EMF exposure of the skin at the mmW

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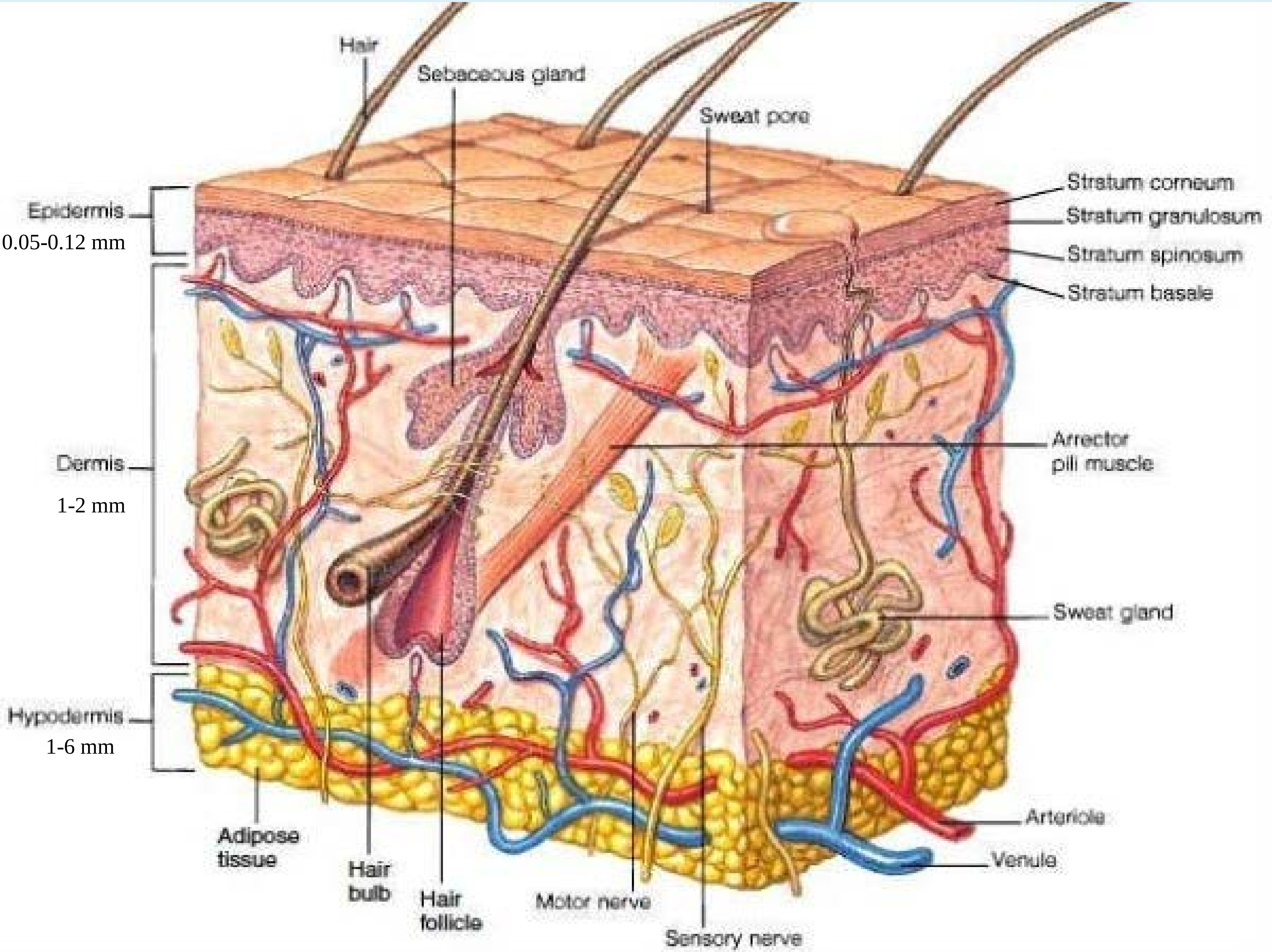
***Speaking as an individual and not for the IEEE**

Outline

- Skin morphology
- RF penetration depths
- mmW therapy applications
- Thermal modeling in skin
- Temperature and pain thresholds
- DRL (epithelial power density) and ERL (incident power density) to limit temperature rise in skin


Hair
Sebaceous gland
Sweat pore
Stratum corneum
Stratum granulosum
Stratum spinosum
Stratum basale
Epidermis
0.05-0.12 mm
Dermis
1-2 mm
Arrector pili muscle
Sweat gland
Hypodermis
1-6 mm
Arteriole
Venule
Adipose tissue
Hair bulb
Hair follicle
Motor nerve
Sensory nerve

Epidermis
(150 – 200 μm Thick)

Layer	Thickness (μm)	Water (per cent)
1. Horny	13 - 15	2
2. Clear	0 - 20	10-45
3. Granular	10 - 20	10-47
4. Prickle Cell	85 - 115	72
5. Basal Cell	15 - 18	72

Skin Thickness

Region	Epidermis (µm)	
	Male	Female
Eyelid	58	50
Postauricular Region	69	65
Back	88	60
Forehead	96	90
Back of Arm	101	73
Cheek	115	85
Buttock	148	128
Dorsum of Foot	180	175
Dorsum of Hand	247	132
Palm	557	647
Sole	793	478
AVERAGE	223	180

Effects of Age on Skin

Skin of Infant

Skin is completely formed at birth

Stratum corneum is thinner and water content is higher

Papillary dermis is thinner than in adults

Production of sweat is reduced

Effects of Age on Skin

Skin of a Child

After reaching one year of age, the skin of a child is essentially the same as that of an adult.

Effects of Age on Skin

Skin in Elderly

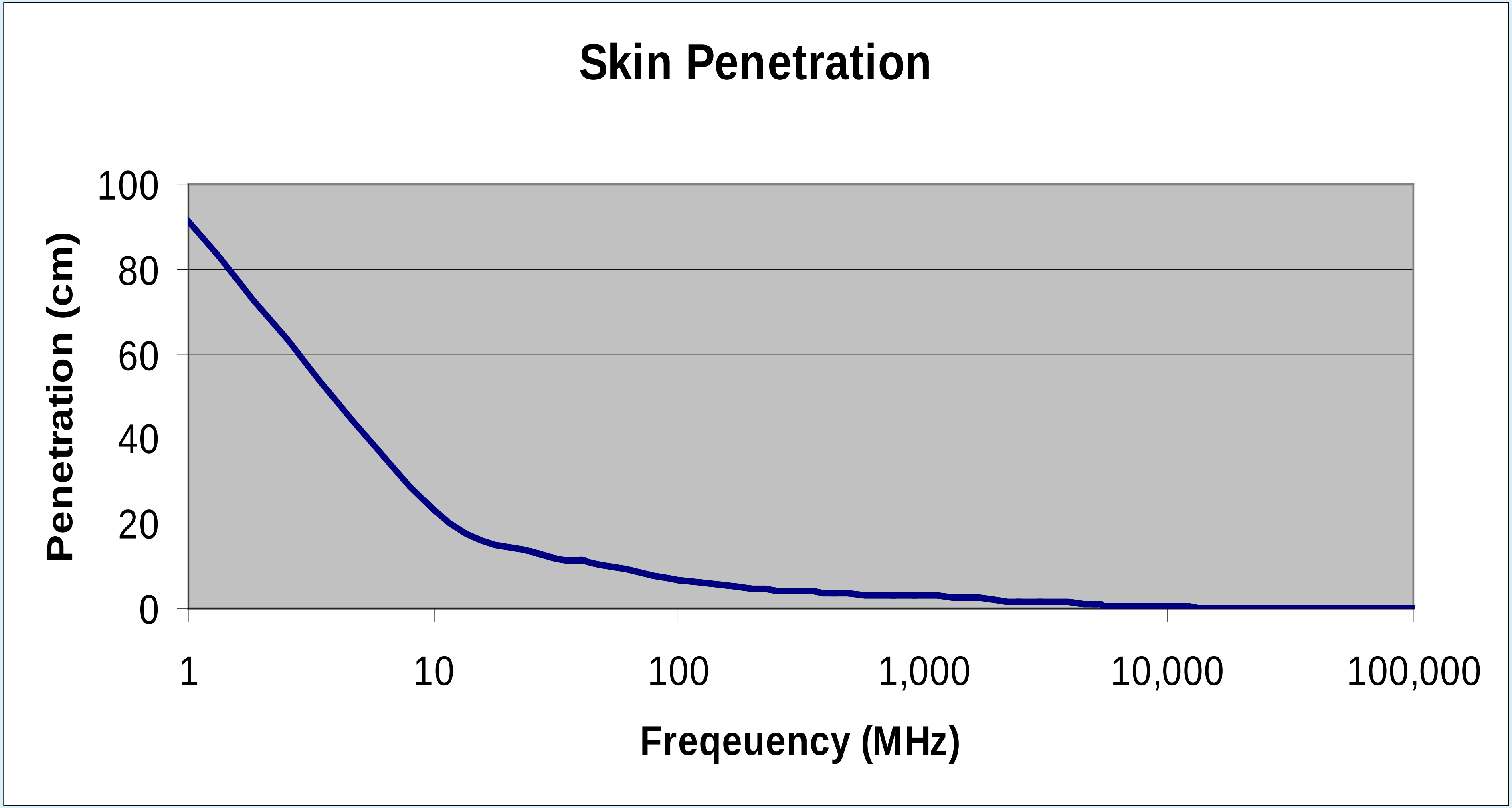
Epidermis thins

Blood vessels of the dermis become more fragile

Sebum production decreases leading to increased dryness and itching

Fat layer thins leading to decreased ability to maintain body temperature

Sweat production decreases making it harder to lose heat


Skin Penetration
Penetration (cm)
100
80
60
40
20
0
1
10
100
1,000
10,000
100,000
Freqeuency (MHz)

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94 GHz and 35 GHz penetrations in SKIN

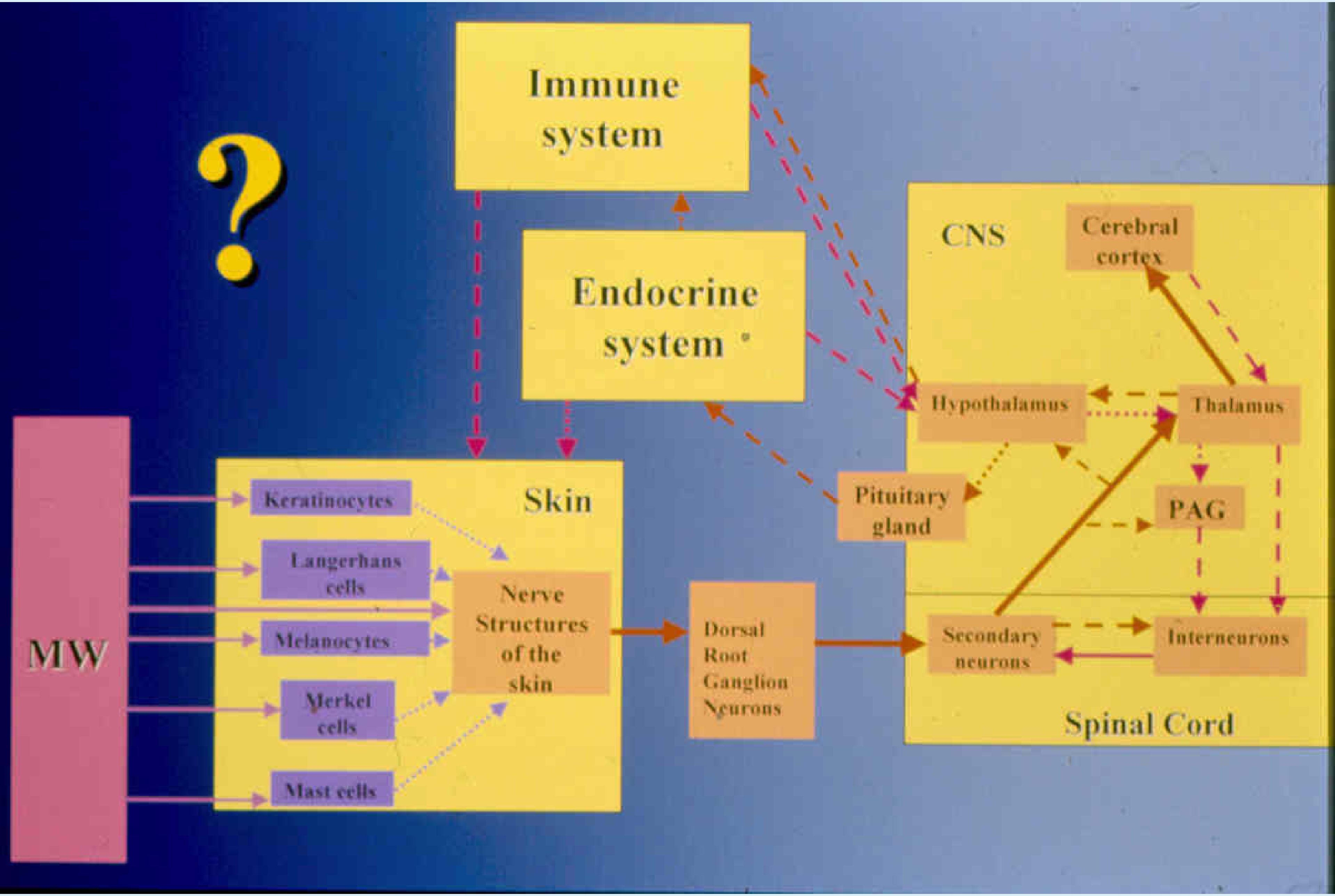
Selected Frequency (GHz)	Skin Depth (mm)
6	4.09
10	1.90
30	0.43
60	0.24
100	0.18
300	0.14

Millimeter Wave Therapy

- “Therapeutic” wavelengths:
  4.9, 5.6, and 7.1 mm
  (frequencies 61.22, 53.57 and 42.25 GHz)

- Exposure of patient’s skin:
  acupuncture points, forehead, occiput sternum; big joints, surgical wounds

- 15-30 min session; one session per day; 10-15 sessions per course



?
Immune system
Endocrine system
CNS
Cerebral cortex
Hypothalamus
Thalamus
Pituitary gland
PAG
Skin
Keratinocytes
Langerhans cells
Nerve Structures of the skin
Melanocytes
Merkel cells
Mast cells
MW
Dorsal Root Ganglion Neurons
Secondary neurons
Interneurons
Spinal Cord

mmW therapy

Millimeter wave irradiation used in therapy,

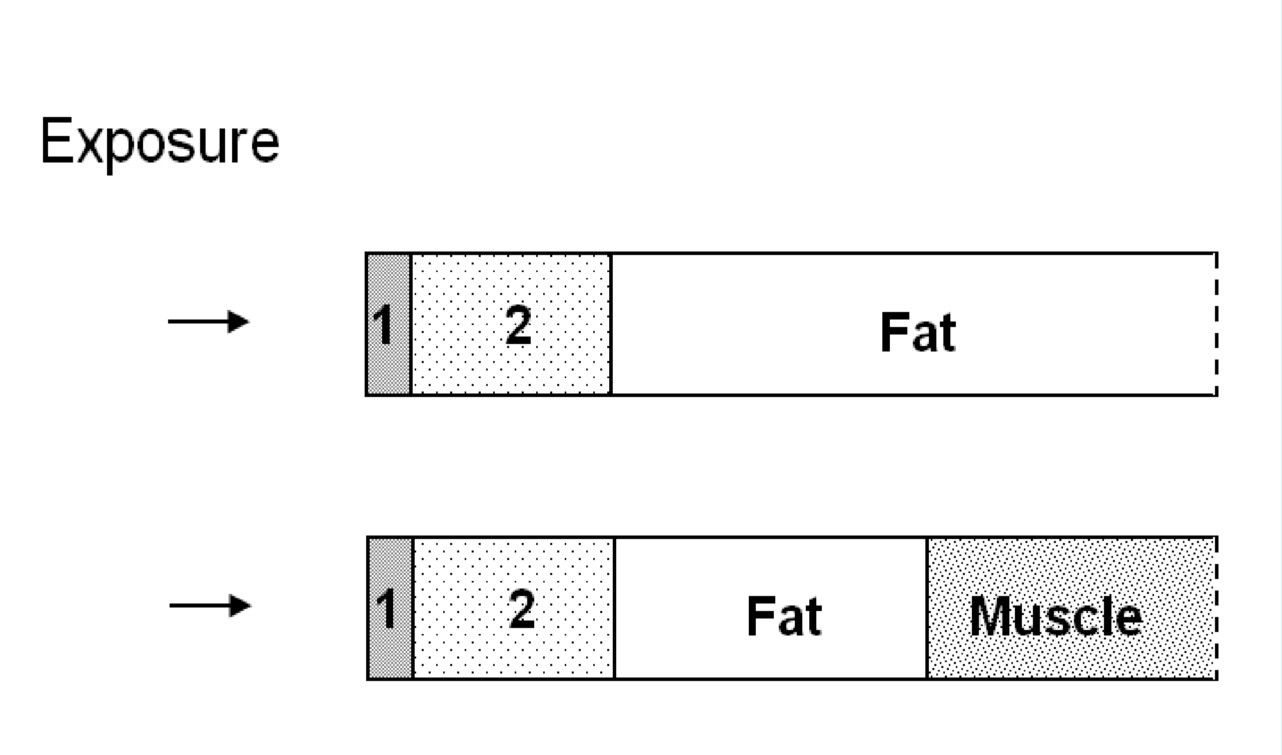
if sufficiently intense, can activate thermo-receptors and free nerve endings in the outer layers of the skin.

Typical therapeutic exposures	**=**	**100 – 200 W/m^2**
No sensation for exposures	**<**	**350 W/m^2**
No pain for exposures	**<**	**1000 W/m^2**

Millimeter Wave Irradiation

- Heating is a major mechanism for bioefffects
- Most of energy is absorbed within a few tenths of a millimeter
- Wavelengths in tissue are comparable with biological structures
- Irradiation is frequently in the near field

Skin Thermal modeling



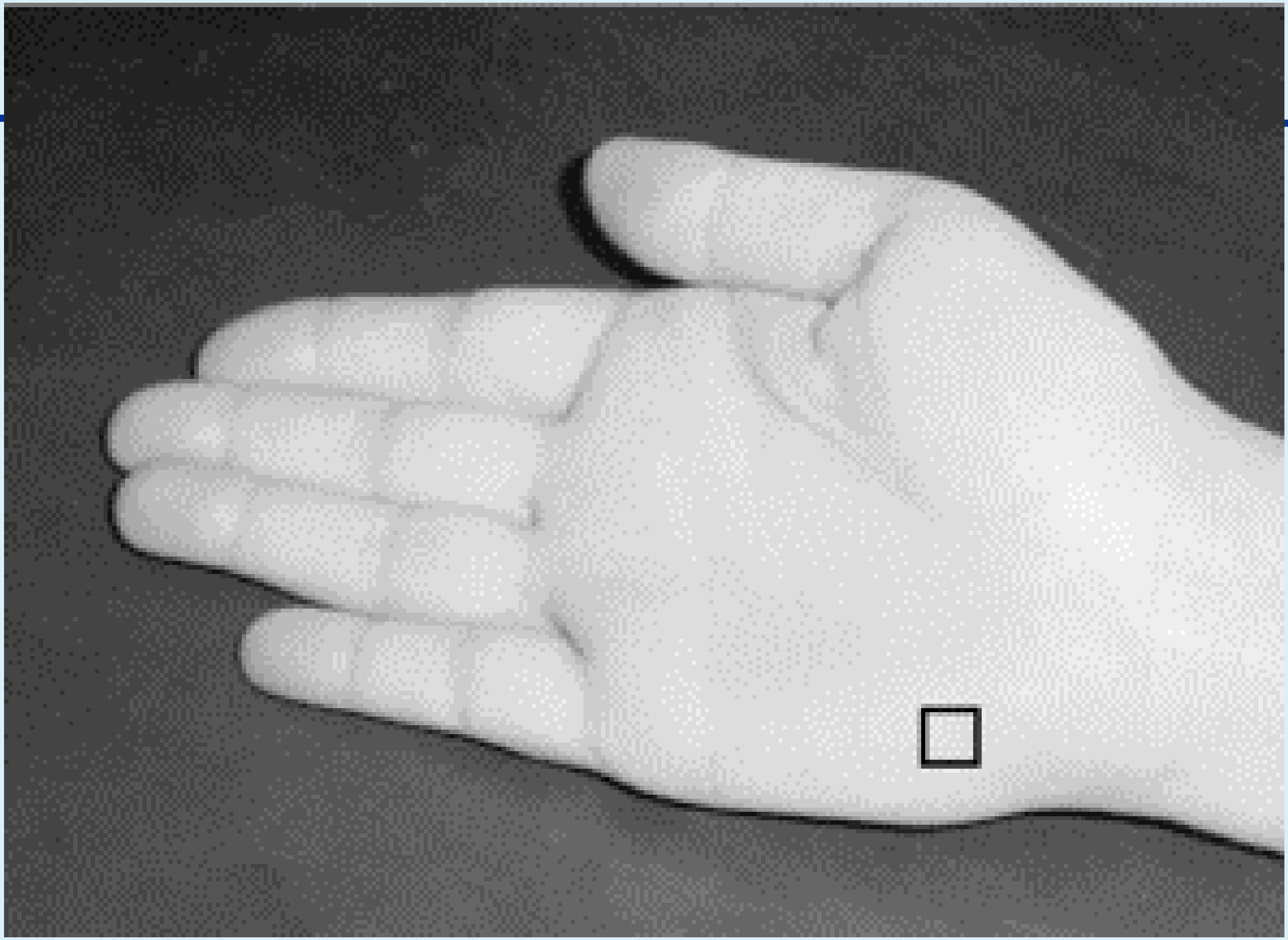
3-Layer Model

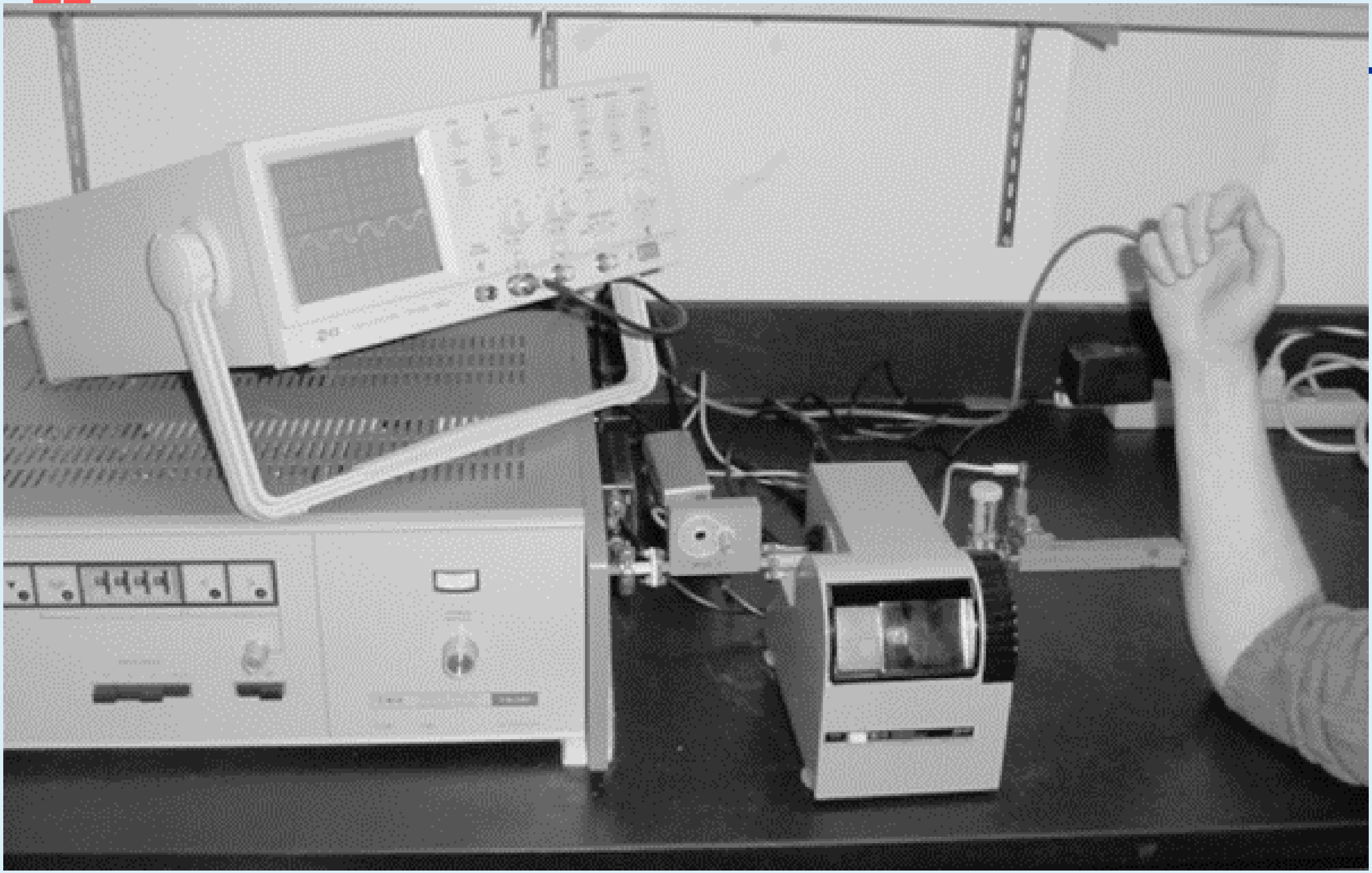
4-Layer Model

Where

1 = Stratum Corneum

2 = Epidermis + Dermis





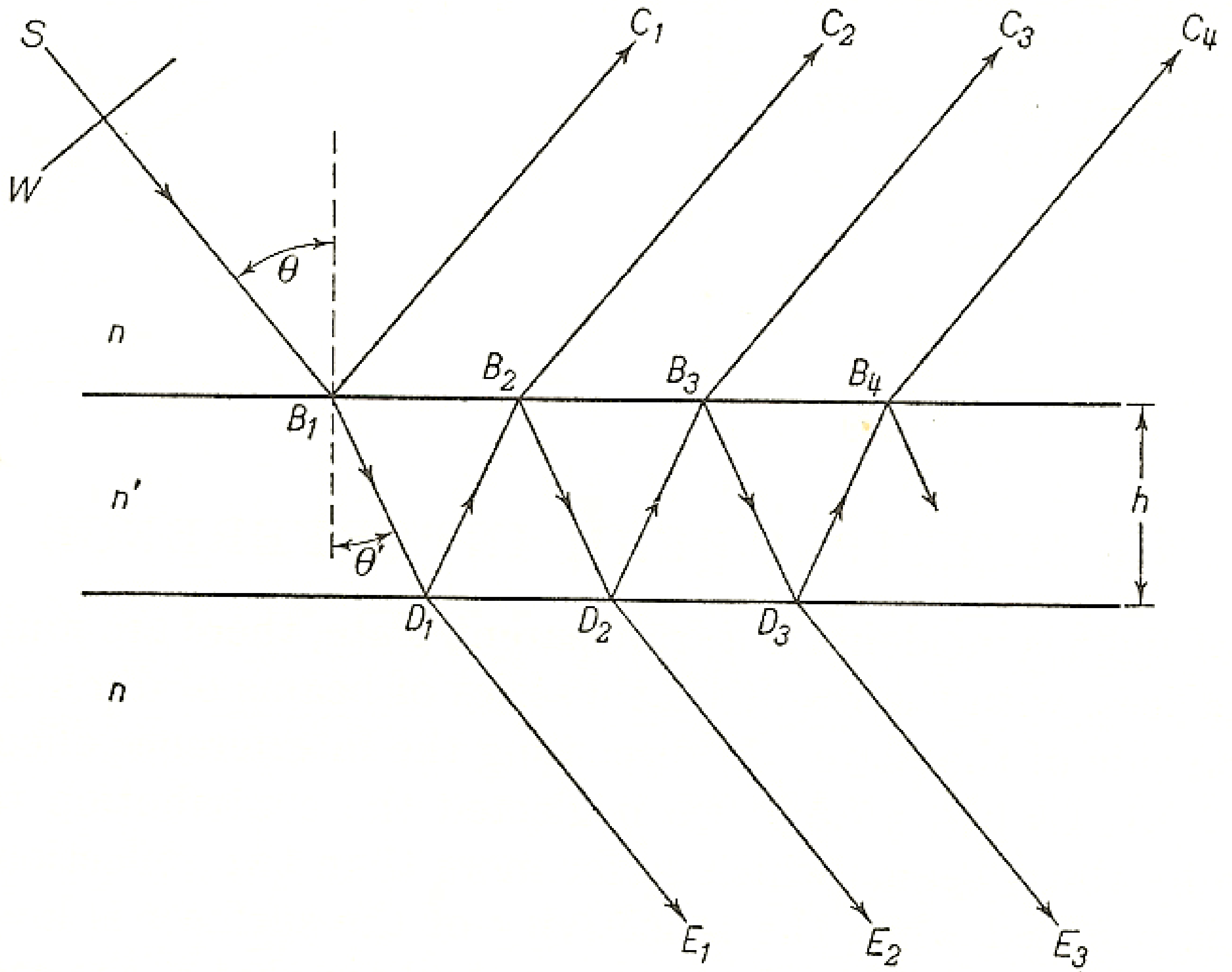


Fig. 7.56. Reflection of a plane wave in a plane parallel plate.

Reflection from boundary between two tissues

$$r_i(f) = \frac{n_i - n_{i+1}}{n_i + n_{i+1}}$$

Where

r_i = amplitude reflection coefficient

n_i = complex index of refraction of tissue i

n_{i+1} = complex index of refraction of tissue i+1

$$R(f)=\Bigg|\Bigg\{\frac{r_1(f)+r_2(f)\cdot e^{j\cdot\varphi_2(f)}+r_3(f)\cdot e^{j\cdot(\varphi_2(f)+\varphi_3(f))}+r_1(f)\cdot r_2(f)\cdot r_3(f)\cdot e^{j\cdot\varphi_3(f)}+}{1+r_1(f)\cdot r_2(f)\cdot e^{j\cdot\varphi_2(f)}+r_1(f)\cdot r_3(f)\cdot e^{j\cdot(\varphi_2(f)+\varphi_3(f))}+r_2(f)\cdot r_3(f)\cdot e^{j\cdot\varphi_3(f)}+}$$

$$\frac{r_4(f)\cdot e^{j\cdot(\varphi_2(f)+\varphi_3(f)+\varphi_4(f))}+r_1(f)\cdot r_2(f)\cdot r_4(f)\cdot e^{j\cdot(\varphi_3(f)+\varphi_4(f))}+}{r_1(f)\cdot r_4(f)\cdot e^{j\cdot(\varphi_2(f)+\varphi_3(f)+\varphi_4(f))}+r_2(f)\cdot r_4(f)\cdot e^{j\cdot(\varphi_3(f)+\varphi_4(f))}+}$$

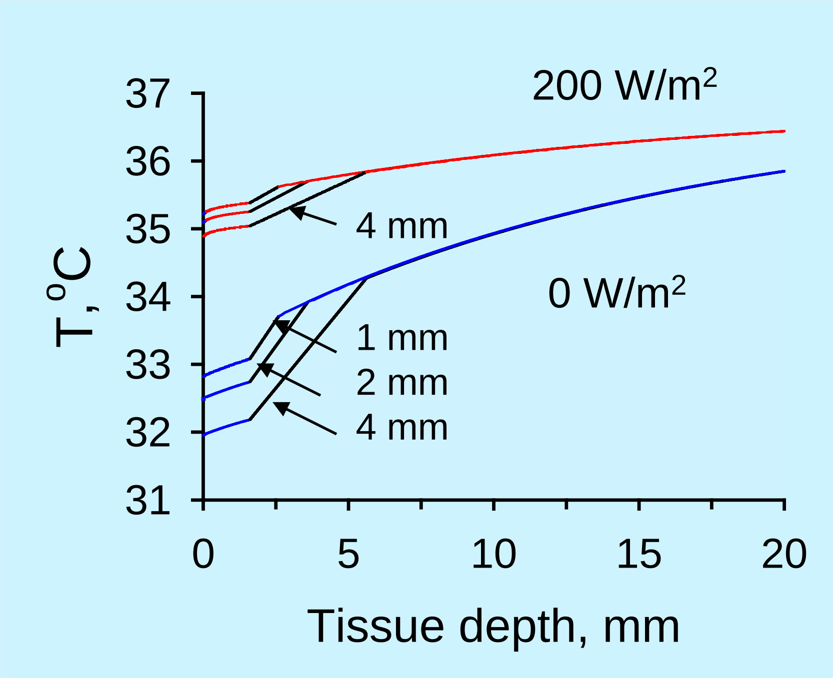
$$\frac{r_3(f)\cdot r_4(f)\cdot e^{j\cdot\varphi_4}(r_1(f)+r_2(f)\cdot e^{j\cdot\varphi_2(f)})}{r_3(f)\cdot r_4(f)\cdot e^{j\cdot\varphi_4}+r_1(f)\cdot r_2(f)\cdot r_3(f)\cdot r_4(f)\cdot e^{j\cdot(\varphi_2(f)+\varphi_4(f))}}\Bigg\}\Bigg|^2$$

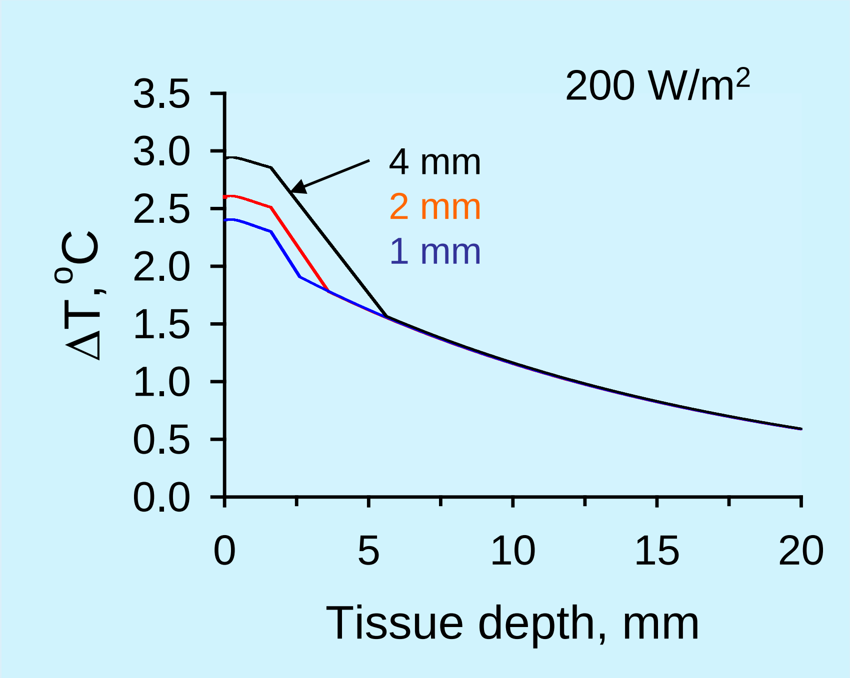
where $r_i(f)=\dfrac{n_i-n_{i+1}}{n_i+n_{i+1}}$ $\qquad \varphi_m(f)=2\cdot\omega(f)\cdot n_m(f)\cdot\dfrac{h_m}{c}$

Parameters used in thermal modeling

Parameter	3-layer model			4-layer model			
	SC	E^{-}+D	Fat*	SC	E^{-}+D	Fat*	Muscle *
ε_{∞}	2.96	4.0	2.5	2.96	4.0	2.5	4.0
$\Delta\varepsilon$	1.5±0.2	32.4±4.7	3.0	1.5±0.2	32.4±4.7	3.0	50.0
d, mm	0.015	1.45	∞	0.015	1.45	1-6	∞
σ, S/m	0	1.4	0.01	0	1.4	0.01	0.1
$\tau \times 10^{12}$, s	6.9	6.9	7.96	6.9	6.9	7.96	7.23

Temperature distributions in multilayer tissue model with a fat thickness of 1, 2, or 4 mm before and after exposure to 42 GHz at 200 W/m²



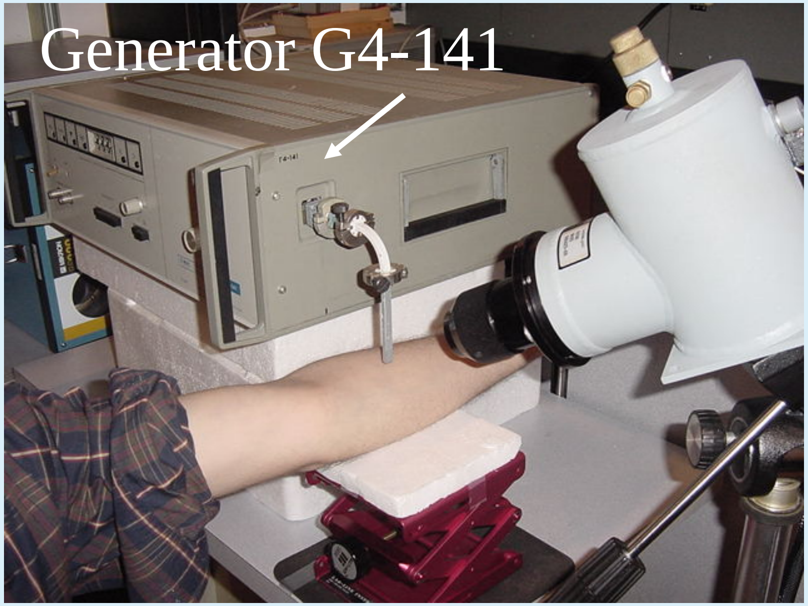


Epidermis - 0.1 mm
Dermis - 1.5 mm

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

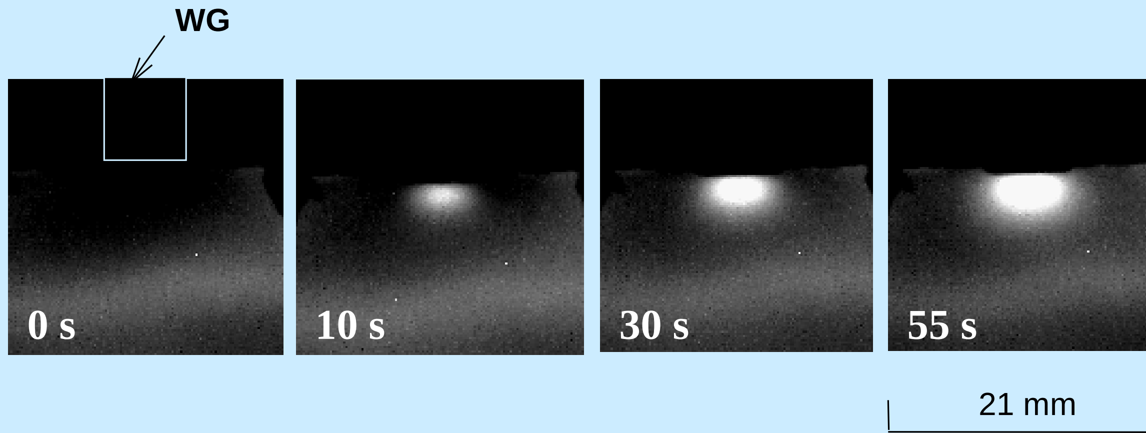
Lower forearm

Index finger



Frequency: 42.25 GHz
Output power: 52 mW

RESULTS

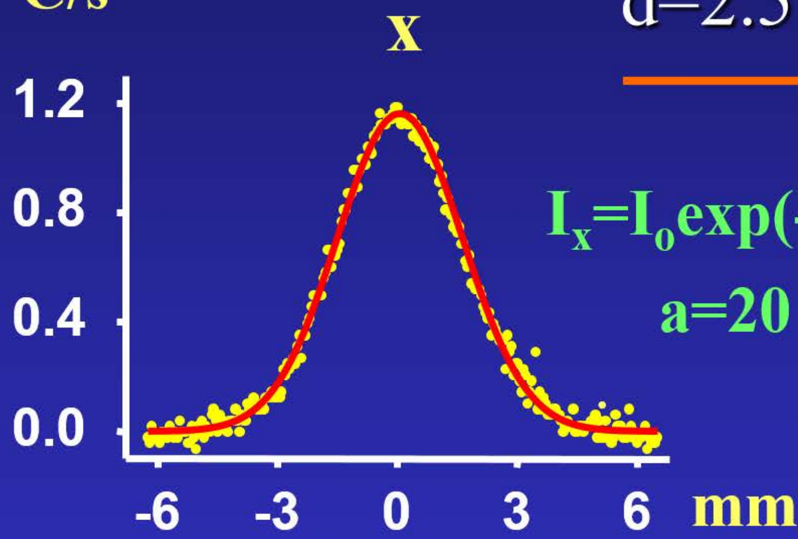


IR images show the forearm skin at 0, 10, 30, and 55 s following exposure with the WG (I_o = 2080 W/m^2). The distance between the open end of WG and skin surface was 2.5 mm. The lighter band on the bottom of each thermogram corresponds to the warmer skin area located above a vein. Baseline skin temperature was 32.5 ^{o}C. Maximum temperature at 55 s was 35.7 ^{o}C.

Temperature rise rate profiles at d=2.5 mm from waveguide opening

$\Delta T / \Delta t$

$^{o}C/s$

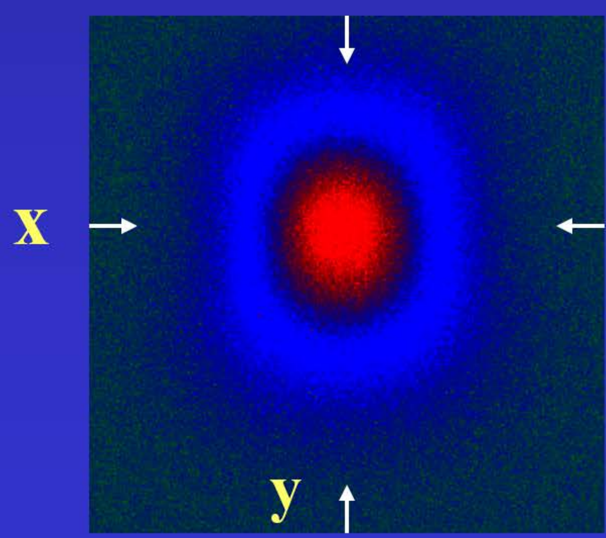


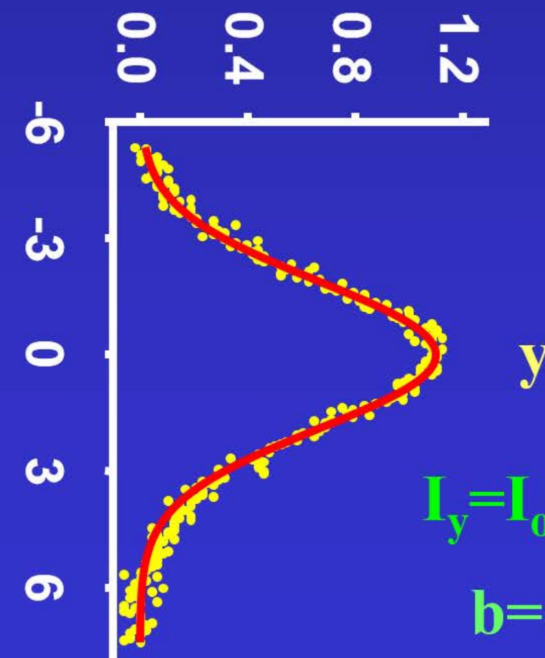
$I_x = I_o \exp(-ax^2)$

$a = 20\ cm^{-2}$

$I_r = I_o \exp(-cr^2)$

$c = \sqrt{ab} = 17\ cm^{-2}$

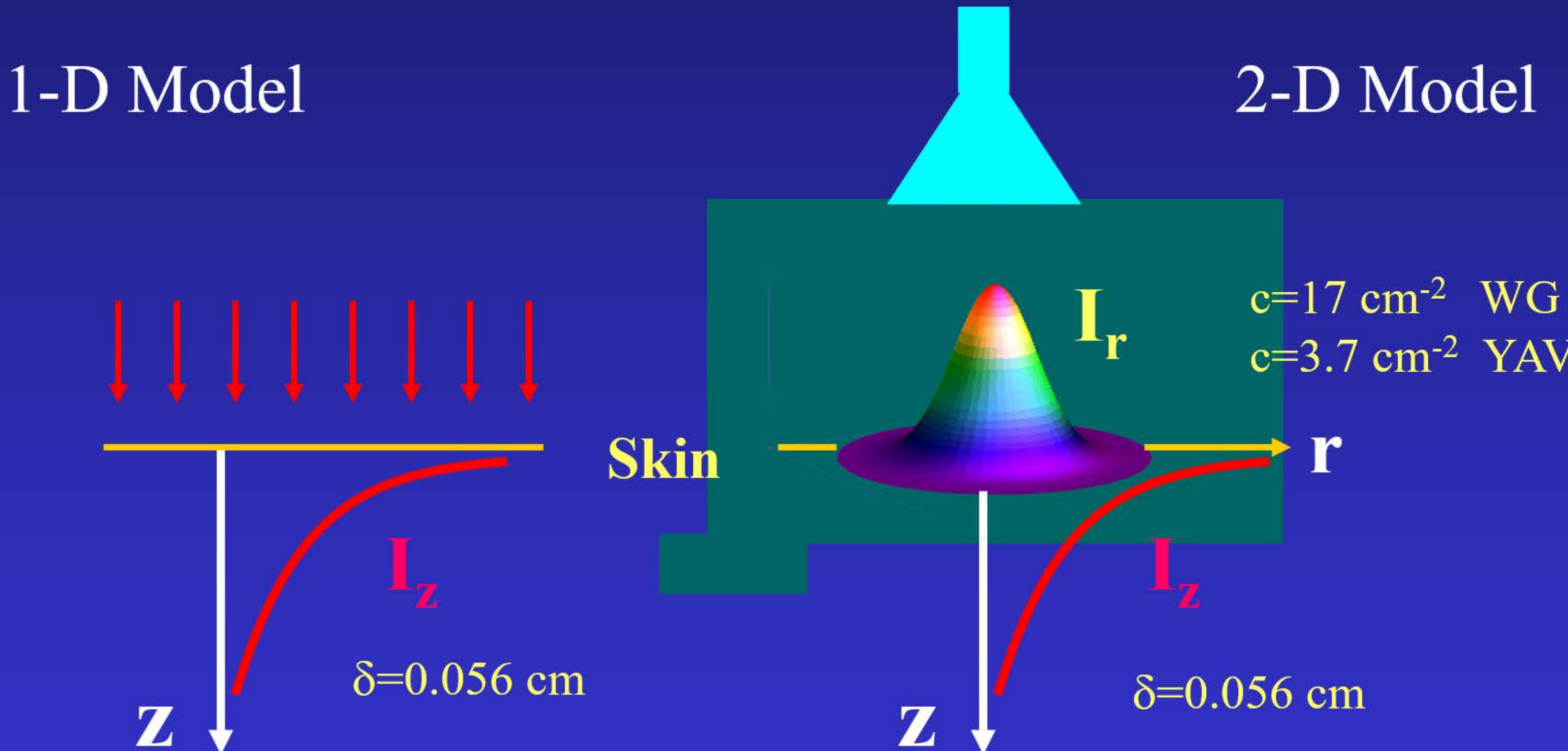




$I_y = I_o \exp(-by^2)$

$b = 14.5\ cm^{-2}$

Skin Exposure Modes



Heat input from exposure:

$$Q(z) = q_o \times e^{-\frac{2z}{\delta}} \qquad Q(r,z) = q_o \times e^{-cr^2} \times e^{-\frac{2z}{\delta}}$$

Heat Transport Equations in the Skin

1-D:

$$\frac{\rho C}{k} \times \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} - \frac{V_s}{k} \times (T - T_b) + Q(z)$$

2-D:

$$\frac{\rho C}{k} \times \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} - \frac{V_s}{k} \times (T - T_b) + Q(z, r)$$

ρ – tissue density

C – specific heat

k – heat conduction coefficient

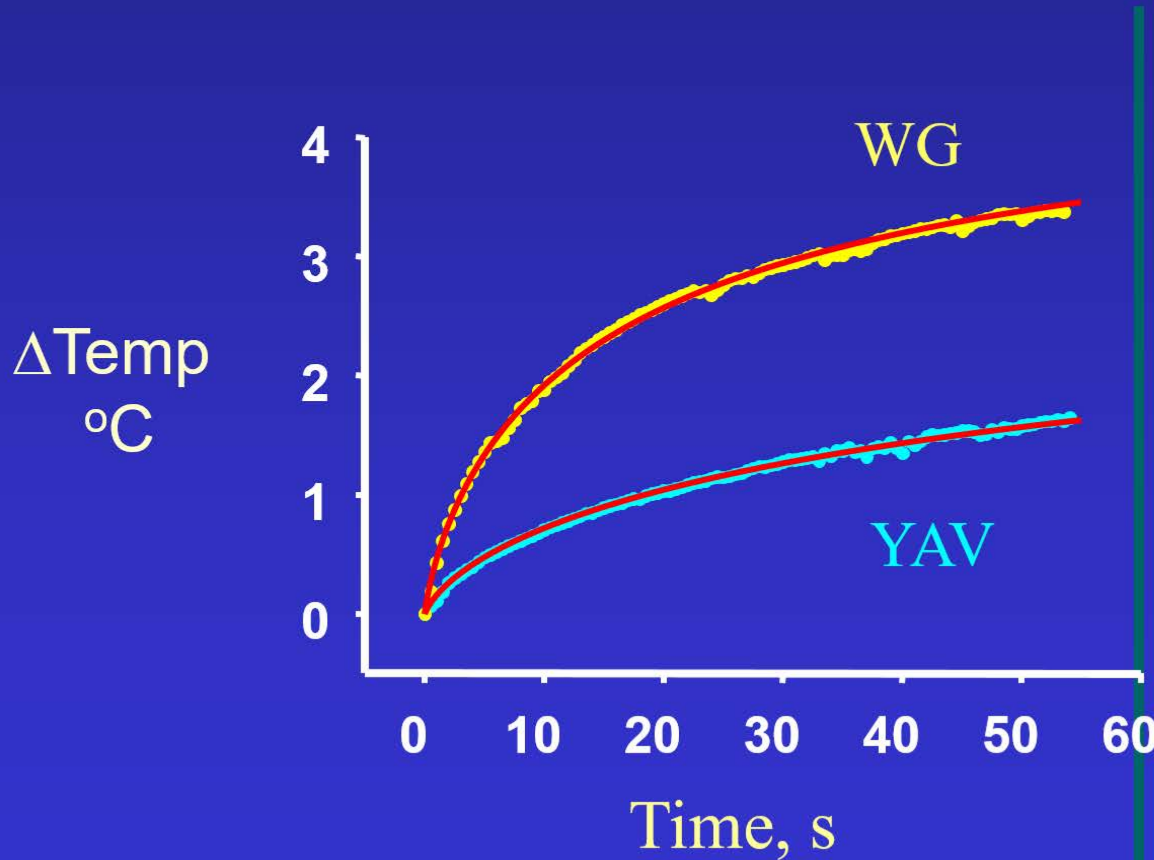
T – tissue temperature

T_b - arterial blood temperature

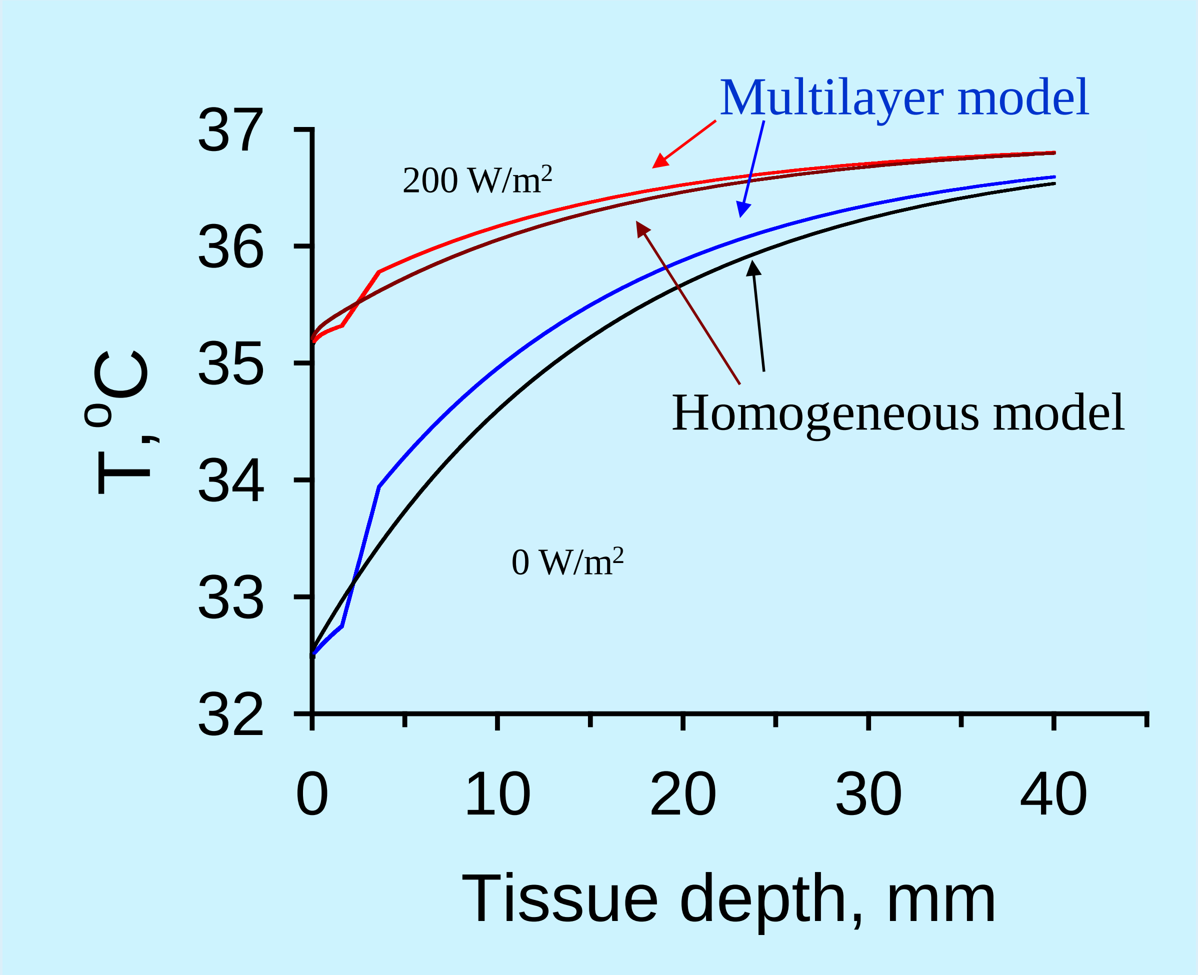
V_s – product of blood flow and heat capacity

Q – heat input from mm-wave exposure

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

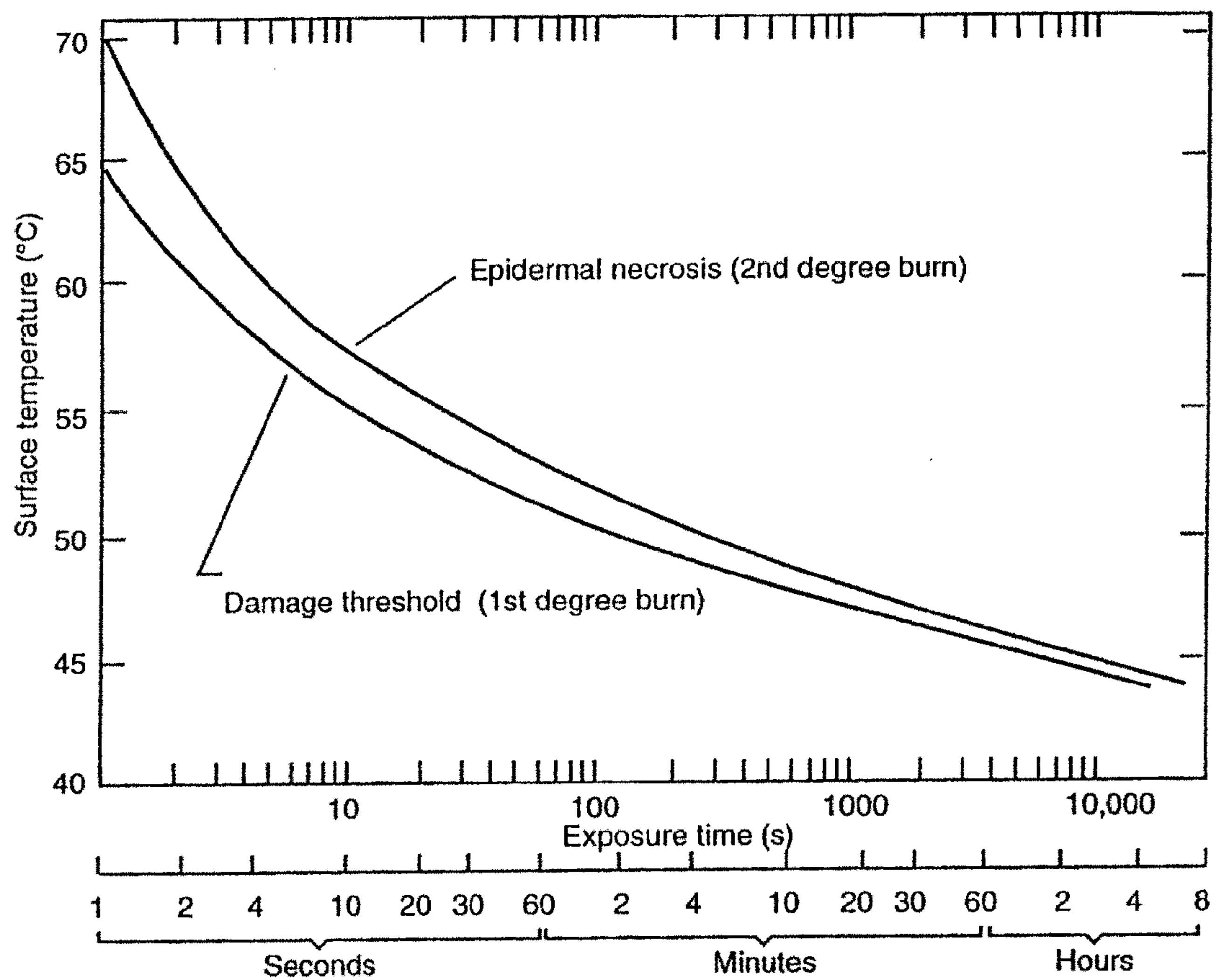


Temperature distributions in homogeneous and multilayer tissue models before and after exposure to 42 GHz at 200 W/m²



Epidermis - 0.1mm
Dermis -1.5 mm
Fat - 2.0 mm

SURFACE TEMPERATURE THRESHOLDS FOR HUMAN OR PORCINE SKIN
(Moritz and Henriques, p. 711, 1947)



ICES

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

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

Abstract—Cutaneous thresholds for thermal pain were measured in 10 human subjects during 3-s exposures at 94 GHz continuous wave microwave energy at intensities up to ≈ 1.8 W cm^{-2}. During each exposure, the temperature increase at the skin's surface was measured by infrared thermography. The mean (± s.e.m.) baseline temperature of the skin was 34.0 ± 0.2°C. The threshold for pricking pain was 43.9 ± 0.7°C, which corresponded to an increase in surface temperature of ≈ 9.9°C (from 34.0°C to 43.9°C). The measured increases in surface temperature were in good agreement with a simple thermal model that accounted for heat conduction and for the penetration depth of the microwave energy into tissue. Taken together, these results support the use of the model for predicting thresholds of thermal pain at other millimeter wave (length) frequencies.

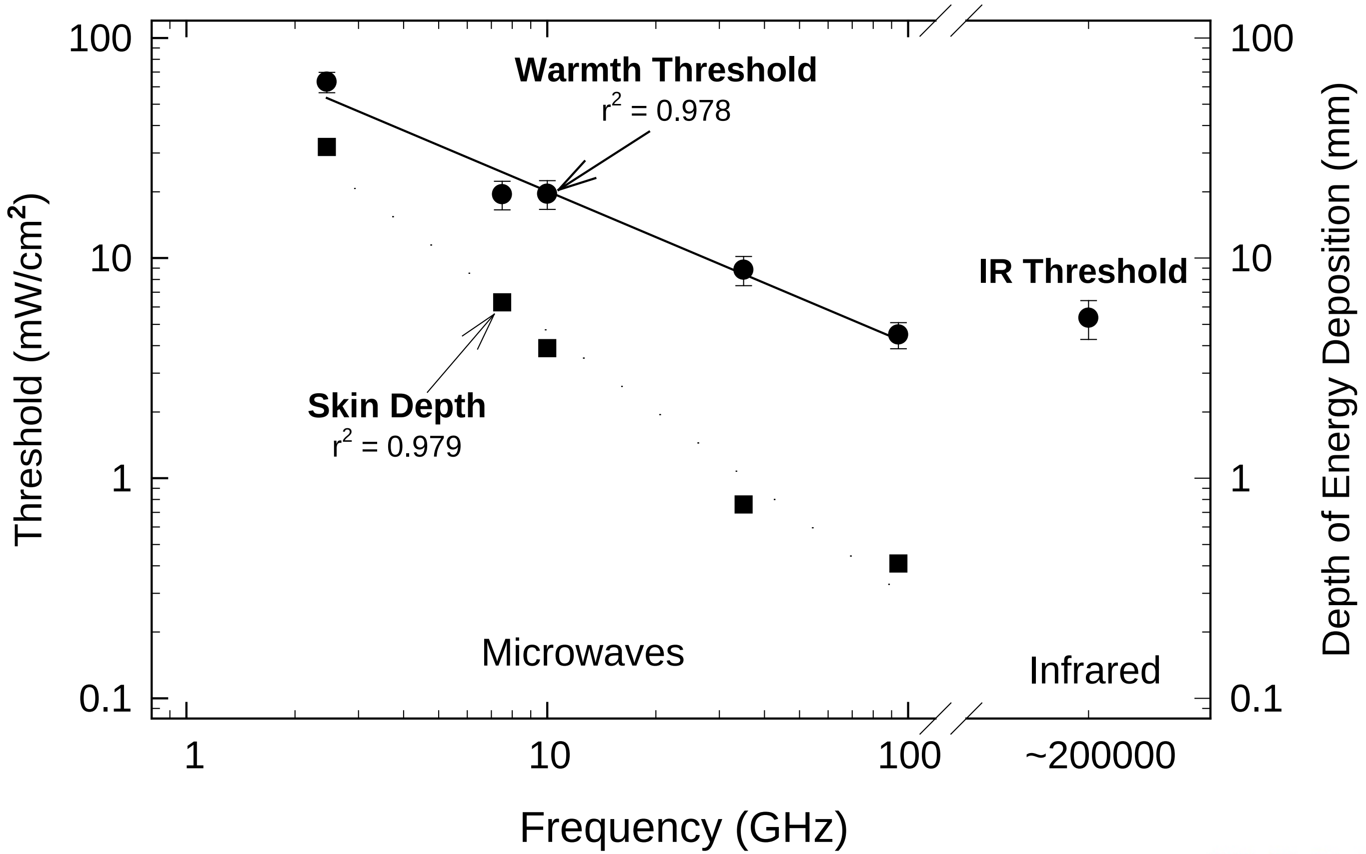
Health Phys. 78(3):259–267; 2000

Key words: skin dose; radiofrequency; radiation, nonionizing; microwaves

Only limited data are available concerning the thermal responses of humans to microwave energy, and most of those data are for frequencies below 10 GHz. We have measured warmth detection-thresholds across a wide range of microwave frequencies, including millimeter wavelengths, within the same subject population (Blick et al. 1997). We have also shown that these thresholds of sensation can be interpreted as reflecting an increase in surface temperature that is independent of the irradiation frequency (Riu et al. 1997). The use of a standard protocol that incorporated measurements over a broad frequency range enabled us to determine the importance of energy-penetration depth both to sensation and to the underlying cutaneous events.

The threshold for thermal pain has been determined for microwave (3 GHz; Cook 1952b) and infrared irradiation (Cook 1952b; Hardy et al. 1952) in human subjects. The threshold for pain was found to be a

Warmth Detection Threshold and Penetration Depth: Variation with Microwave Frequency



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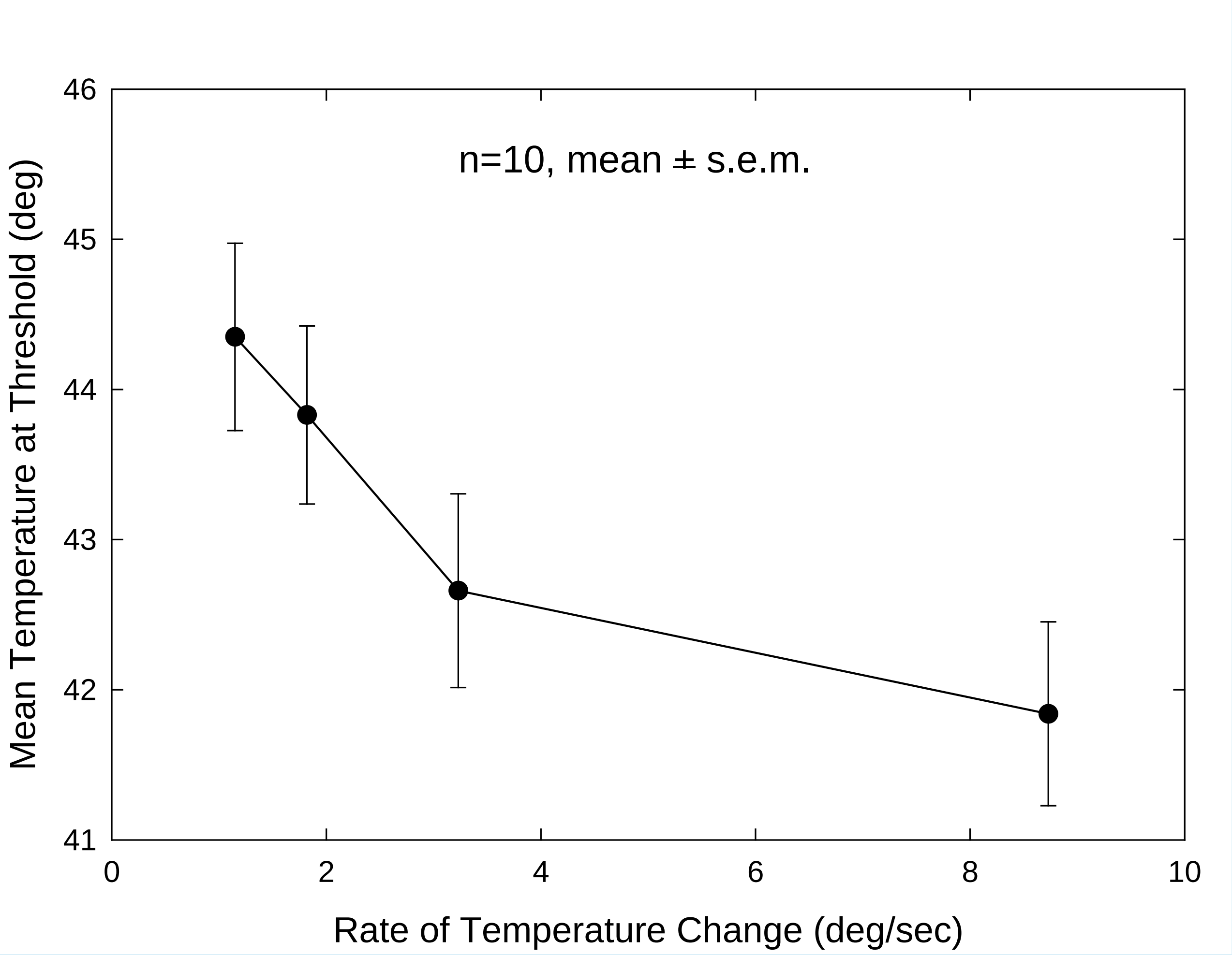
Threshold vs. Heating Rate



Pain Thresholds and Safety Margins

- Normal Skin Temperature = 34 °C
- Pain Threshold = 44-45 °C
- First Degree Burn = 55-60 °C
- Second Degree Burn = 60-65 °C
- Third Degree Burn = > 70 °C

RF Exposure Limits

- To limit steady state temperature rise < 3 ^{o}C in skin for the upper tier
- DRL is epithelial power density
- ERL is incident power density
- Averaging time 6 minutes
- Averaging area 4 cm^2 (for single pulses at 30-300 GHz, 1 cm^2)


Thank you
Protect your skin