Biological Considerations for Setting Exposure limits Above 6 GHz

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Millimeter Wave Therapy

"Therapeutic" wavelengths:

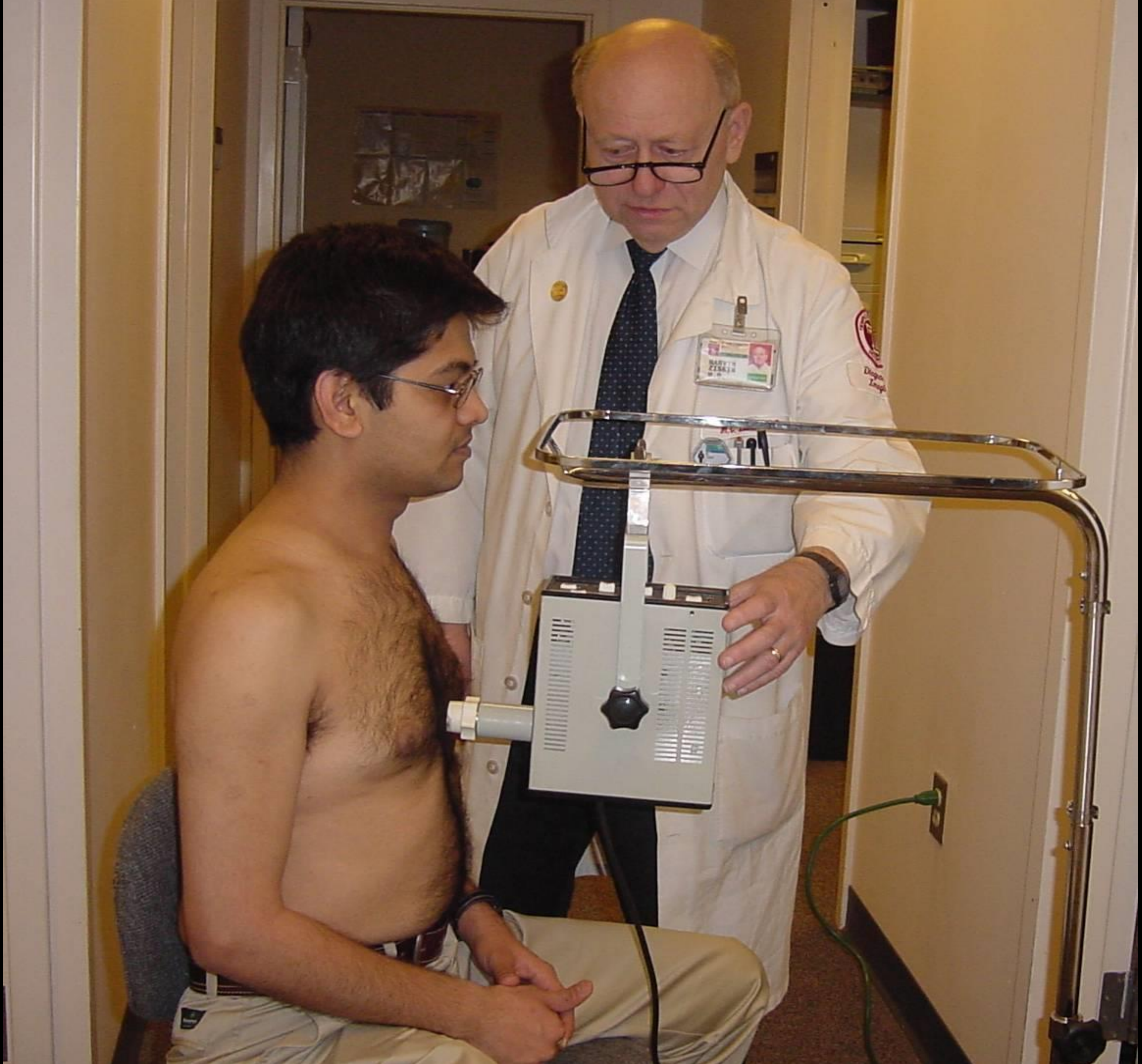
4.9, 5.6, and 7.1 mm

(frequencies 61.22, 53.57 and 42.25 GHz)

Exposure of patient's skin:

acupuncture points, forehead, occiput
sternum; big joints, surgical wounds

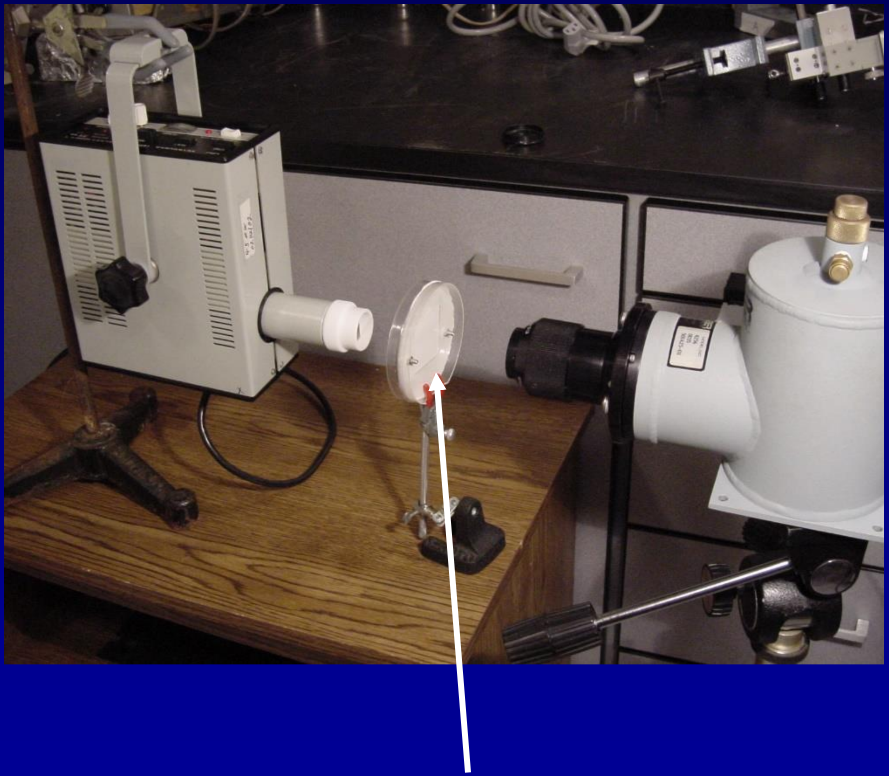
Use to treat thousands of patients in the Former Soviet Union for many diseases



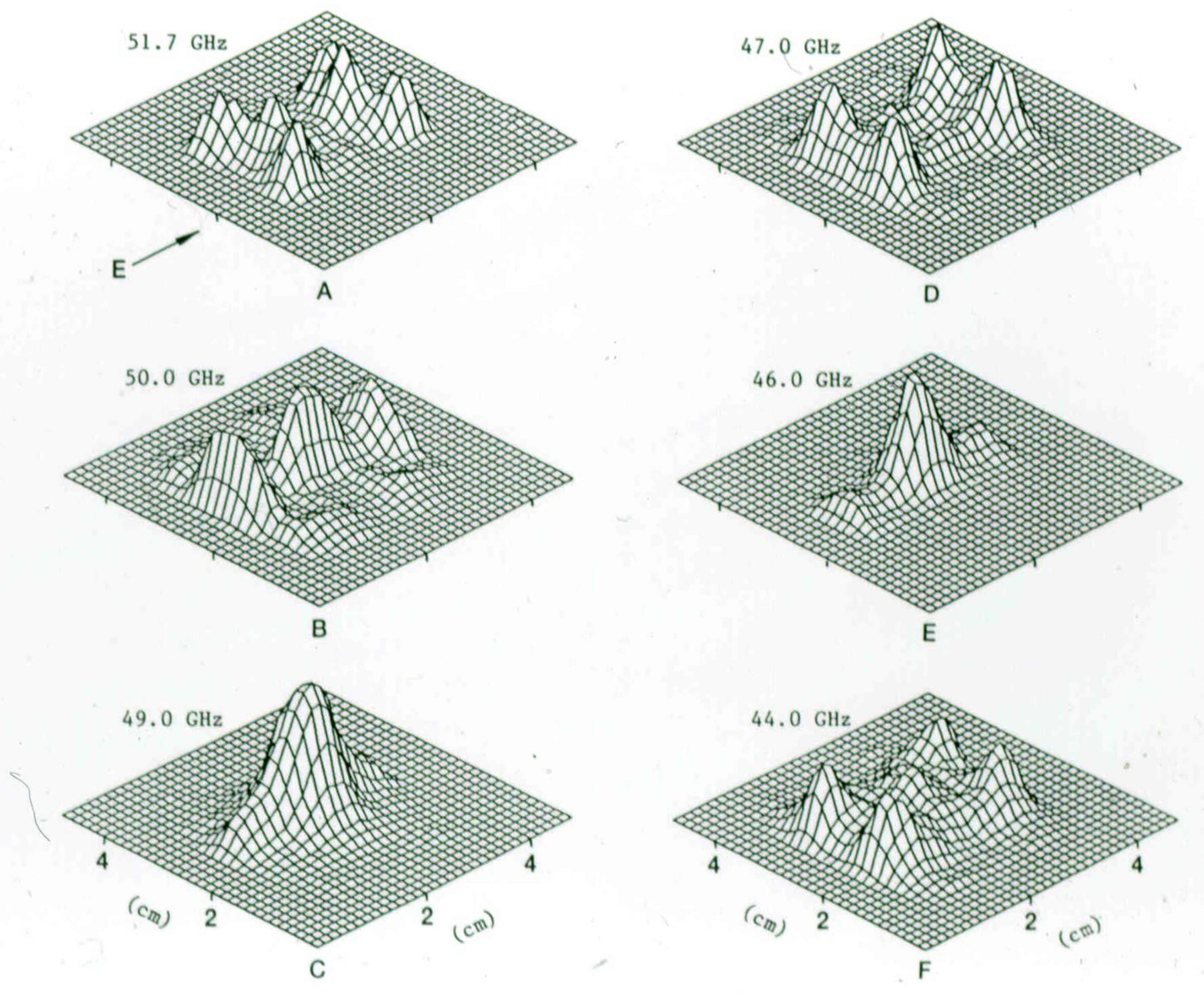
Millimeter Wave Irradiation

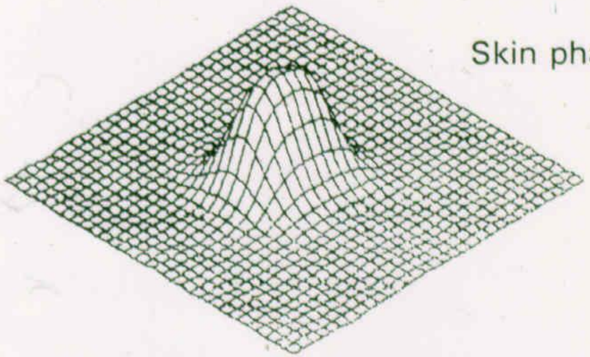
- Heating is a Major Mechanism for Bioefffects
- Most of Energy is Absorbed within a Few Tenths of a Millimeter
- Wavelengths in Tissue are Comparable with Biological Structures
- Irradiation is frequently in the Near Field

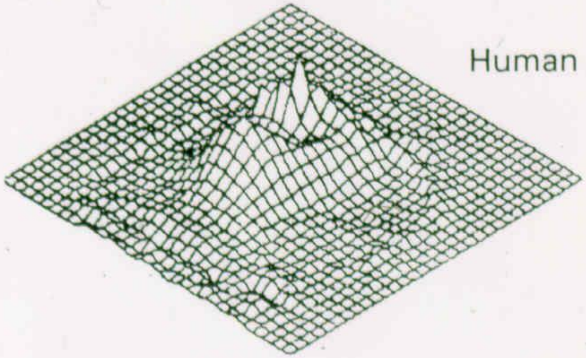
IR-camera measurements of mm-wave heating of phantom with YAV devices



Phantom- 0.2 mm thick saline saturated filter paper absorber


51.7 GHz
E
A
47.0 GHz
D
50.0 GHz
B
46.0 GHz
E
49.0 GHz
4
(cm)
2
2
(cm)
4
C
44.0 GHz
4
(cm)
2
2
(cm)
4
F





Heating patterns resulting from mm-wave irradiation from the open side of a rectangular waveguide under similar exposure conditions

CONCLUSIONS

- **Millimeter waves can produce non-uniform heating patterns in irradiated objects, especially when these objects are irradiated in the near-field area.**

- **SAR values in hot-spots area can exceed 500 W/kg at 10 mW/cm2 average incident power density.**

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Specific Absorption Rate (SAR)

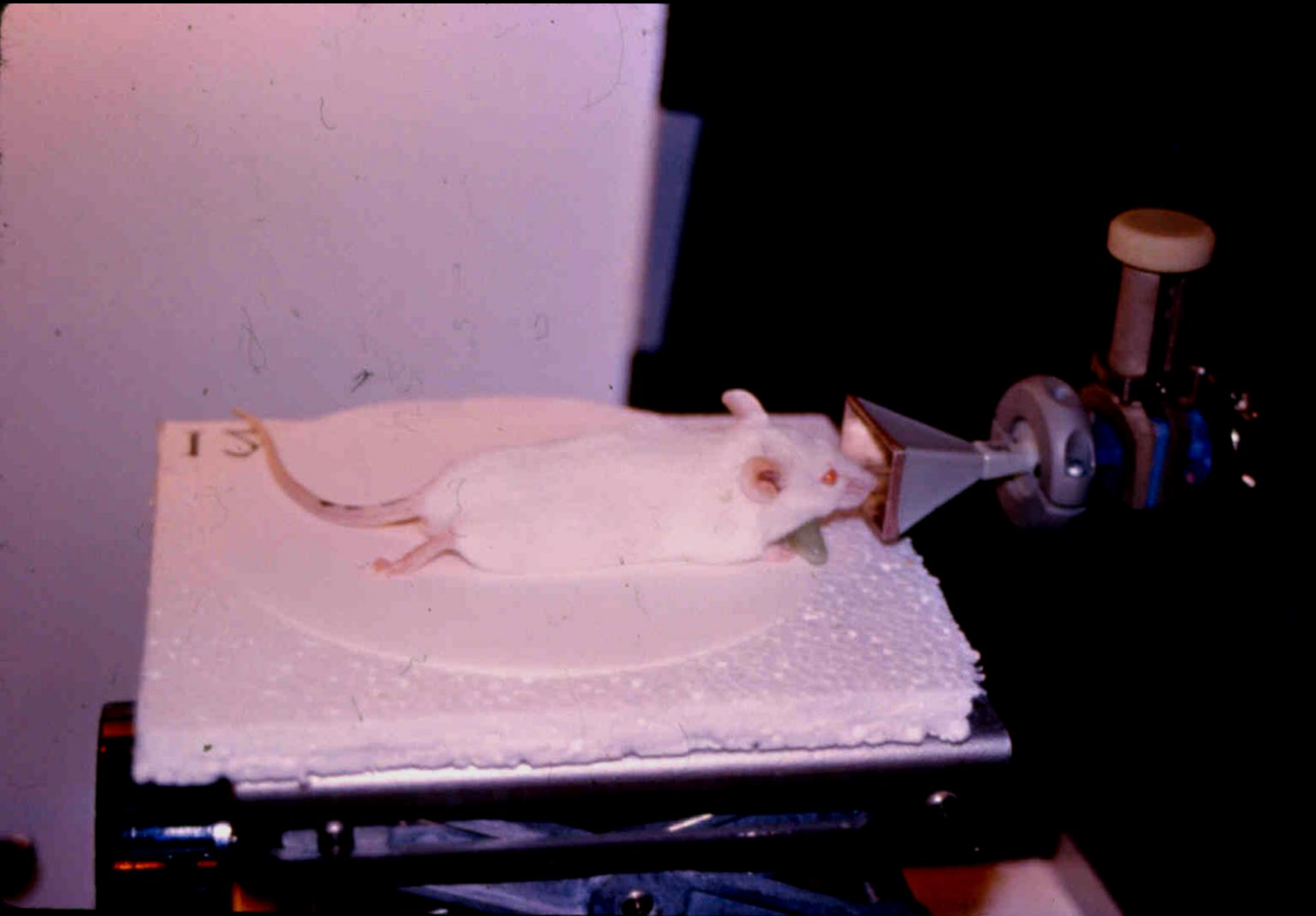
For RF Standards:

- SAR is chosen over Power Density because it is a better predictor of Biological Effects
- But not for frequencies greater than ~6 GHz, where penetration is limited to skin.

CONCLUSIONS

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	**=**	**10 – 20 mW/cm^2**
No sensation for exposures	**$<$**	**40 mW/cm^2**
No pain for exposures	**$<$**	**100 mW/cm^2**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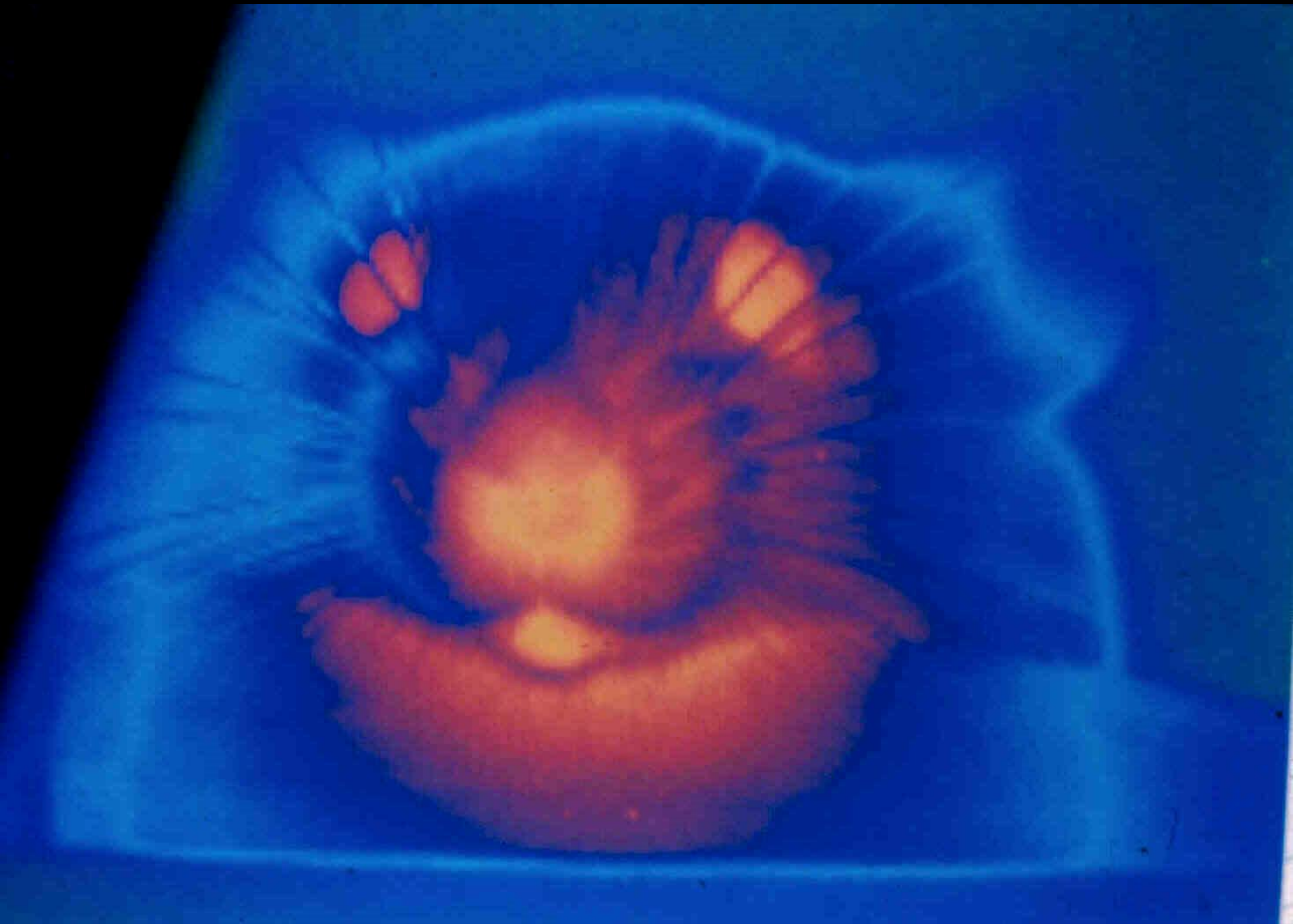
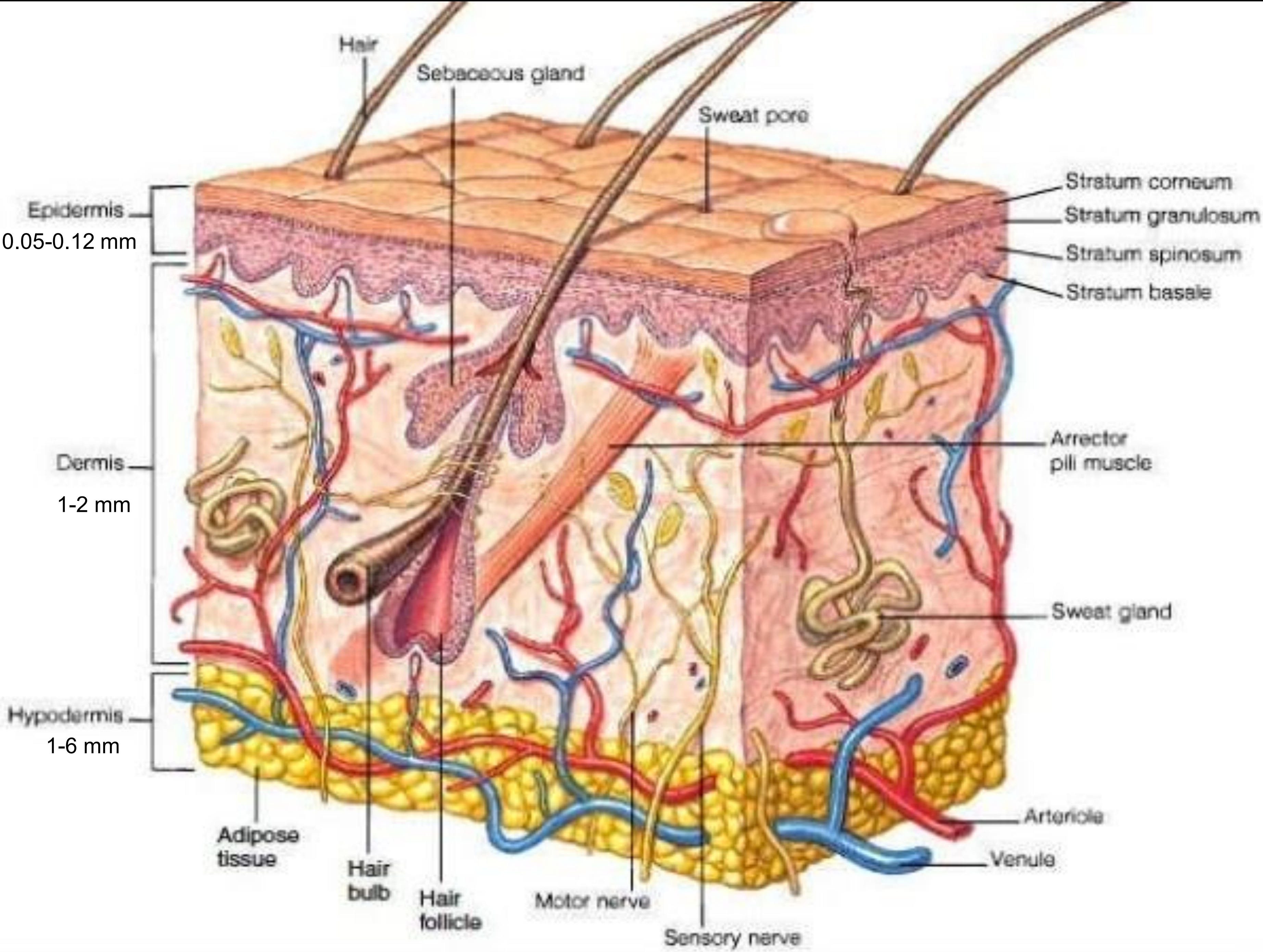


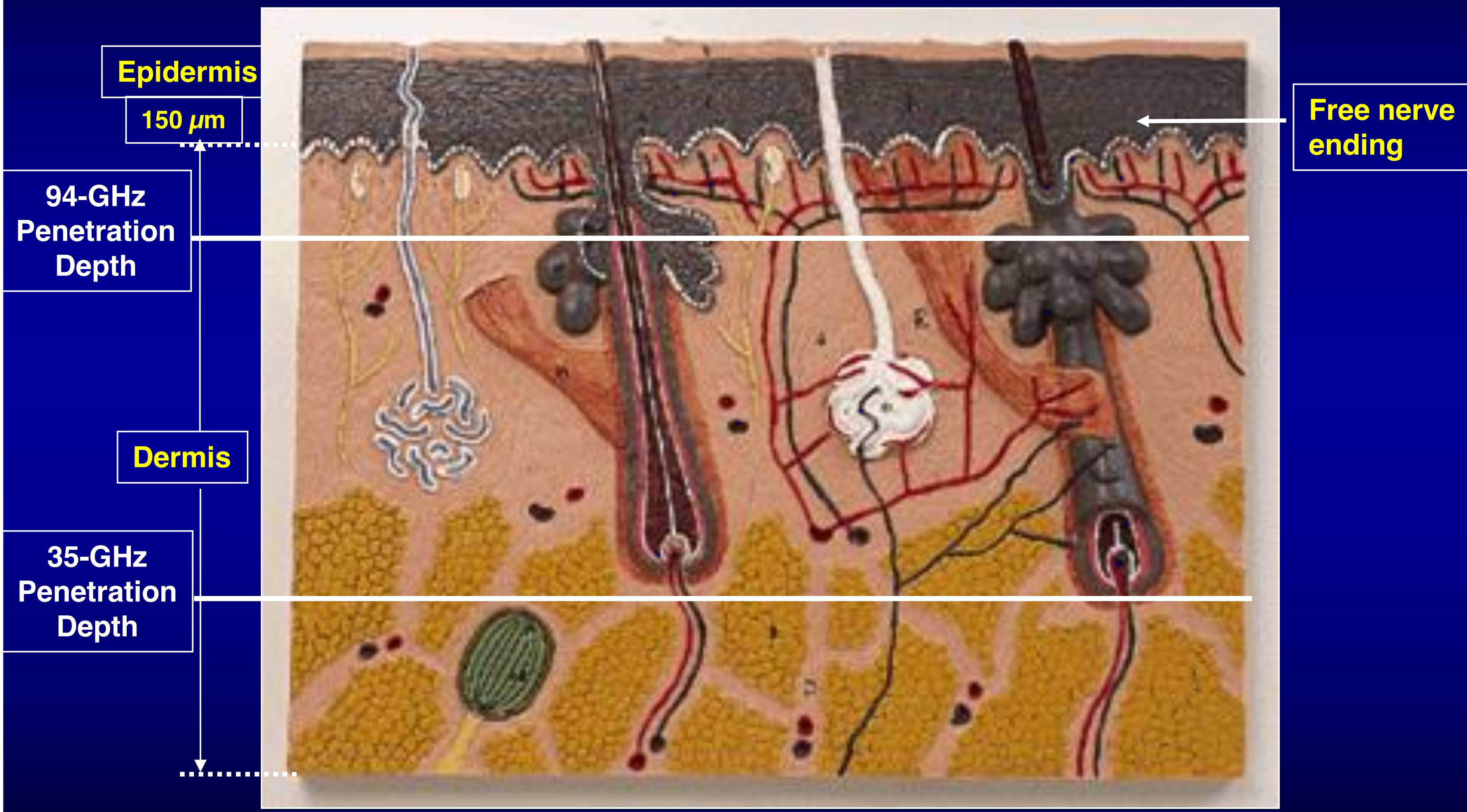

Hair
Sebaceous gland
Sweat pore
Stratum corneum
Stratum granulosum
Stratum spinosum
Stratum basale
Epidermis
0.05-0.12 mm
Dermis
1-2 mm
Arrector pili muscle
Sweat gland
Hypodermis
1-6 mm
Arteriole
Venule
Adipose tissue
Hair bulb
Hair follicle
Motor nerve
Sensory nerve

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

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

ANATOMY OF THE SKIN



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

Effect 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

Effect 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

Effect of Age on Skin

Skin in Elderly

Epidermis thins

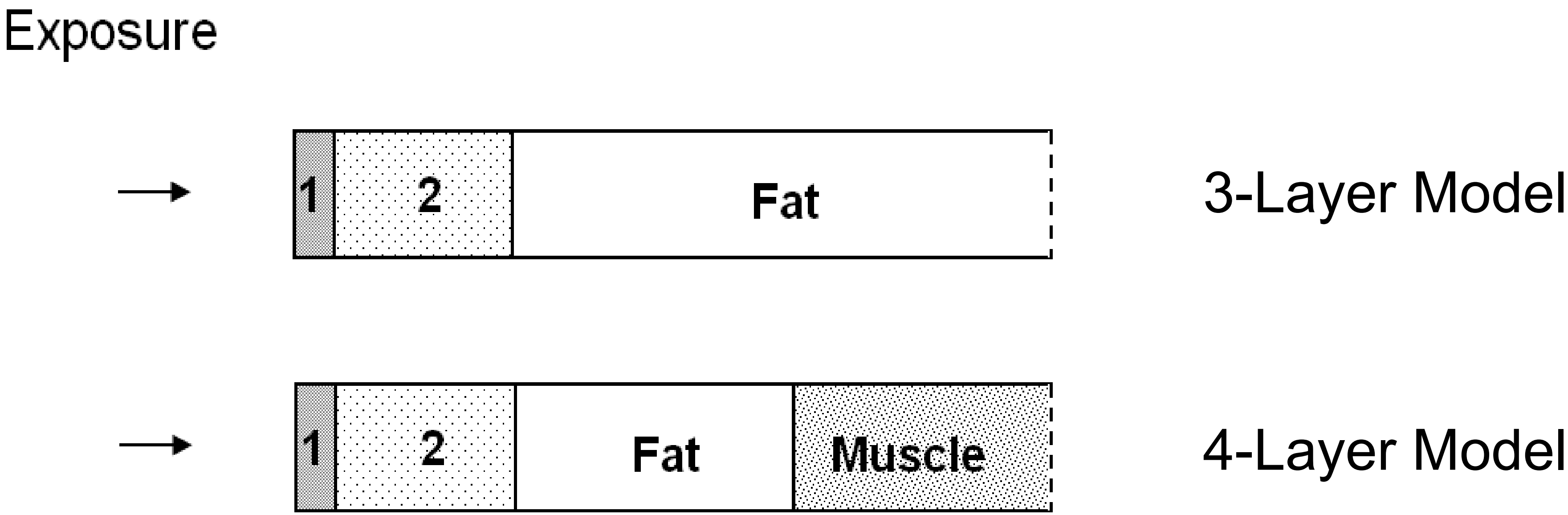
Blood vessels of the dermis become more fragile

Sebrum 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

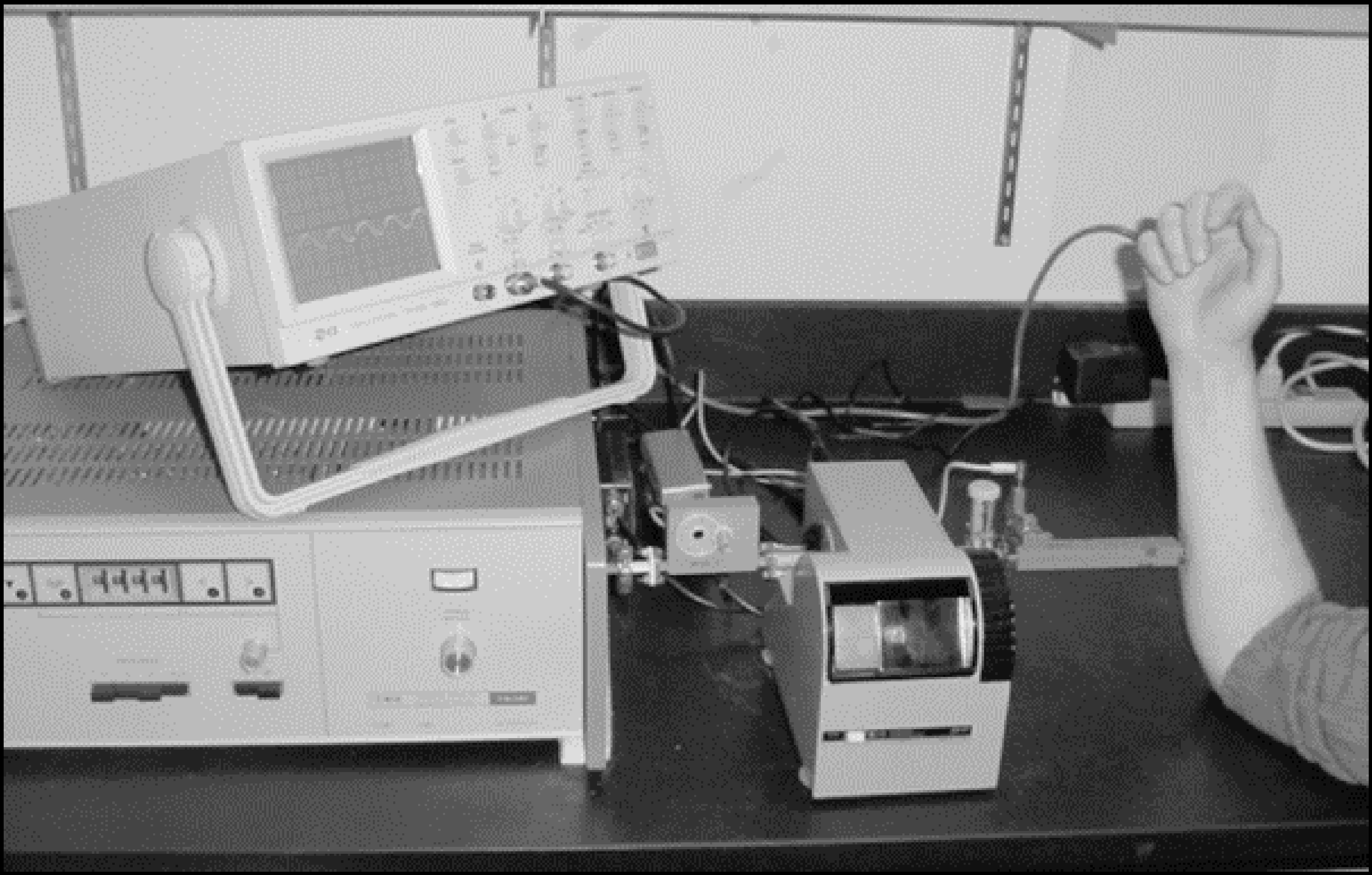
Skin Models

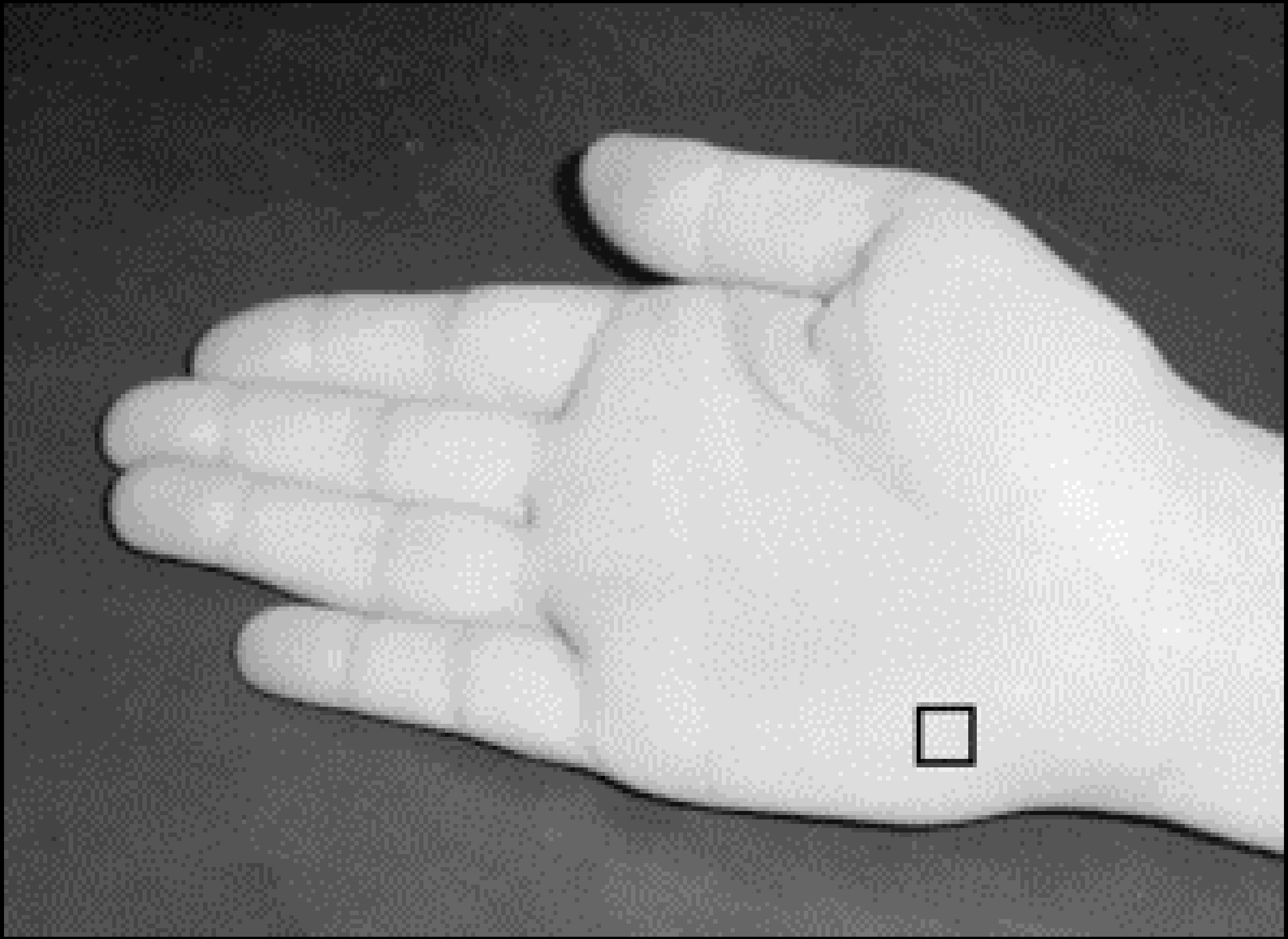


Where

1 = Stratum Corneum

2 = Viable Epidermis + Dermis





Reflection from boundary between two tissues

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

Where

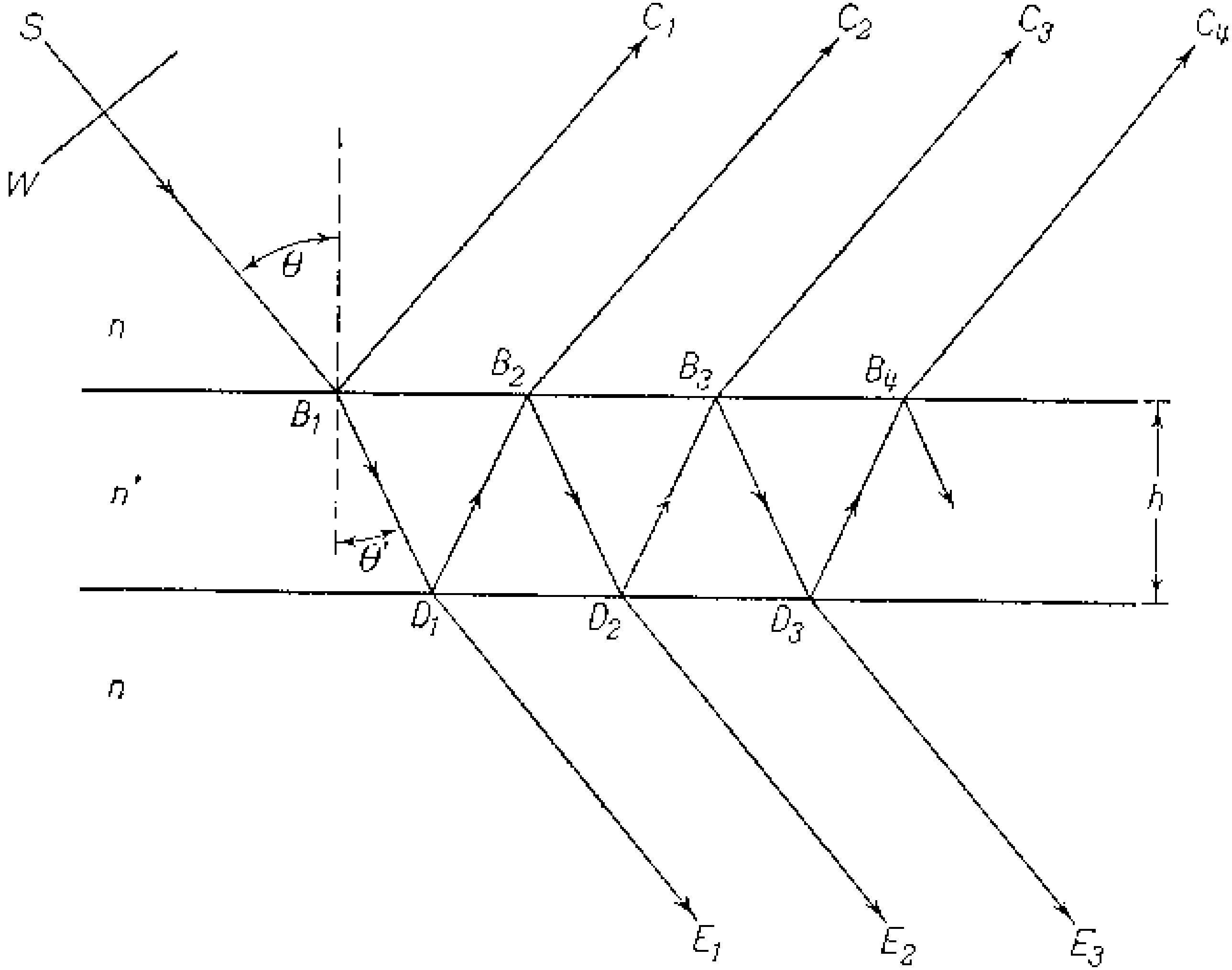
r_i = amplitude reflection coefficient
n_i = complex index of refraction of tissue i
n_{i+1} = complex index of refraction of tissue i+1

Reflection from boundary between two tissues

$$R(f) \quad = \quad |r_i\,(f)|^2$$

Where

$R(f)$ = Power reflection coefficient
$r_i(f)$ = Amplitude reflection coefficient


S
W
C_1
C_2
C_3
C_4
θ
n
B_1
B_2
B_3
B_4
n'
θ'
h
D_1
D_2
D_3
n
E_1
E_2
E_3

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

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

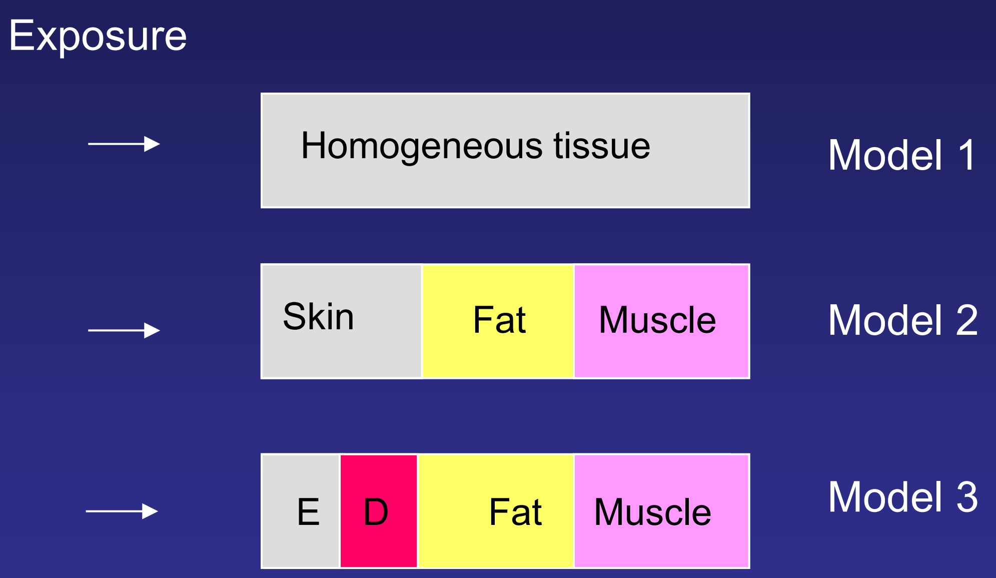
$$\frac{r_3(f)\cdot r_4(f)\cdot e^{j\cdot\varphi_4}\left(r_1(f) + r_2(f)\cdot e^{j\cdot\varphi_2(f)}\right)}{r_3(f)\cdot r_4(f)\cdot e^{j\cdot\varphi_4} + r_1(f)\cdot r_2(f)\cdot r_3(f)\cdot r_4(f)\cdot e^{j\cdot(\varphi_2(f)+\varphi_4(f))}} \Bigg\} \Bigg|^2$$

where

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

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

Tissue models used for thermal modeling of mm wave heating

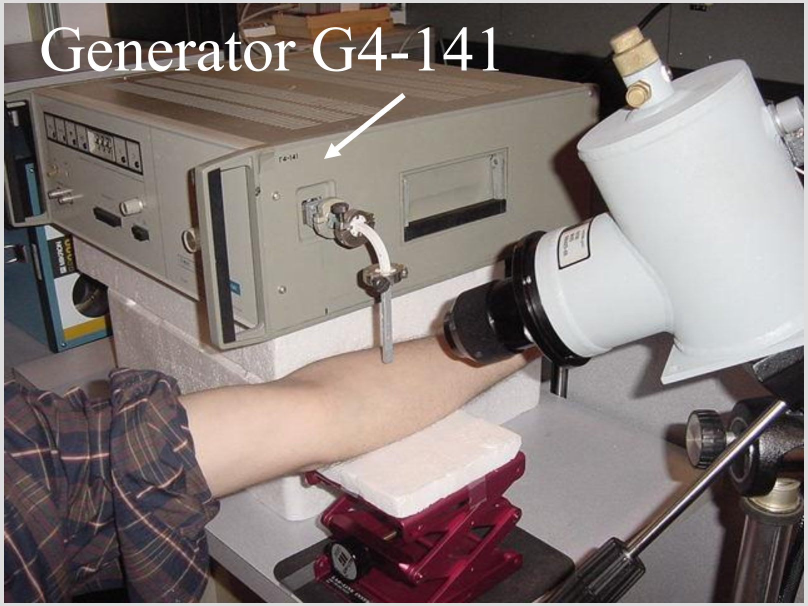


E - Epidermis
D - Dermis

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

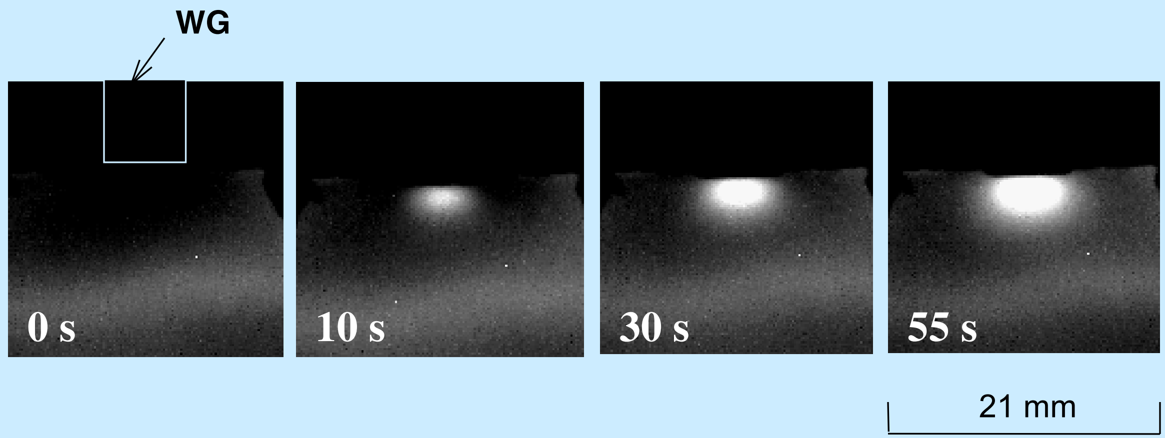
Lower forearm

Index finger



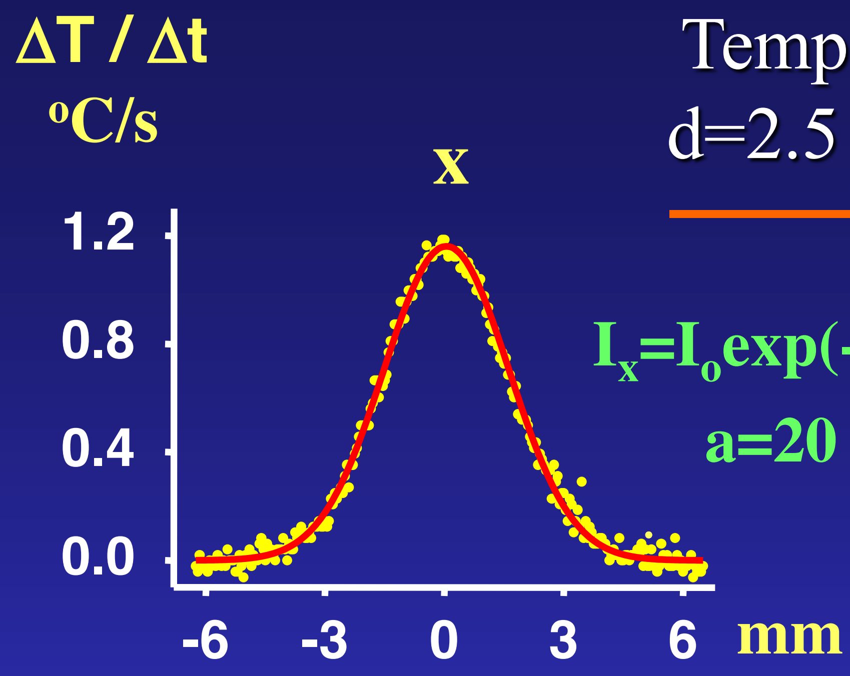
Frequency: 42.25 GHz
Output power: 52 mW

RESULTS



IR images show the forearm skin at 0, 10, 30, and 55 s following exposure with the WG (I_o = 208 mW/cm^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

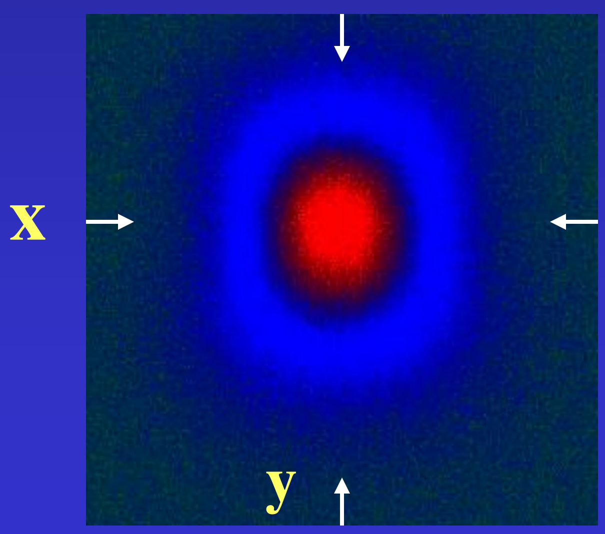


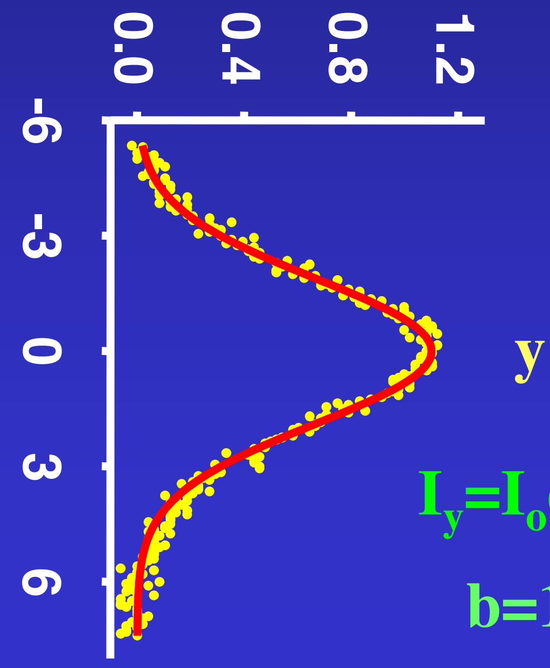
$I_x = I_o \exp(-ax^2)$

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

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

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





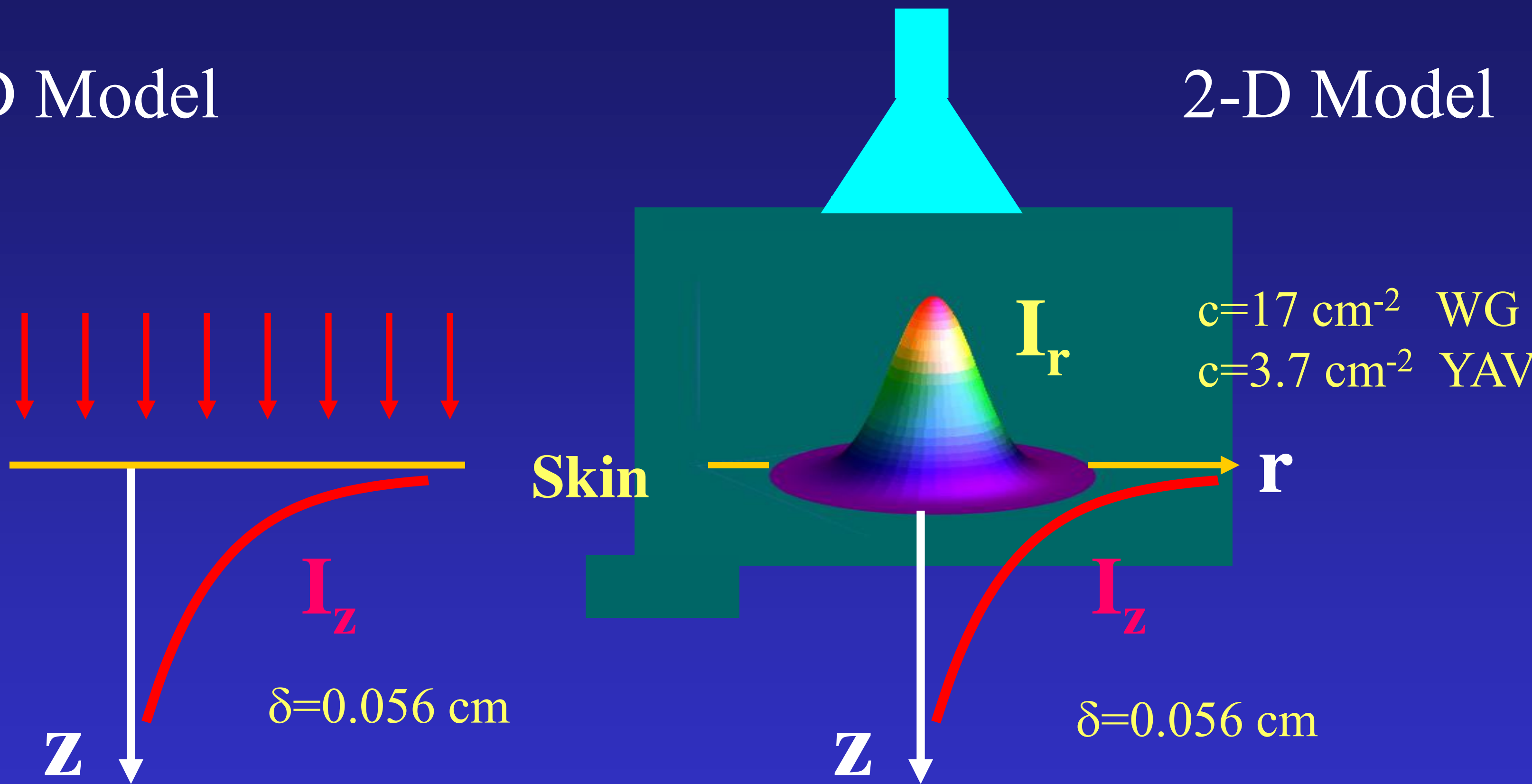
$I_y = I_o \exp(-by^2)$

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

Skin Exposure Modes

1-D Model

2-D Model



Heat input from exposure:

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

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

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

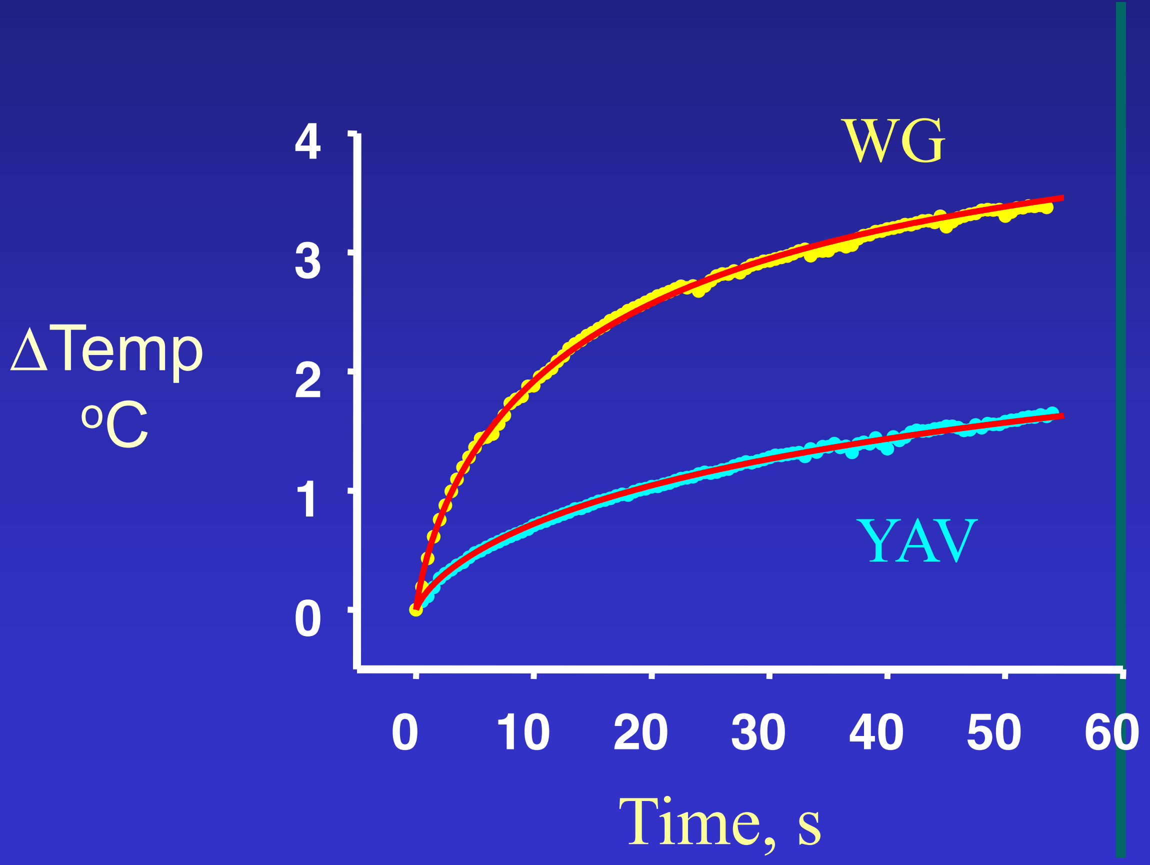
T – tissue temperature

T_b - arterial blood temperature

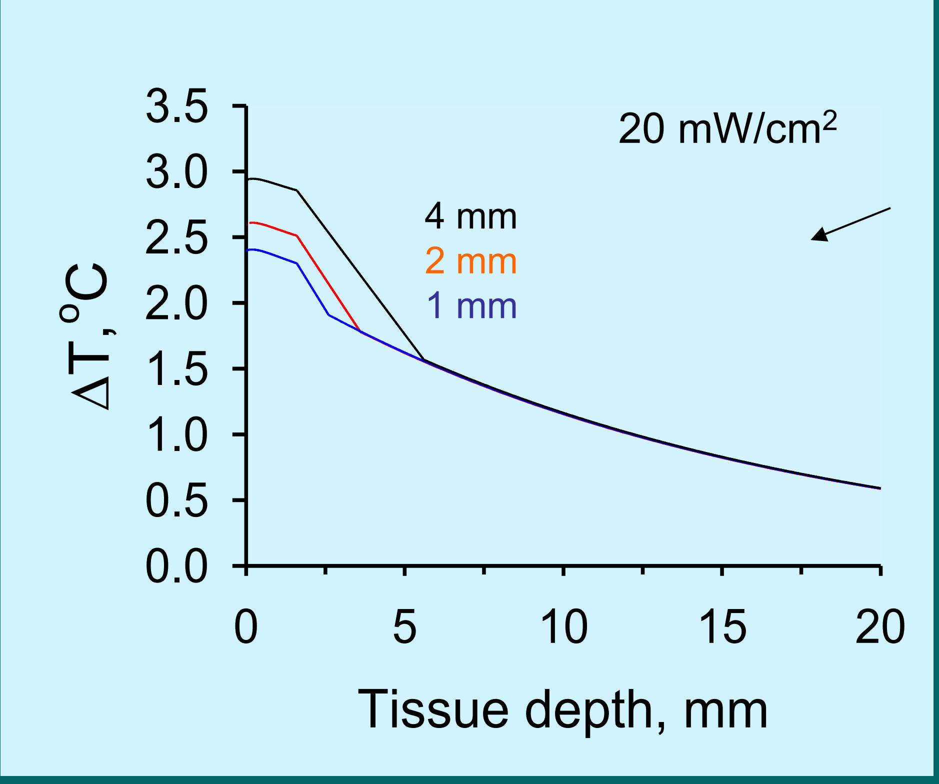
V_s – product of blood flow and heat capacity

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 multilayer tissue model with a fat thickness of 1, 2, or 4 mm after exposure to 42 GHz at 20 mW/cm^2



Epidermis - 0.1 mm
Dermis - 1.5 mm

Effective Thermal Conductivity

$$k_{eff} = k \cdot (1 + \beta \cdot BF)$$

where

Keff	=	Effective thermal conductivity
K	=	True thermal conductivity
B	=	975 (ml / s /ml)-1
BF	=	Blood Flow

Effective Thermal Conductivity

Body Site	Blood Flow	k_{eff}
	ml /s / ml	W / (m · ^{0}C)
Forehead	$7.2 \cdot 10^{-3}$	2.57
Face	$12.0 \cdot 10^{-3}$	4.06
Thorax	$1.1 \cdot 10^{-3}$	0.66
Abdomen	$1.4 \cdot 10^{-3}$	0.76
Forearms	$0.3 \cdot 10^{-3}$	0.41
Hands	$3.3 \cdot 10^{-3}$	1.35

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

Setting Exposure Limits Above 6 GHz

For Acute Effects:

Temperature elevation – duration concerns are important.

But:

Unlimited duration exposures must be considered.

Setting Exposure Limits Above 6 GHz

Temperatures < 40 °C

will not damage skin.

For example,

consider hot tubs and Jacuzzi's

Setting Exposure Limits Above 6 GHz

In addition to skin damage,

protect people from bodily harm.

Insure that core temperature

rises < 1 °C

Setting Exposure Limits Above 6 GHz

For core temperature to rise > 1°C:

Exposures greater than 6 GHz would have to be:

Whole body

Prolonged

Produce a skin temperature ~ 40°C

Setting Exposure Limits Above 6 GHz

To keep core temperature < 1°C

Keep skin temperatures < 37 °C,

A rise of ~ 4°C under most conditions

Use appropriate skin model(s)

to accomplish this

Setting Exposure Limits Above 6 GHz

Keep brain temperature rise < 0.5 °C

Daily circadian temperature rise = 0.5 °C

Use appropriate skin model(s)

to accomplish this

Thank You