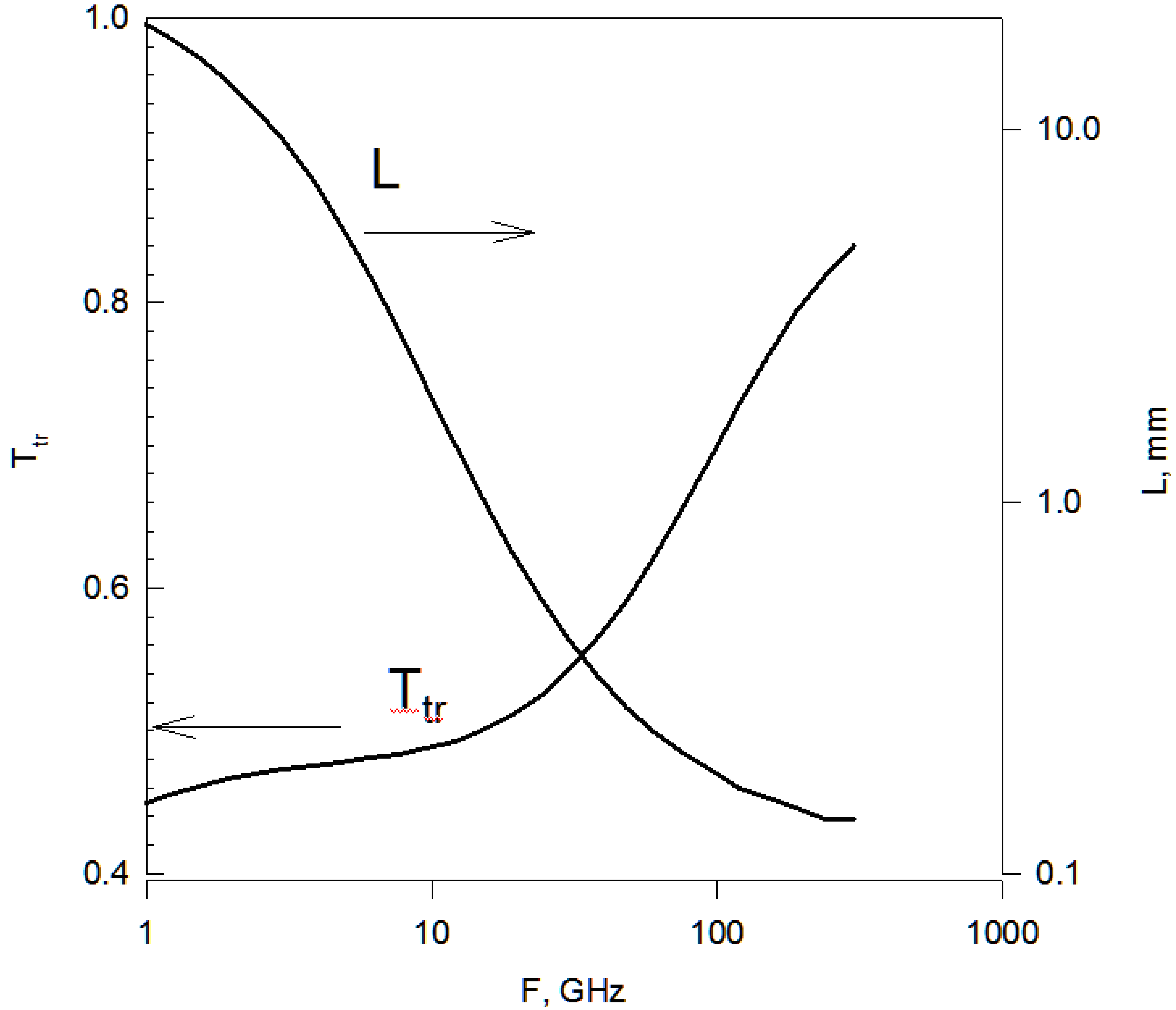
C is the heat capacity of the tissue (3390 W sec/kg°C)

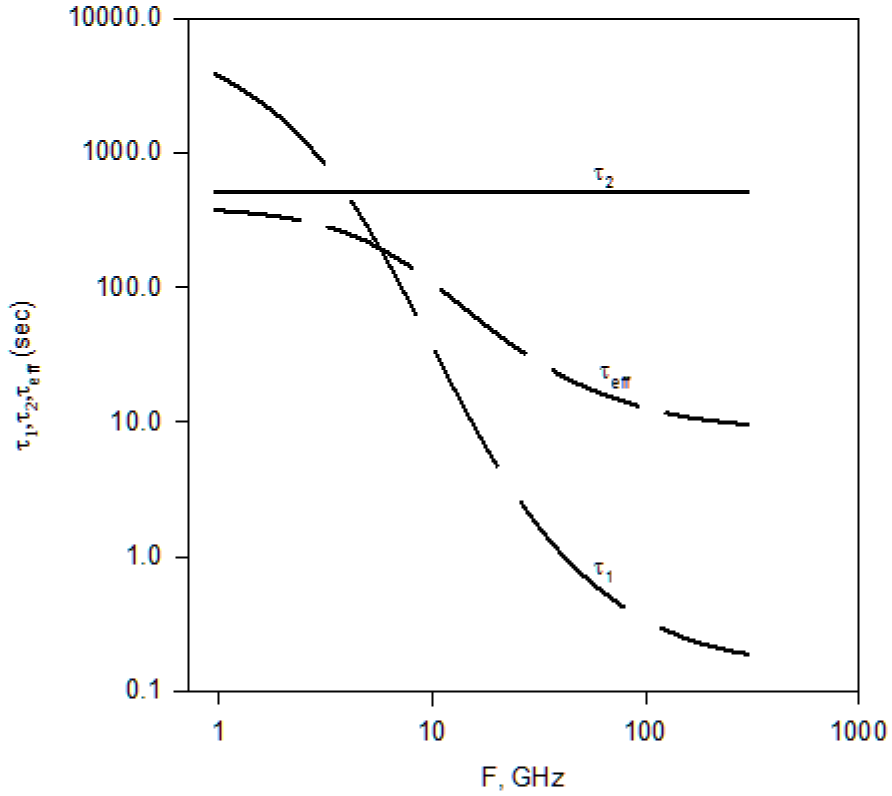
ρ is the tissue density (1109 kg/m³)

and m_b is the volumetric perfusion rate of blood ($1.767 \cdot 10^{-6}$ m³/(kg sec) or 106 ml/min/kg in the mixed units typically used in the physiology literature).

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

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


1.0
0.8
0.6
0.4
T tr
L
T tr
10.0
1.0
0.1
L, mm
1
10
100
1000
F, GHz


10000.0
1000.0
100.0
10.0
1.0
0.1
τ2
τeff
τ1
1
10
100
1000
F, GHz
τ1,τ2,τeff (sec)

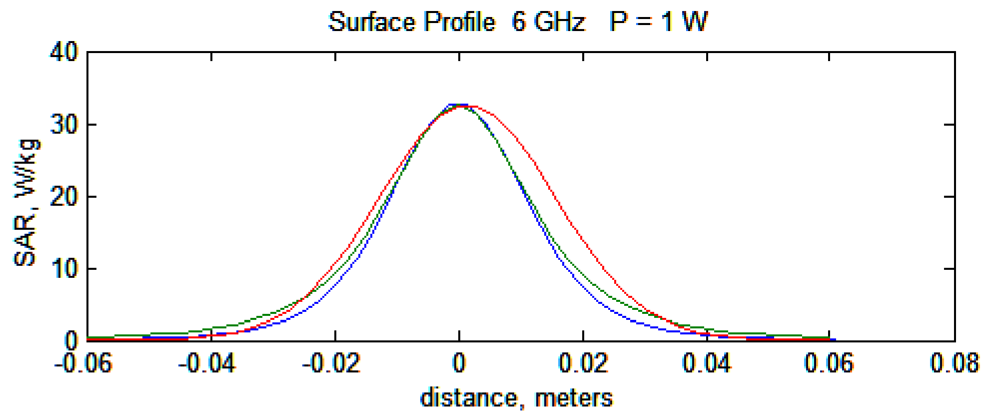
Steady State Solution – 1D problem

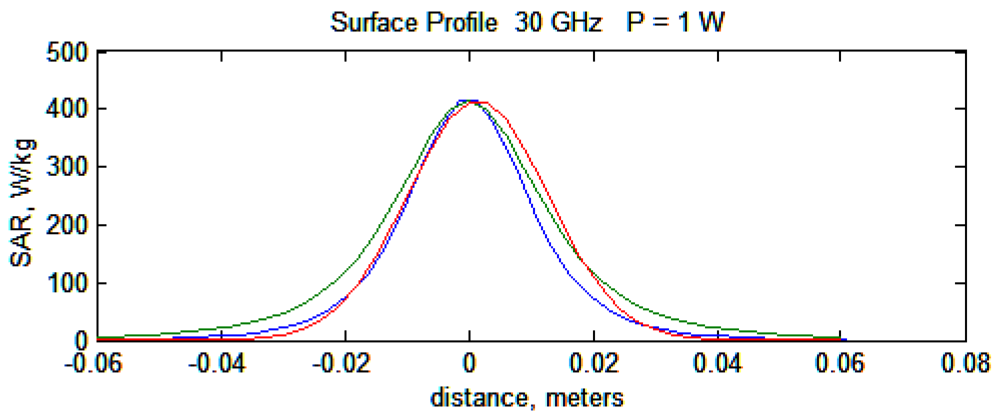
$$T_{ss} = \frac{SAR_o}{C}\tau_{eff} \quad \text{(surface temperature, steady state)}$$

where

$$\tau_{eff} = \frac{\tau_2 - \sqrt{\tau_1\tau_2}}{\tau_2/\tau_1 - 1}$$

$$SAR_o = \frac{I_o T_{tr}}{\rho L}$$





Gaussian Beam Pattern

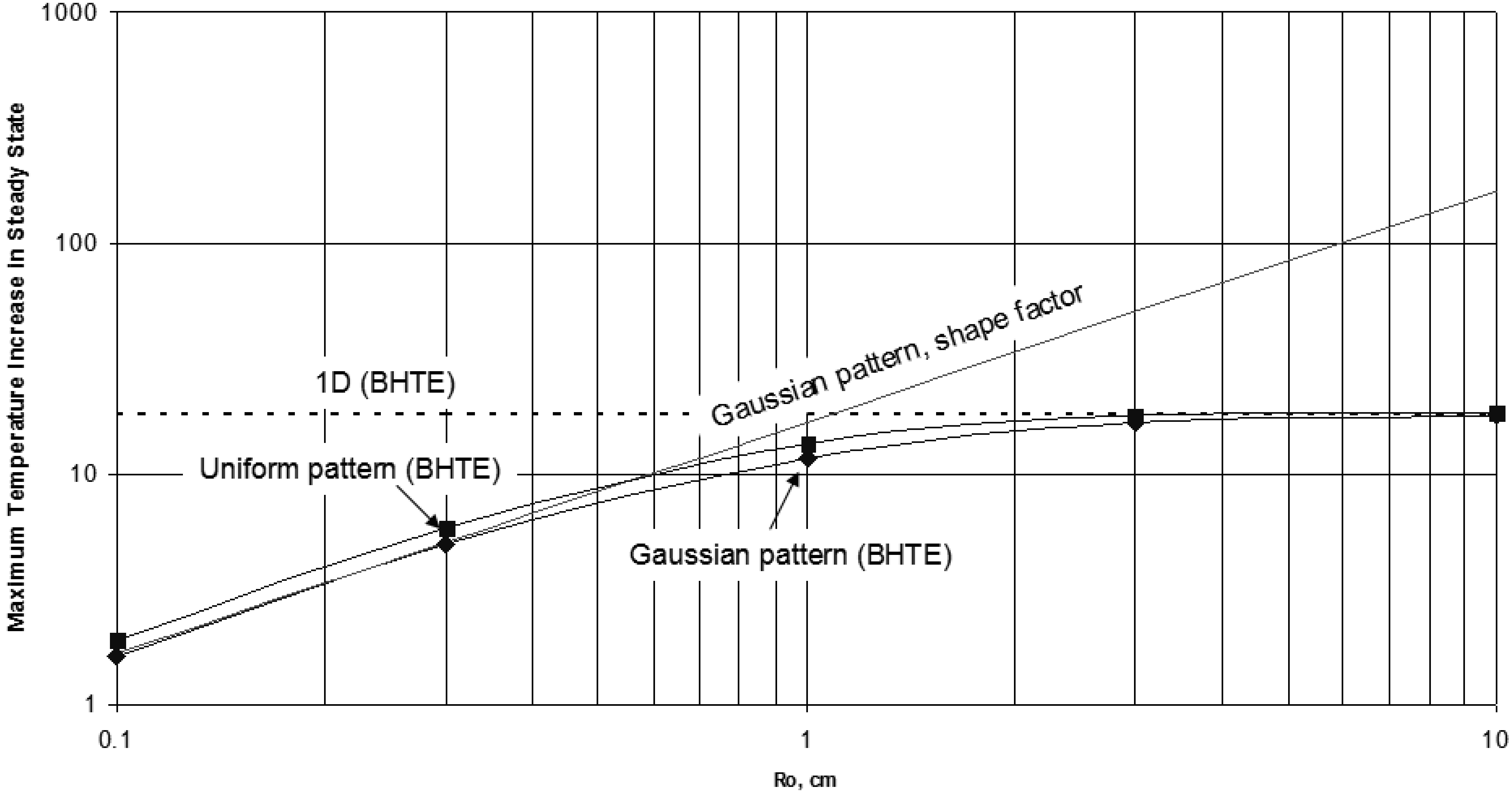
Solutions - 2D problem

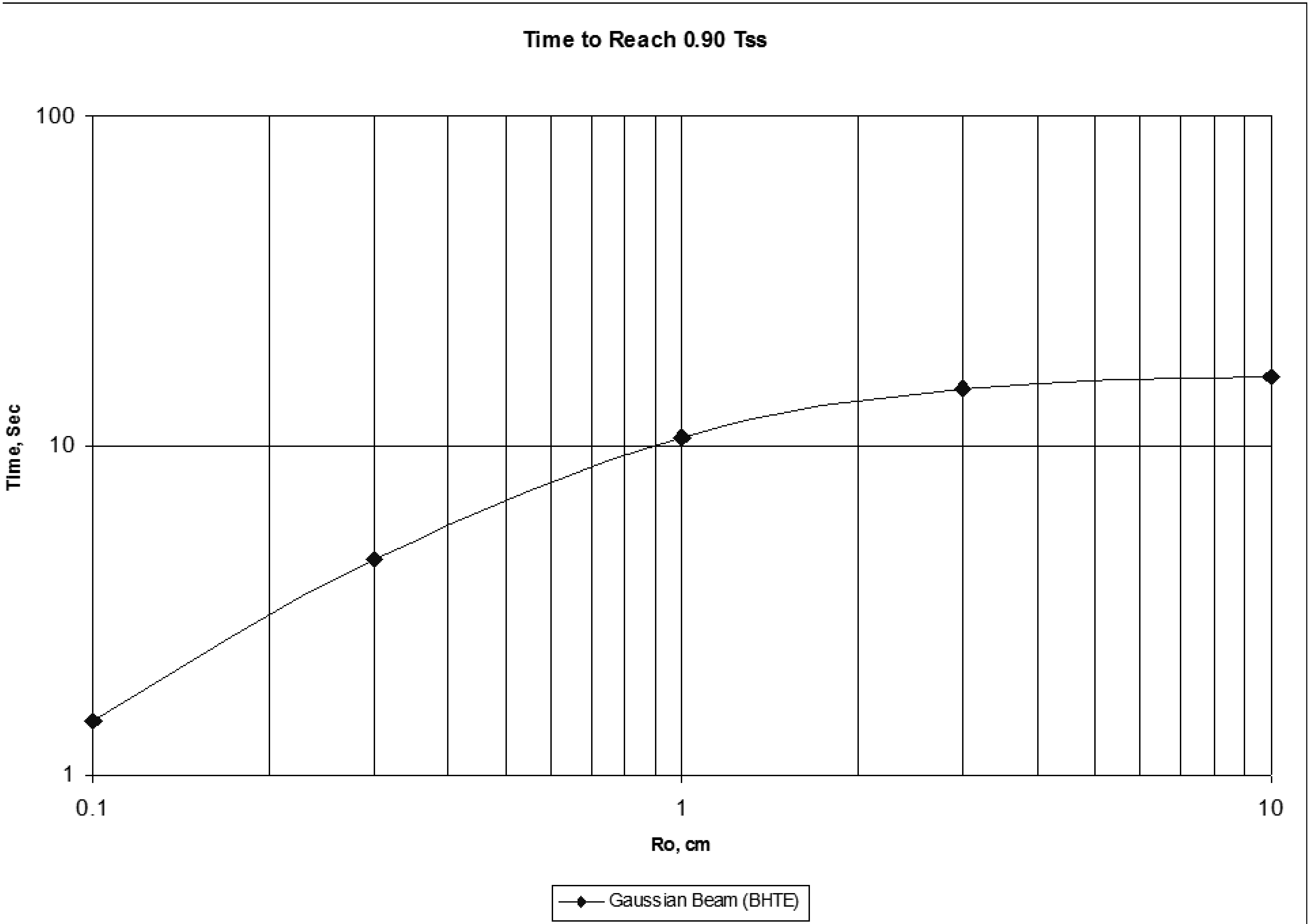
1. Finite element solution

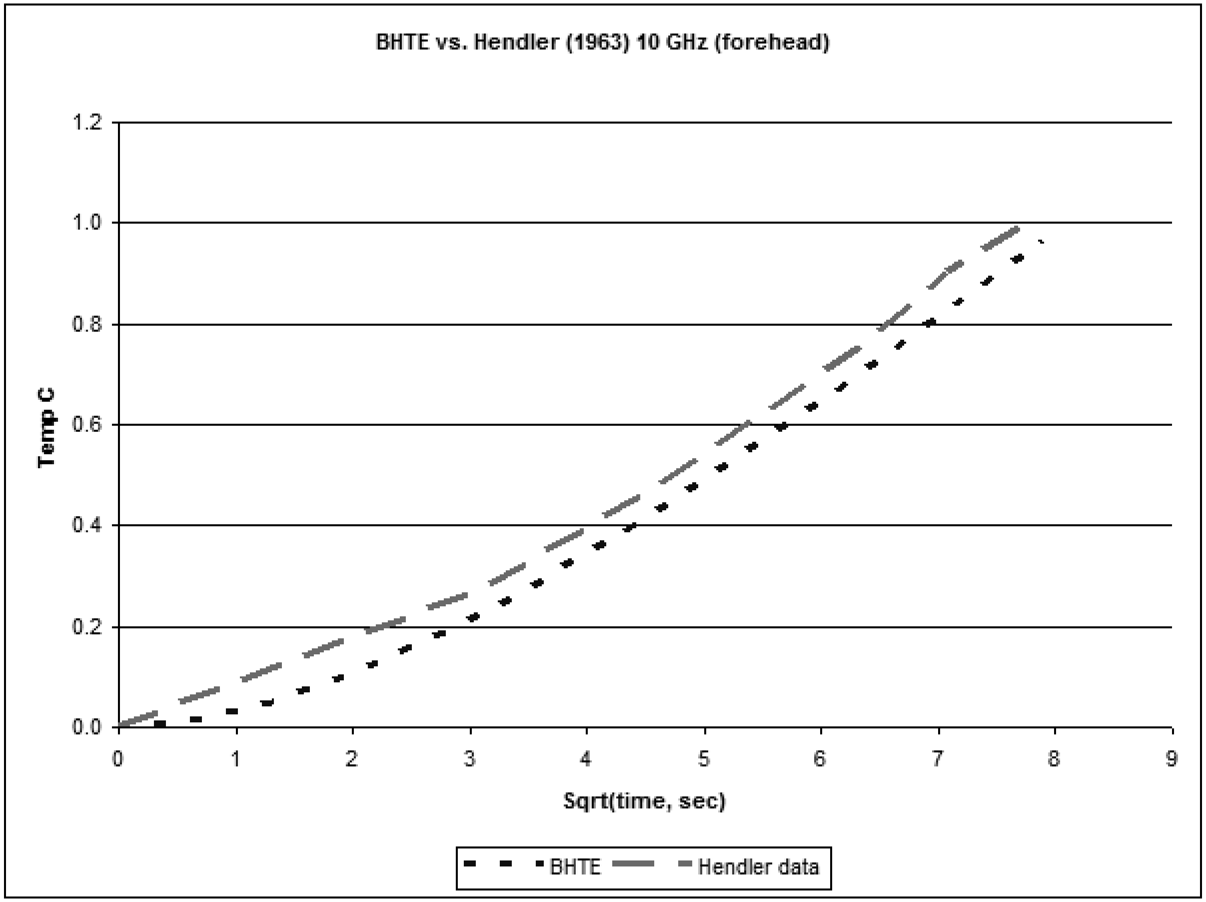
1. Shape factor approximation

$$T_{ss} \approx \frac{\pi I_o T_{tr} R_o}{8k} \text{ (shape factor approximation for thin disk, uniformly heated)}$$

$$\approx \frac{\pi I_o T_{tr} R_o}{5k} \text{ (shape factor approximation for thin disk, Gaussian heating)}$$


1000
100
10
1
0.1
1
10
Maximum Temperature Increase in Steady State
Ro, cm
1D (BHTE)
Uniform pattern (BHTE)
Gaussian pattern, shape factor
Gaussian pattern (BHTE)


Time to Reach 0.90 Tss
100
10
1
Time, Sec
0.1
1
10
Ro, cm
Gaussian Beam (BHTE)


BHTE vs. Hendler (1963) 10 GHz (forehead)
Temp C
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
9
Sqrt(time, sec)
BHTE
Hendler data

Alekseev and Ziskin 2005

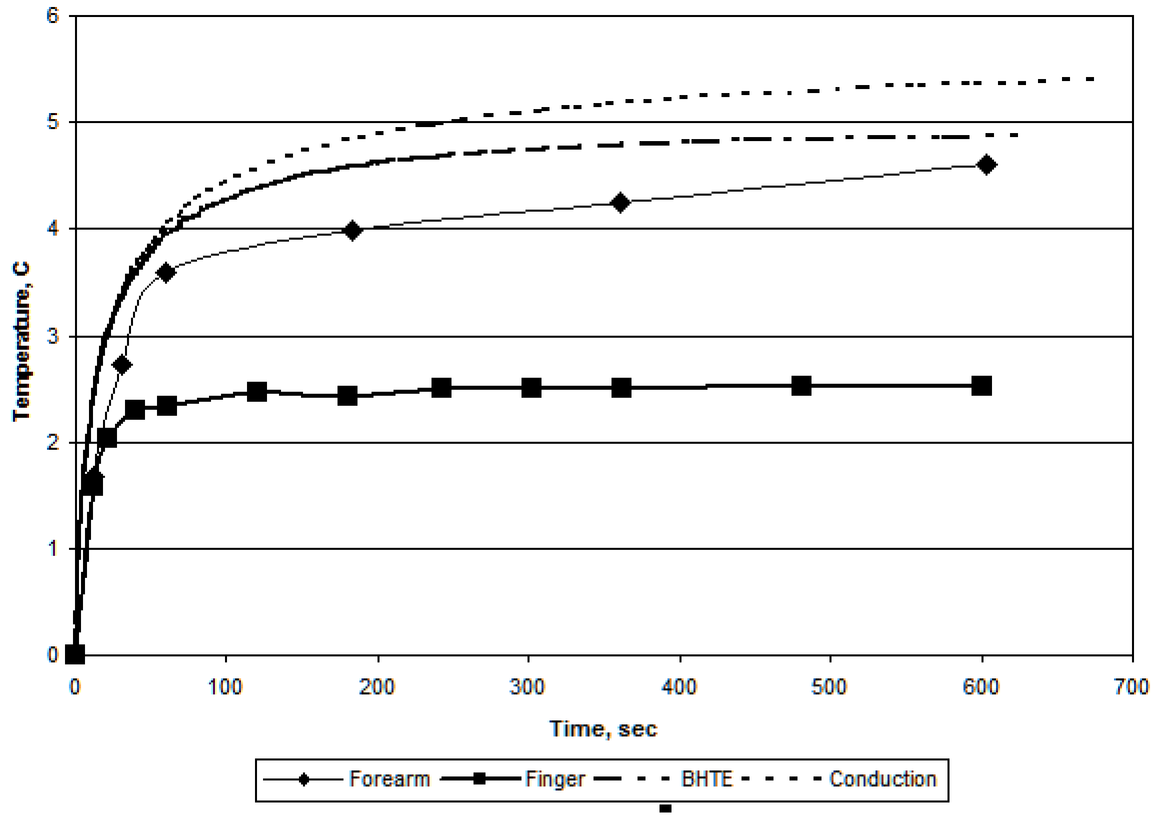


Table 1. Summary of studies reporting temperature increases to skin from RF exposure

Study	Frequency, power density	Radius of heated region, mm)	Exposure time t, sec	Measured skin temperature increase, C	Max temperature increase after time t (numerical solution to BHTE, using parameters given in Eq. 1)	Steady State Temperature increase (from shape factor approximation, Eq. 13b) using parameters below Eq. 1)
Hendler et al. (1963)	10 GHz 2500 W/m^2 (quoted as power absorbed in skin)	(unspecified)	60	1	0.96	n/a
Alekseev and Ziskin (2005)	42.25 GHz, human forearm and finger, 2080 or 549 W/m^2	forearm 2.4 (2080 W/m^2)	600	4.5 (forearm)	4.9	4.9
		5.3 mm (549 W/m^2)		3.0	2.45	2.85
		Finger 2.4 (2080 W/m^2)	600	2.5	4.9	4.9
Nelson et al. (2002)	94 GHz, 1750 W/m^2	5 mm	180	8.4	8.8	10.2
Hu et al. (2011)	33.5 GHz, up to 8530 W/m^2, mouse abdomen	3 mm	240	≈8	21	24

Gustrau and Bahr (2002)	77 GHz, 100 W/m² (human forearm)	Not stated	Not stated (tens of minutes?)	0.7	1.2	n/a
Sasaki et al. (2014	data at 40, 75 GHz, 2000 W/m² rabbit eye	6.5 mm (radius of cornea)	180 sec	10.7 (40 GHz) (cornea) 13.2 (75 GHz) (cornea)	9.2 11.0 (calculations assume m_b=0)	12.6 14.5
Walters et al. (2000)	94 GHz Back of 8 human subjects up to 18000 W/m² 3 sec	2 cm	3 sec	Up to 14 C	Up to 14 C (good agreement with 1D conduction model for 3 sec exposures)	
Walters et al. (2004)	94 GHz, forearms of 6 human subjects "low power" 1750 W/m² (180 or 480 sec) "high power" 10⁴ W/m² (4 sec) or	1.65 cm	180 or 480 sec (low power) 4 sec (high power)	Low power: 9 C after 3 min (normal skin blood flow) 11 C after 5 min (blood flow from times 180-300 sec reduced to approximately baseline (pre-exposure) value High power: 8 C (small effect	BHTE simulations: 12.2 (with m_b given in Eq. 1 11.1 ($2m_b$) 10.2	n/a

Summary

- Simple model fits available data very well with no adjustable parameters
- But most data are for exposure situations where heat conduction dominates
  - Short times – do not reach steady state
  - Small exposed areas
- To assess model need:
  - Extended exposures (minutes or more)
  - Larger exposed areas of skin

Biological Variability

- Variable skin blood flow
- Variable transfer of heat from skin to environment
- Microanatomy
- Intersubject variability

- Will be very difficult to base exposure limits on maximum temperature increase

Table 3. Heat flows across the skin. Data from Stolwijk and Hardy (1977), ILO (2012), Fiala et al (1999).

Mechanism	Typical ranges of heat flow (W/m^2) in skin of human
Cooling of skin by evaporation of sweat	Varies with environmental conditions, from 75 (resting in thermoneutral environment) to > 350 (strenuous exercise)
Convective cooling of skin	Depends on air flow, clothing. Approximately 2-4 W/m^2 per K (100-200 W/m^2 for a 10 C difference between between skin and environment) in still air, to 10-15 W/m^2 per K for forced convection with air velocity 1 m/s.
Radiative cooling/heating of skin	Depends on clothing and radiant temperature of surroundings, approximately 5 W/m^2 per K (approximately 50 W/m^2 for 10 C difference between skin temperature and radiometric temperature of surroundings.
Conduction of heat from core into skin	20-100 W/m^2 (depends on the thermoregulatory status, level of activity, clothing)

Implications of Work

- Thermal response is similar to that from purely surface heating.
- Don't need fine anatomical detail (heat conduction smoothes out effects of varying SAR)
- For small irradiated areas or short irradiation times, temperature increase can be reliably predicted (conduction dominates)
- Thermal model can be useful to develop temporal and spatial averaging
- Need to be used in connection with more detailed models - FDTD