Frequency Dependence of Heating Thermal Thresholds for Teratogenicity, Reproduction, and Development, and mm-Wave Exposure to the Skin

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Frequency Dependence of Heating

Fundamental mechanism of heating is the same for all the RF frequencies, but:

Penetration is frequency dependent

Distribution of temperature elevation varies

Penetration of mm-waves is limited to skin

Complex Relative Permittivity

$$\tilde{\varepsilon} = \varepsilon' - j\varepsilon''$$

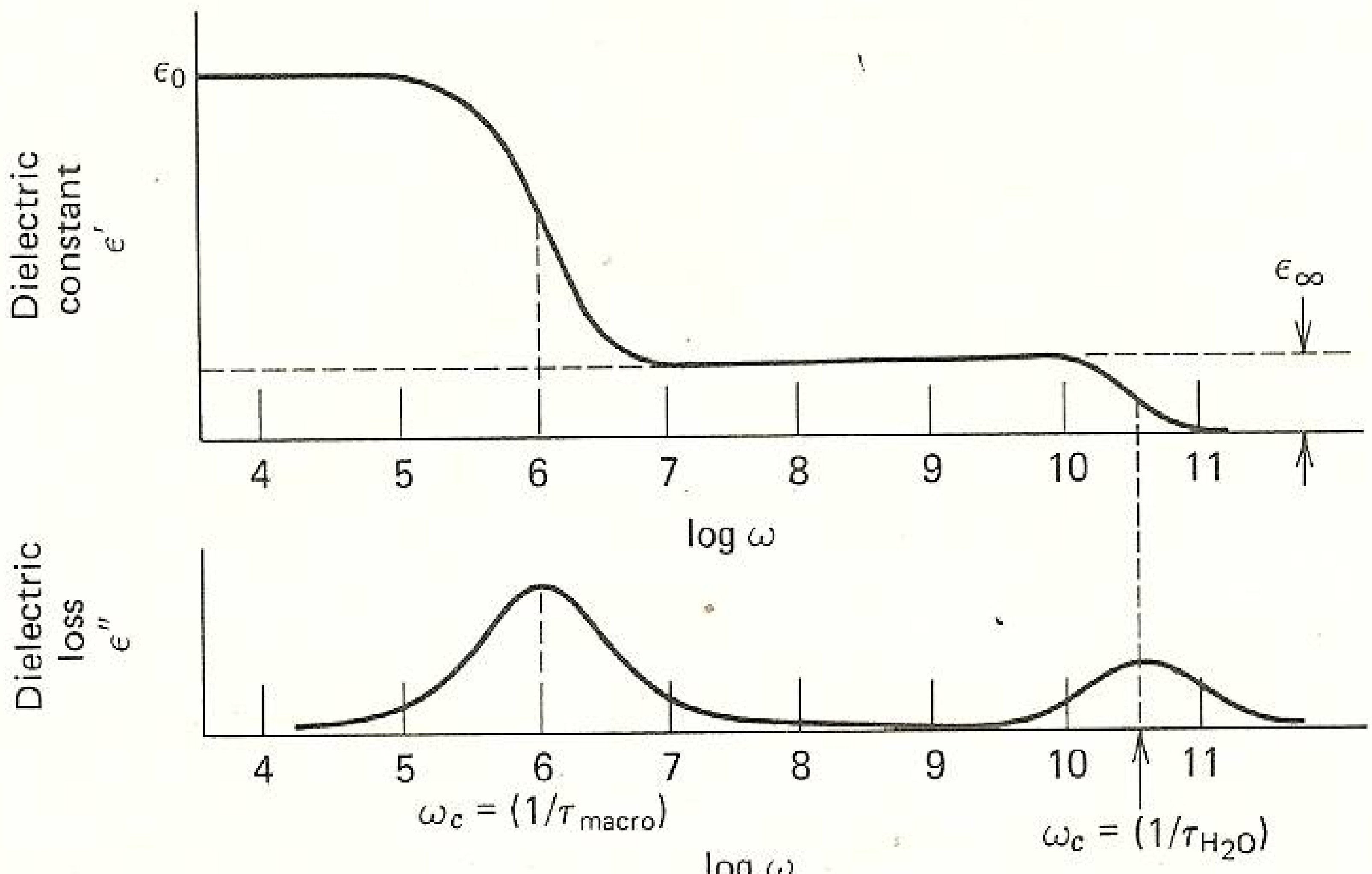
$$where$$

$$\varepsilon' = dielectric\ constant$$

$$(measures\ polarizability)$$

$$\varepsilon'' = dielectric\ loss$$

$$(measures\ energy\ loss)$$



ϵ_0
Dielectric constant ϵ'
ϵ_∞
4
5
6
7
8
9
10
11
log ω
Dielectric loss ϵ''
4
5
6
7
8
9
10
11
$\omega_c = (1/\tau_{macro})$
$\omega_c = (1/\tau_{H_2O})$
log ω

Dielectric Dispersion in Tissue

- Alpha Dispersion
  - Counterion diffusion effect
  - 100 Hz
- Beta Dispersion
  - Capacitive charging of membranes
  - 8 MHz
- Gamma Dispersion
  - Dipolar polarization of tissue water
  - 100 GHz

Complex Relative Permittivity

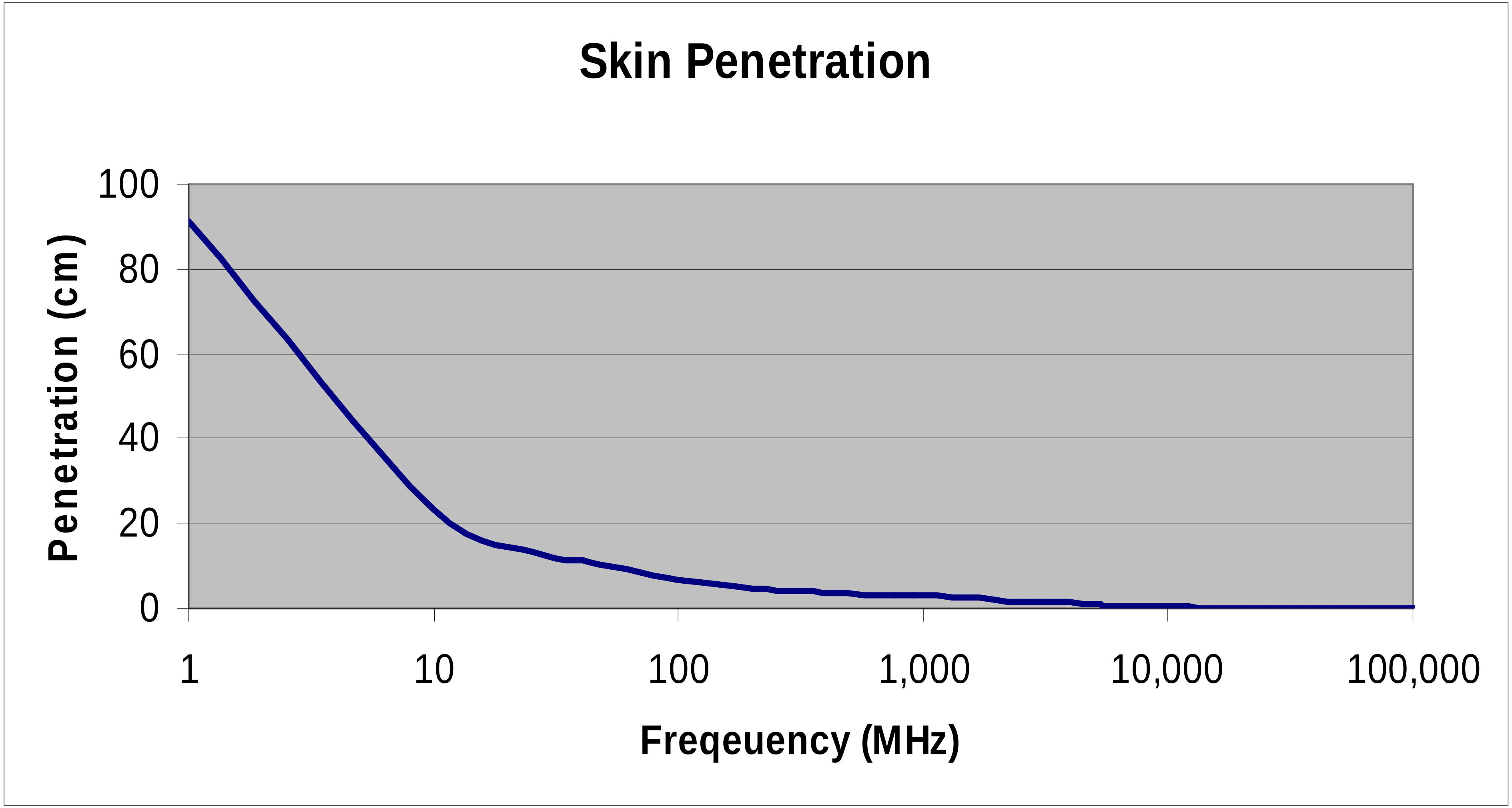
$$\tilde{\varepsilon} = \varepsilon' - j\varepsilon''$$

Attenuation Coefficient

$$\alpha = \frac{\omega}{c}\sqrt{\frac{\sqrt{(\varepsilon')^2 + (\varepsilon'')^2} - \varepsilon'}{2}}$$

Depth of Penetration

$$\delta = \frac{1}{\alpha}$$


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

Selected Frequency		Skin Depth	
1	MHz	913.0	mm
100	"	66.6	"
900	"	30.4	"
2.45	GHz	17.0	"
30	"	0.78	"
90	"	0.34	"
300	"	0.23	"

ANATOMY OF THE SKIN

ICNIRP Standard

Basic Restrictions for
100 kHz – 10 GHz Exposures:

Whole Body:		
	Occupational	**0.4 W/kg**
	General Public	**0.08 W/kg**
Head and Trunk:		
	Occupational	**10 W/kg**
	General Public	**2 W/kg**
Limbs:		
	Occupational	**20 W/kg**
	General Public	**4 W/kg**

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 10 GHz, where penetration is limited to skin.

ICNIRP Standard

Basic Restrictions for
10 GHz to 300 GHz Exposures:

OCCUPATIONAL	50 W / m2
GENERAL PUBLIC	10 W / m2

[redacted]

Thermal Thresholds for Teratogenicity, Reproduction, and Development

Thermal Bioeffects

Most sensitive and important irreversible effects occur in:

- ❖Rapidly dividing cells
- ❖Embryo and Fetus

Impact of Thermal Effect

Most Organs

- Cell death replaced
- Reversible

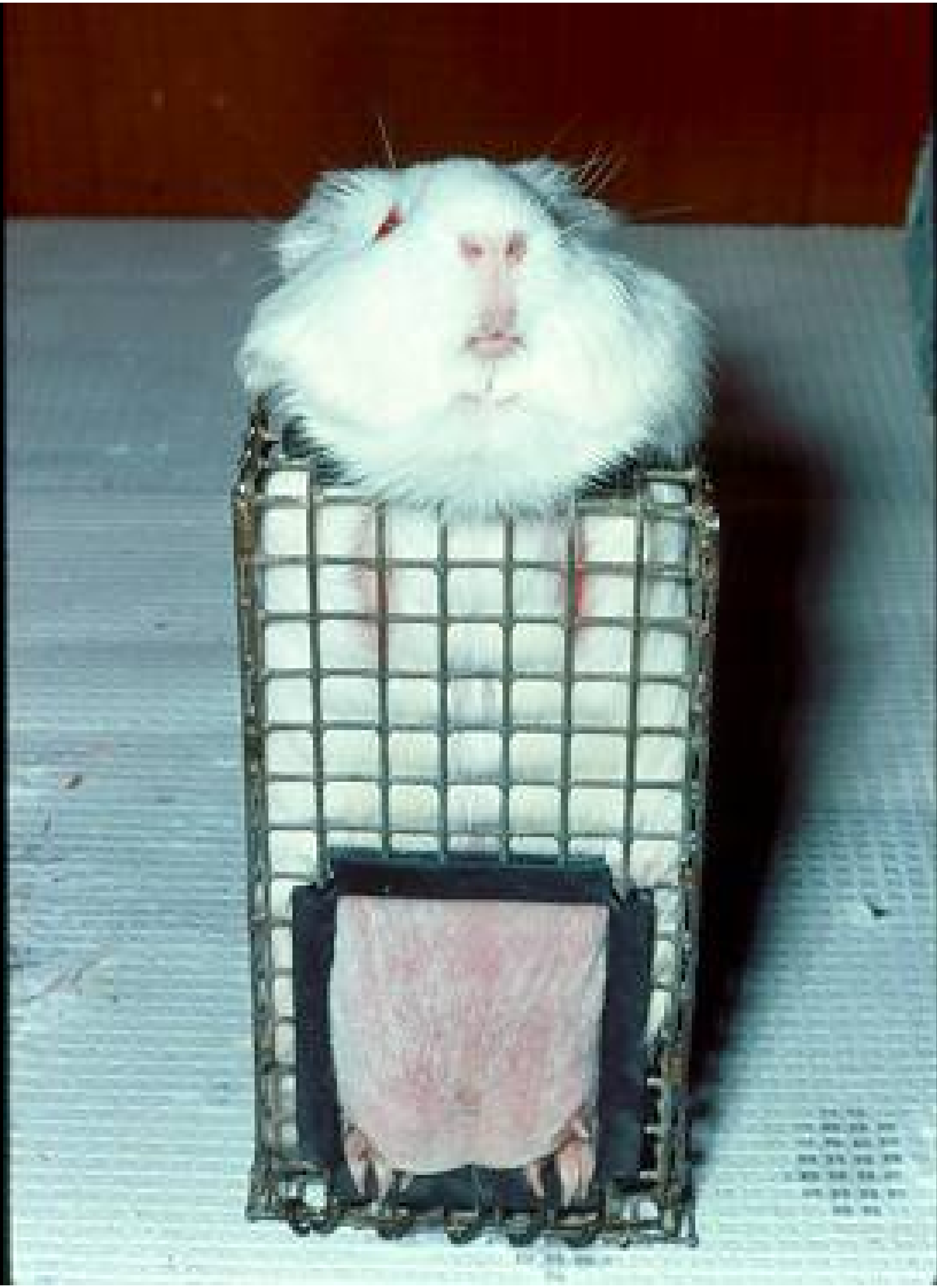
Embryo and Fetus

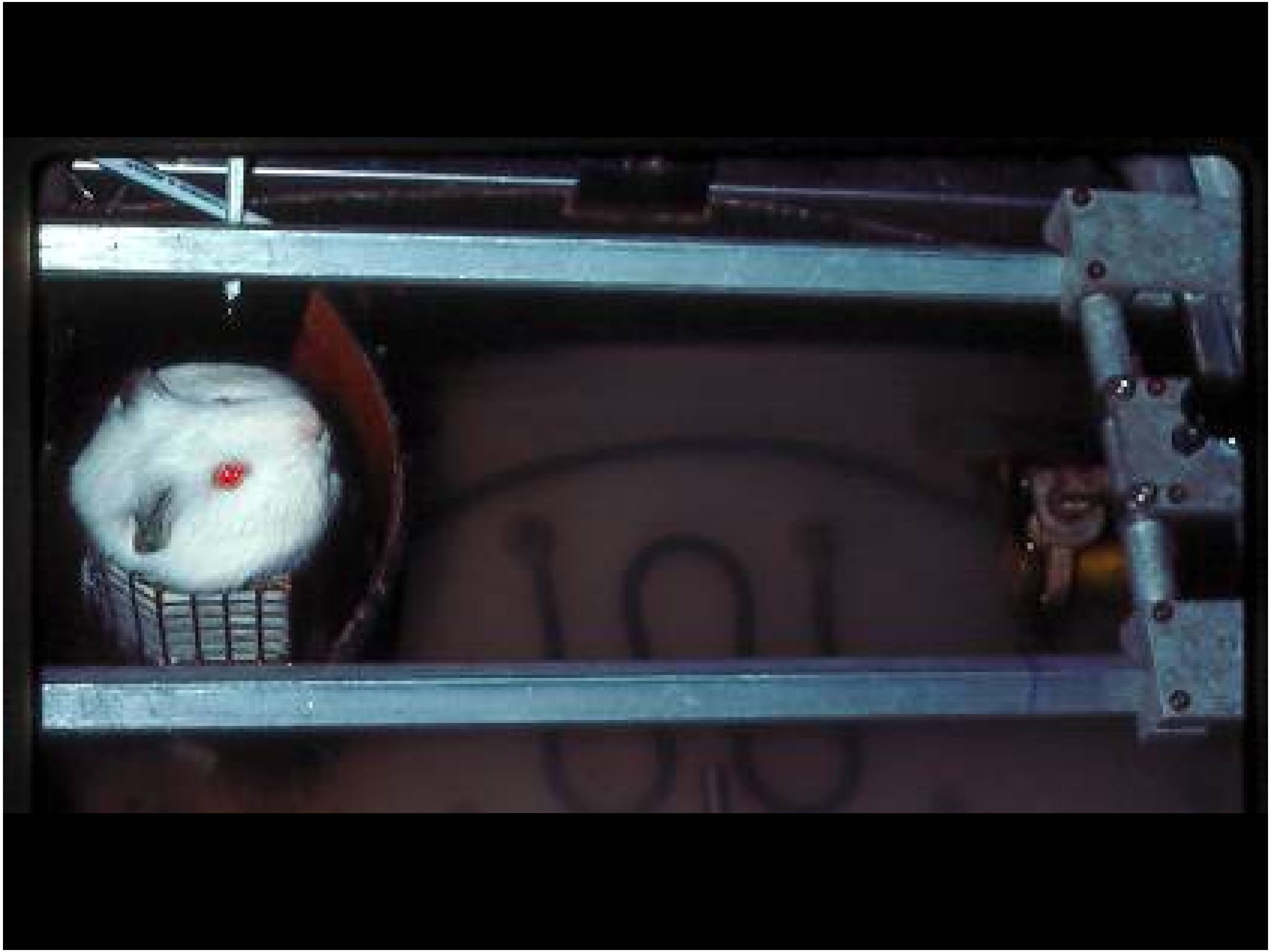
- Cell death has major Effect
- Not reversible

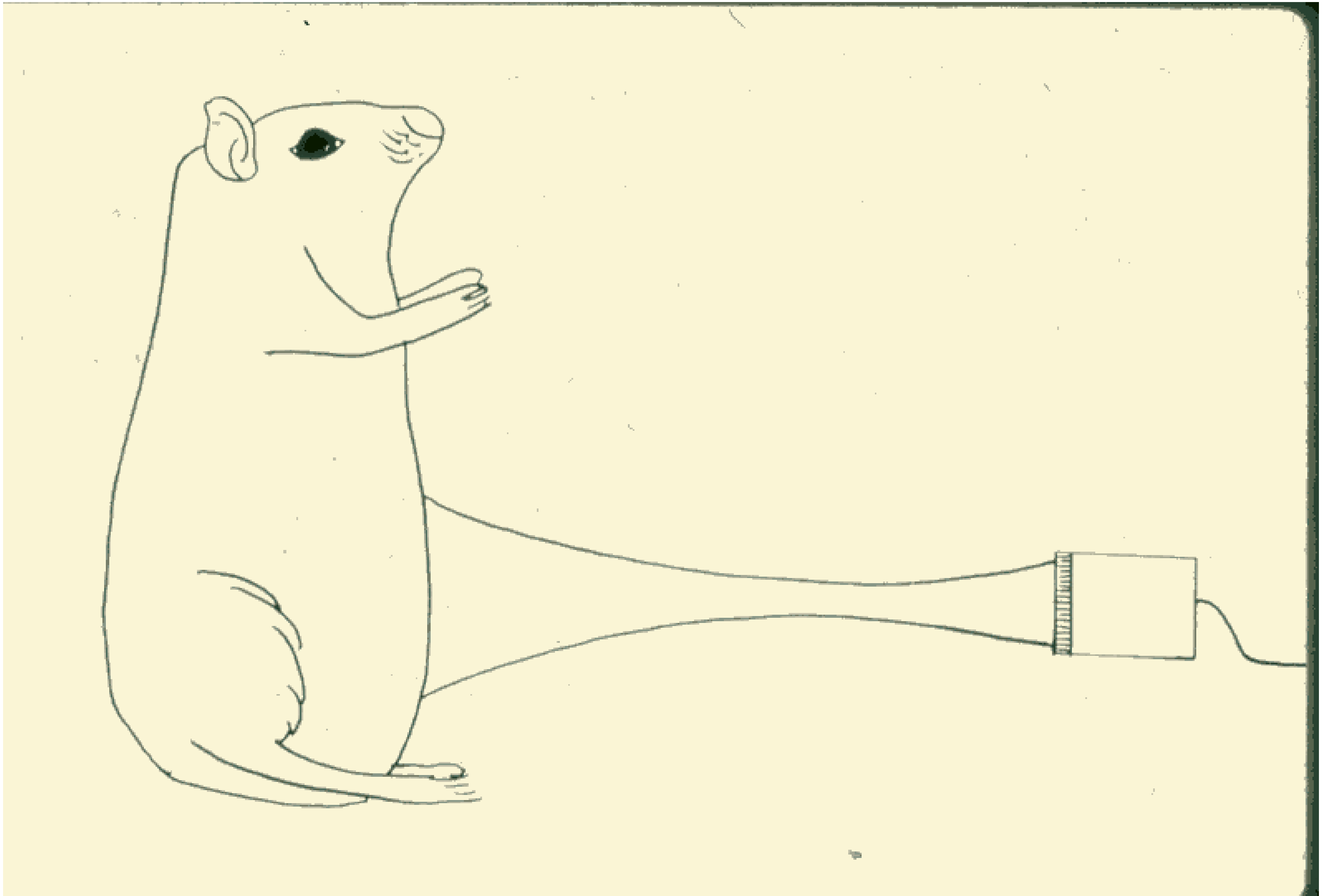
HYPERTHERMIA

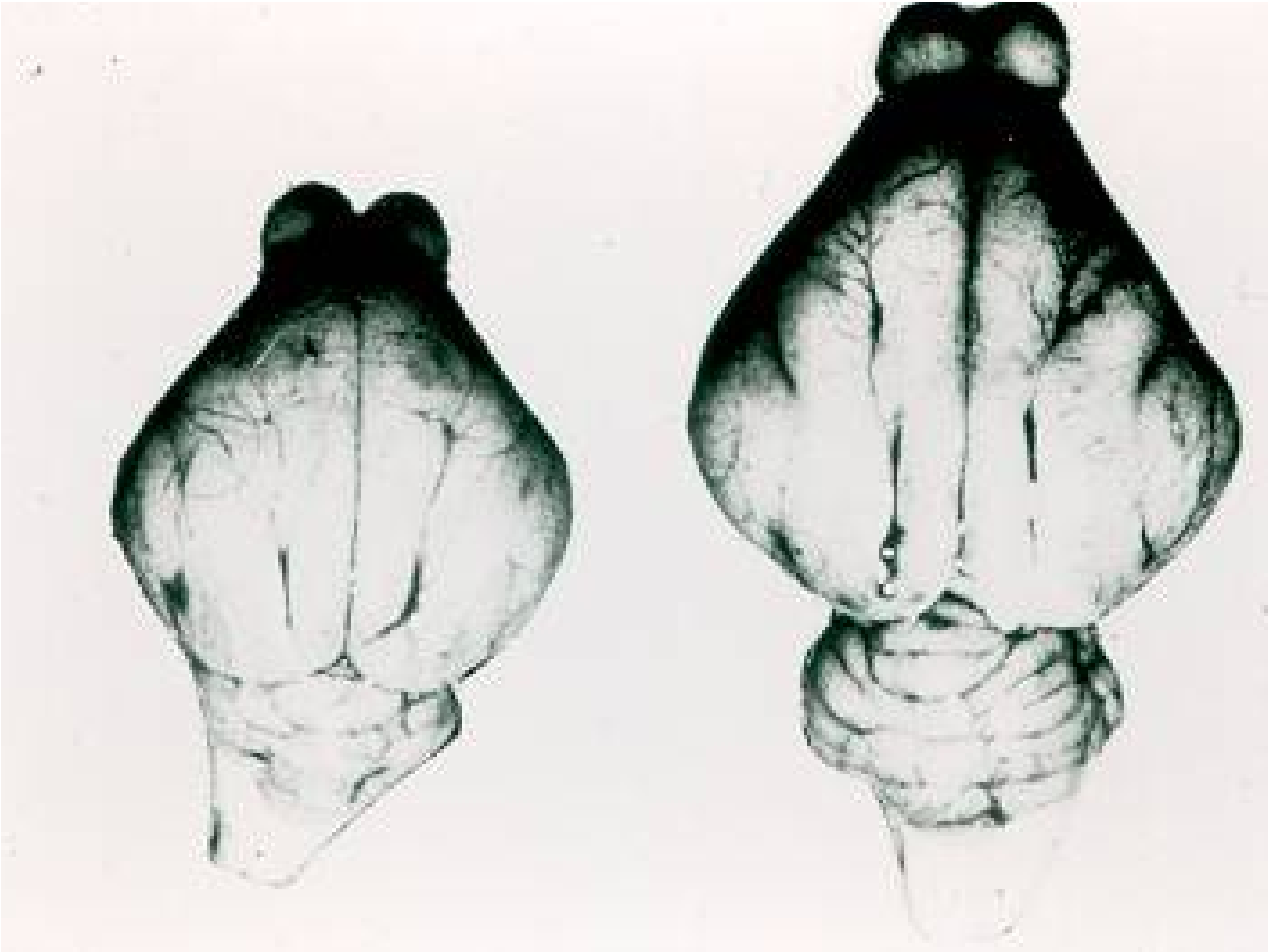
A Known Teratogen in:

Birds
Hamsters
Mice
Rats
Guinea Pigs
Sheep
Cattle
Non-Human Primates







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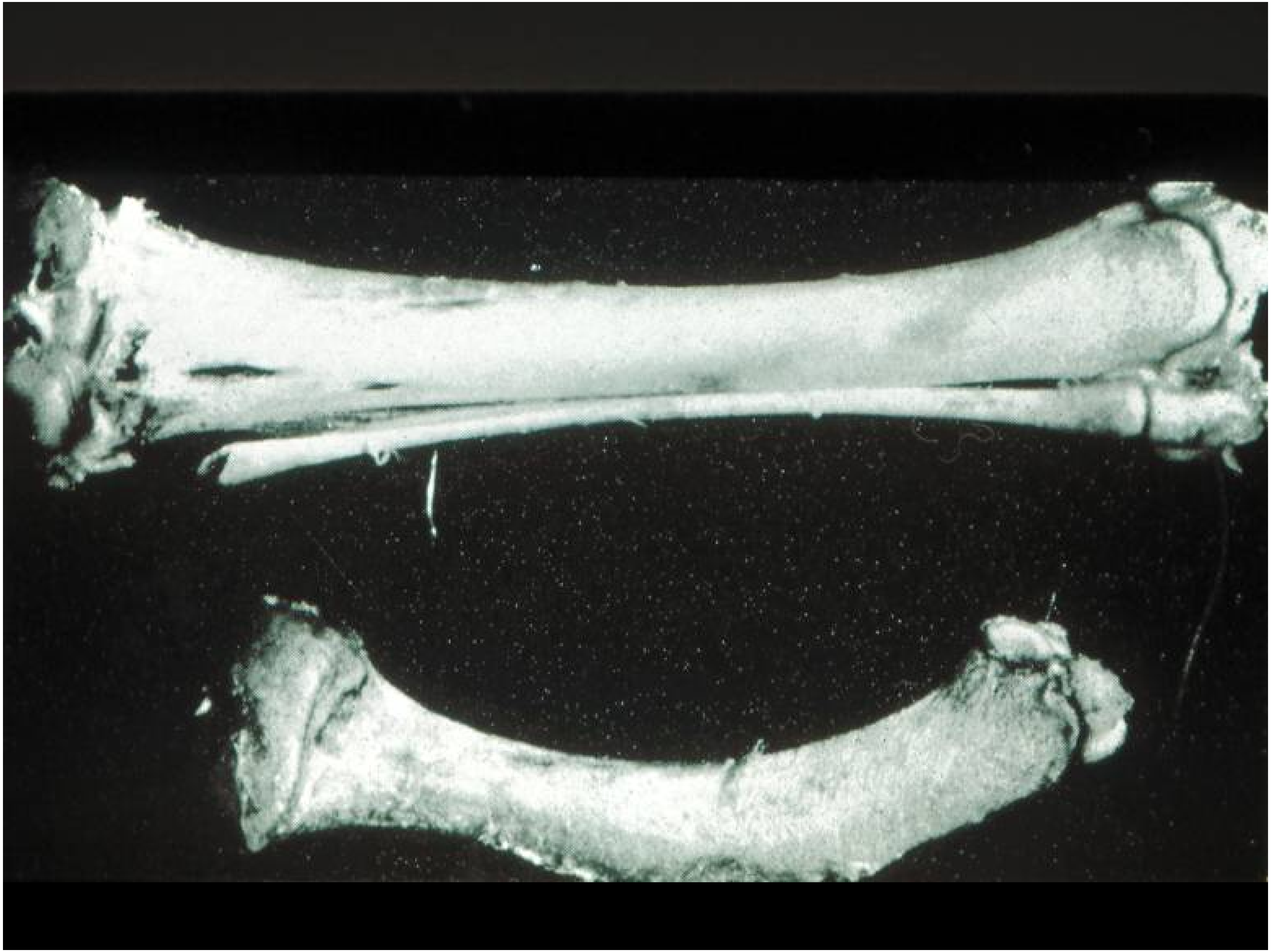
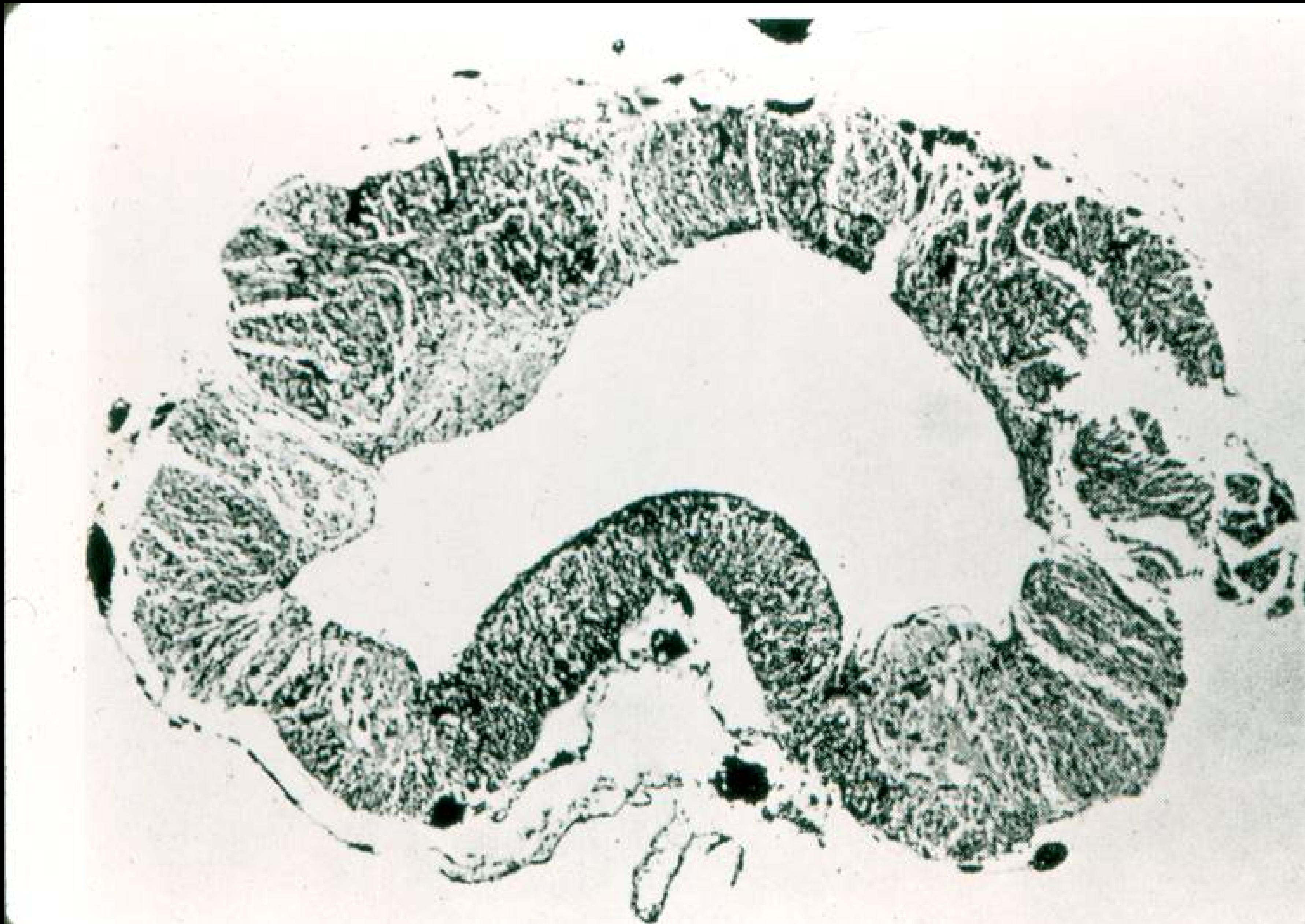
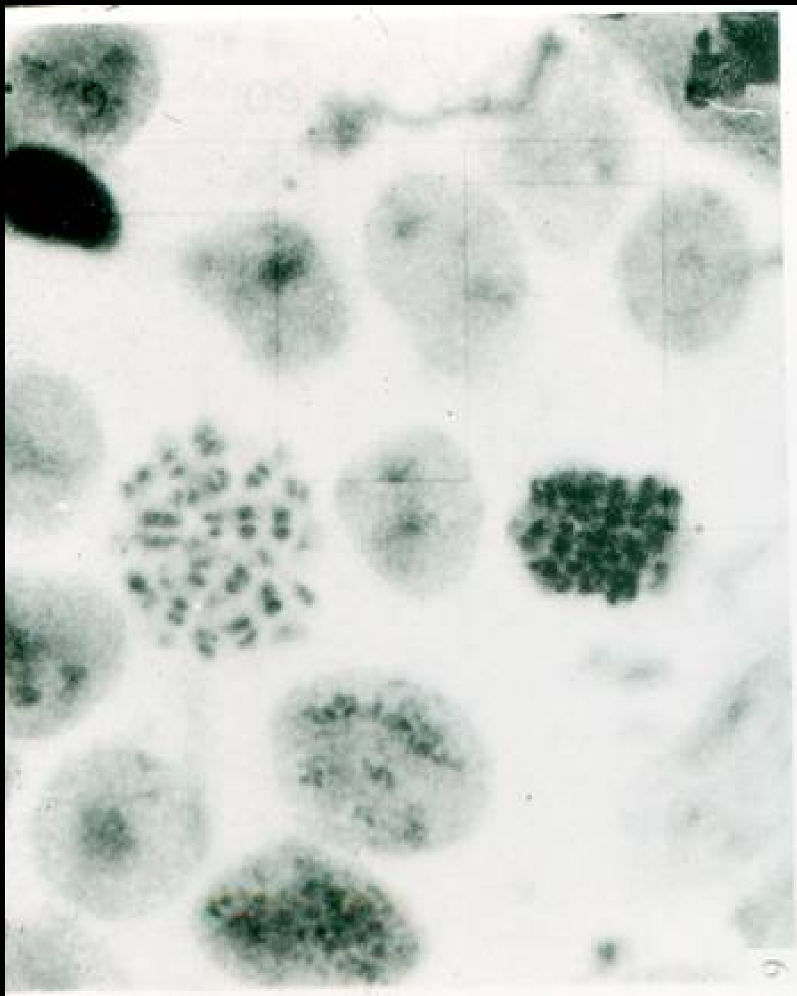
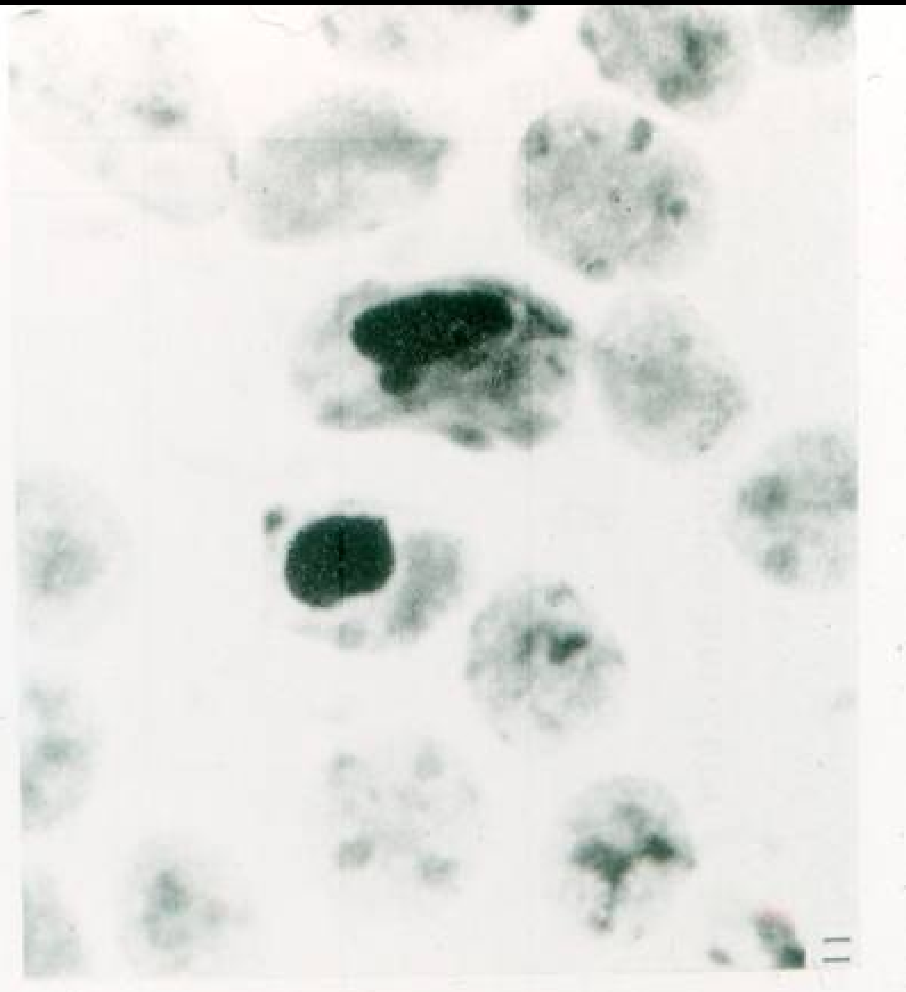
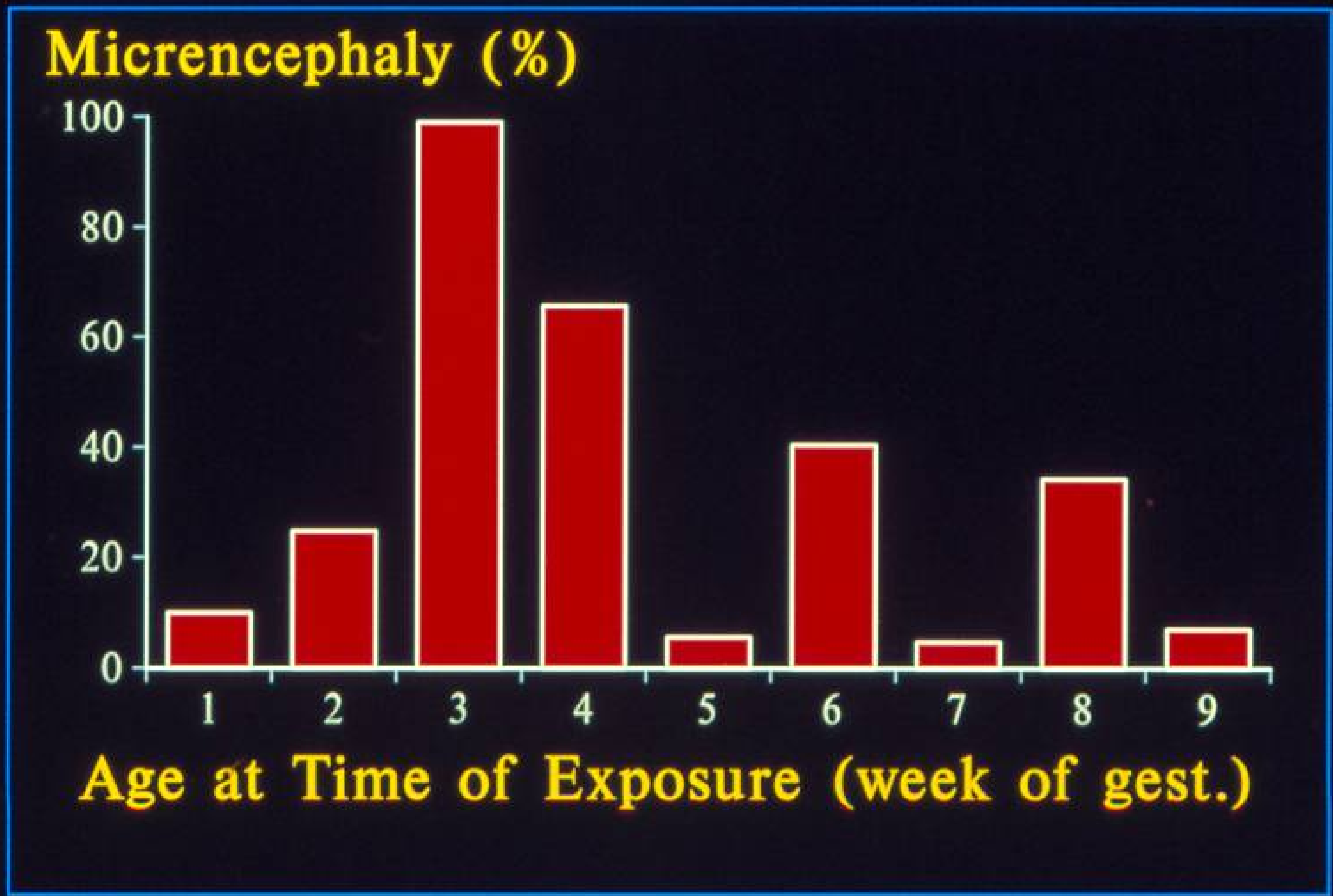
Arthrogryposis Multiforma







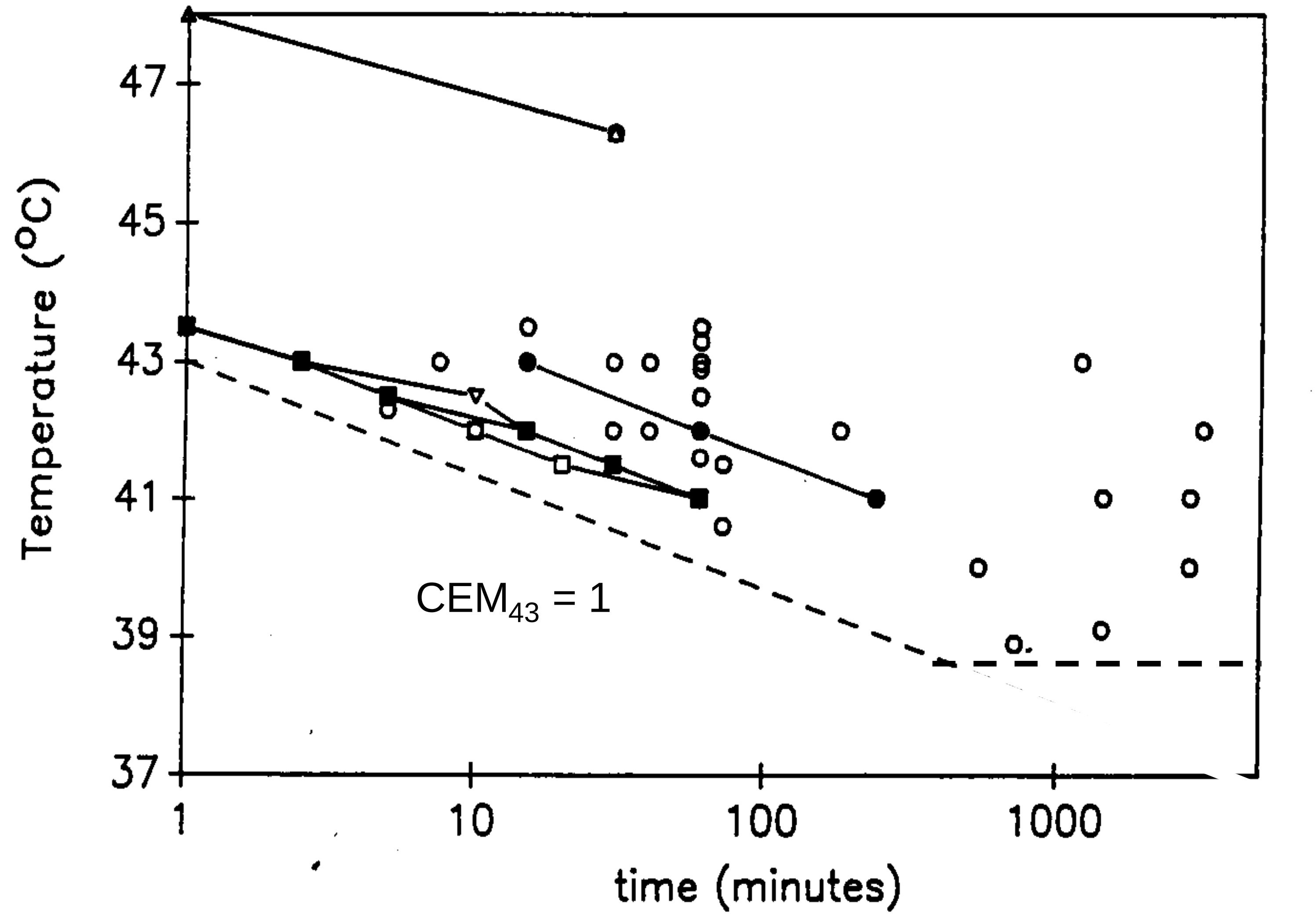



Micrencephaly (%)
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
Age at Time of Exposure (week of gest.)

Temperature Duration Thresholds for Fetal Abnormalities

Thermal effects	Temp (°C)	Exposure duration (min)	t_{43}† (min)	Species	Reference
Abnormal closure of anterior neuropore	43.0	7.5	7.5	Rat	Walsh (1985b)
Abortion	40.6	72	2.6	Monkey	Hendrickx et al. (1979)
Absence of optical vesicles	43.0	7.5	7.5	Rat	Walsh (1985b)
Absent cerebral cortical plate	43.0	60	60.0	Guinea Pig	Upfold et al. (1986)
Aqenesis	43.3	60	90.9	Guinea Pig	Edwards (1971)
Agnathia	43.0	60	60.0	Mouse	Pennycuik (1965)
Anencephaly	43.0	40	40.0	Rat	Edwards (1968)
Anophthalmia	40.6	72	2.6	Monkey	Hendrickx (1979)
Arthrogryposis	42.9	60	52.2	Guinea Pig	Edwards (1971)
Beak defects	41.0	1440	90.0	Chicken	Nielsen (1969)
Behavioral abnormalities	41.5	60	7.5	Marmoset	Poswillo et al. (1974)
Blebbing of cell membrane	43.0	180	180.0	Chin. Hamster	Bass et al. (1978)
Brain cavitation	40.0	540	8.4	Sheep	Hartley et al. (1974)
Brain growth retardation	40.0	2880	45.0	Rat	Cockcroft and New

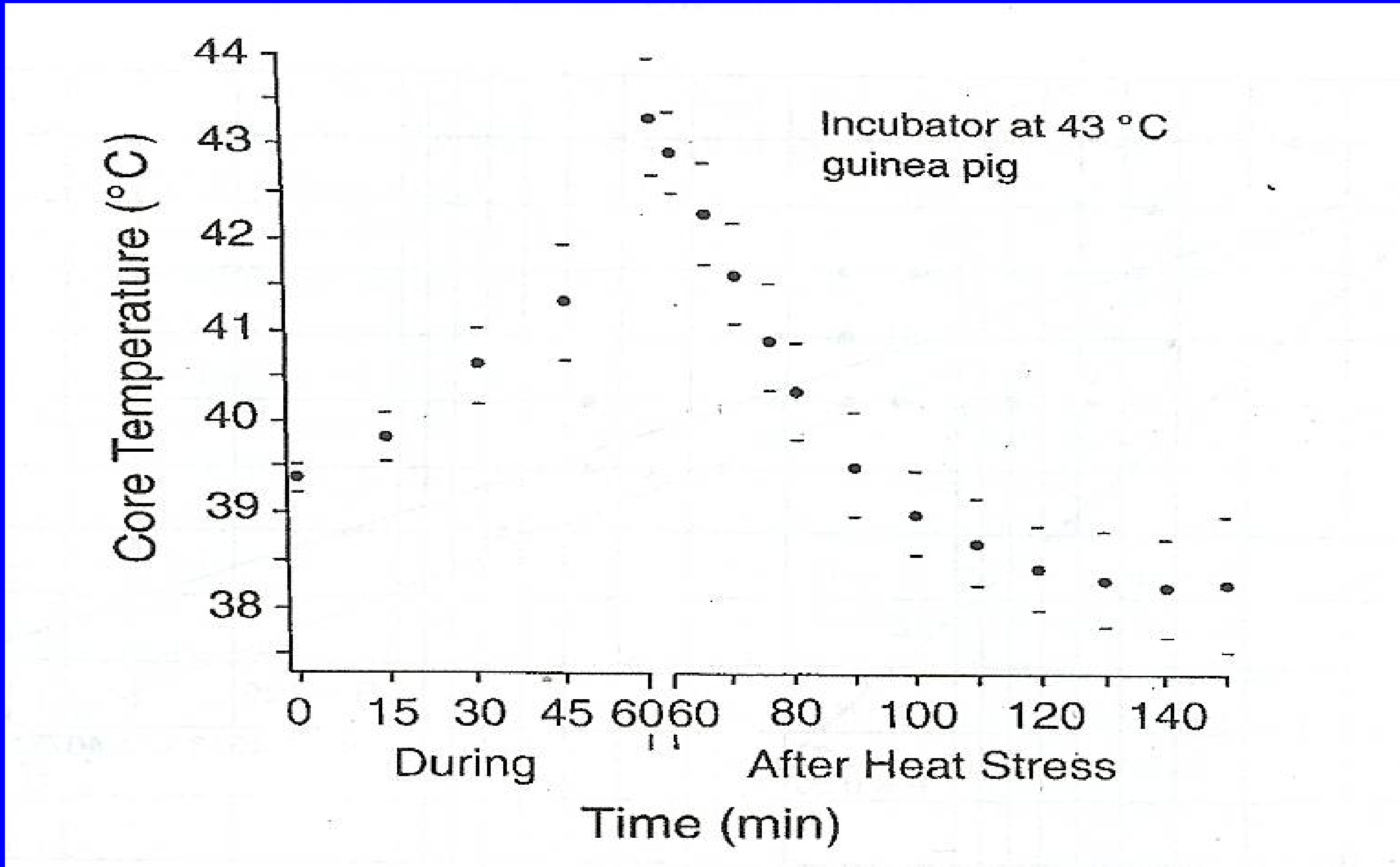
Fetal Developmental Abnormality Thresholds



Normal Rectal Temperatures

Baboons & Monkeys	37.0 – 39.0
Camel	34.0 – 40.0
Cat	39.0
Chicken	41.0 – 42.5
Cow	38.0 – 39.0
Dog	38.0 – 39.0
Gerbil	38.5
Goat	38.0 – 40.0
Guinea Pig	39.0 – 39.5
Human	37.0 – 37.5
Mouse	37.0 – 39.0
Pig	37.0 – 39.0
Rat	37.5 – 38.5
Sheep	39.0 – 39.5
Sparrow	43.0 – 44.0

Fetal Temperature During Thermal Exposure



The thermal equivalent time (t43) is defined mathematically as:

$$t_{43} = \int_0^{t_1} R^{\,k\,[T(t)-T_0]}\, dt$$

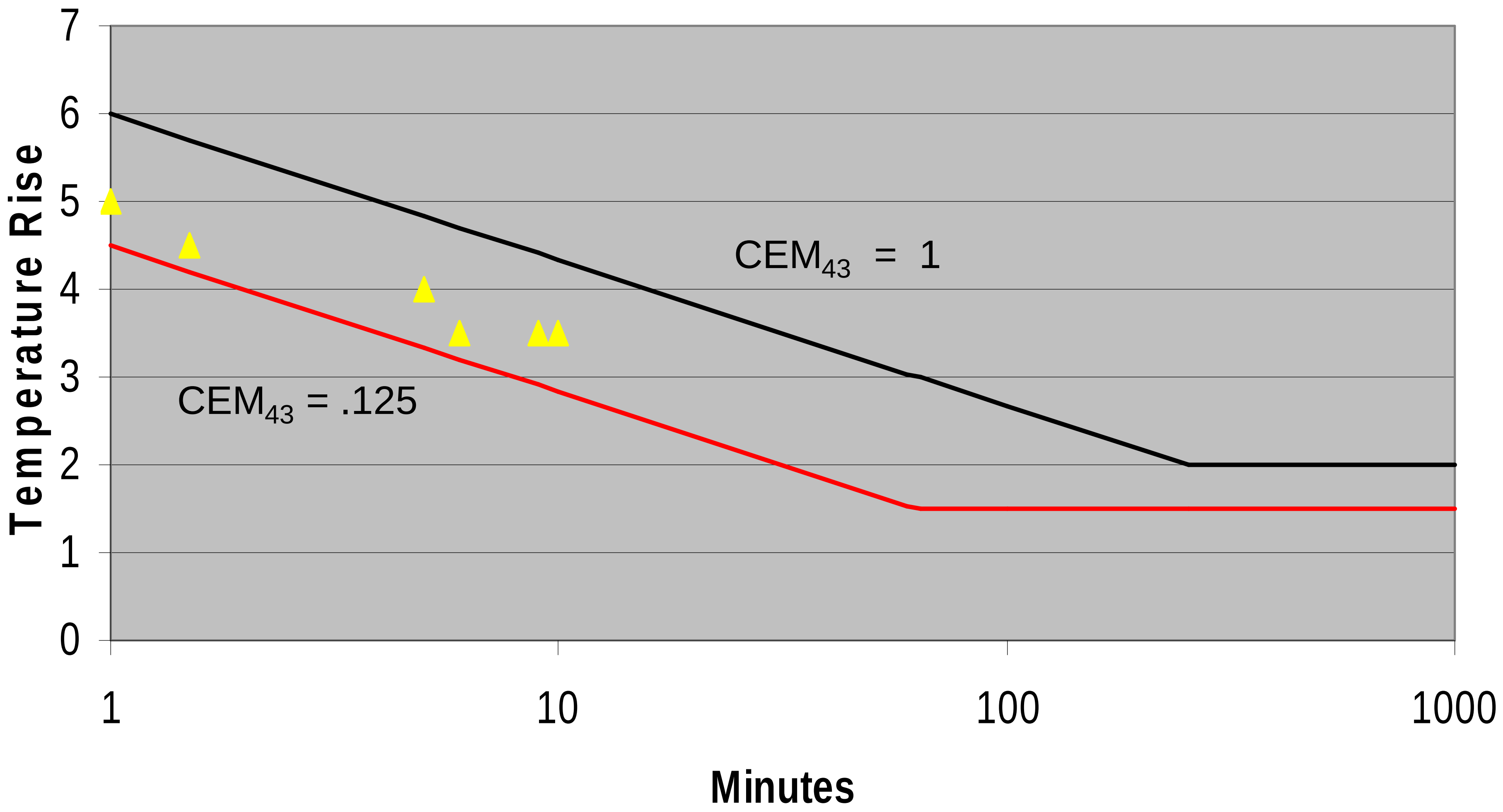
where:

- k = $(1\ °C)^{-1}$, a constant to render the exponent dimensionless
- T_0 = Reference temperature of 43 °C
- $T(t)$ = Temperature (which may vary in time) producing the bioeffect
- t = time
- t_1 = time required to produce the bioeffect at Temperature T
- R = 4.0 if $T \leq 43$ °C
- R = 2.0 if $T > 43$ °C

Abnormalities Occurring below $CEM_{43} = 1$

- Encephalocoele in rats
- Exencephaly in mice
- Microcephaly in guinea pigs
- Neural tube defects in mice
- Skeletal malformations in mice and rats

Fetal Developmental Abnormality Thresholds



Safe Temperatures
For Developmental Abnormalities

Temperature Elevation	Minutes
6 ^{0}C	.25
5 ^{0}C	.5
4 ^{0}C	2
3 ^{0}C	8
2 ^{0}C	32
1.5 ^{0}C	∞

Mitigating Factors in Humans

- Better Thermoregulation
- Fetuses normally are 0.5 ^{0}C above core
- Diurnal temperature variation = ~1 ^{0}C
- Repair mechanisms may be better
- Enzyme kinetics are driven by absolute temperature not relative temperature

Temperature Rise From Whole Body SAR

SAR	Temp Rise	Comment
15 W/kg	4.0 ^{0}C	Abnormality
4 W/kg	1.0 ^{0}C	No Harm
1.5 W/kg	0.4 ^{0}C	Safe Level
0.4 W/kg	0.1 ^{0}C	RF Standard

Note: Diurnal Variation = ± 0.5 ^{0}C

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Millimeter Wave Exposure of the Skin

Russian Reported Successes in Millimeter Wave Therapy

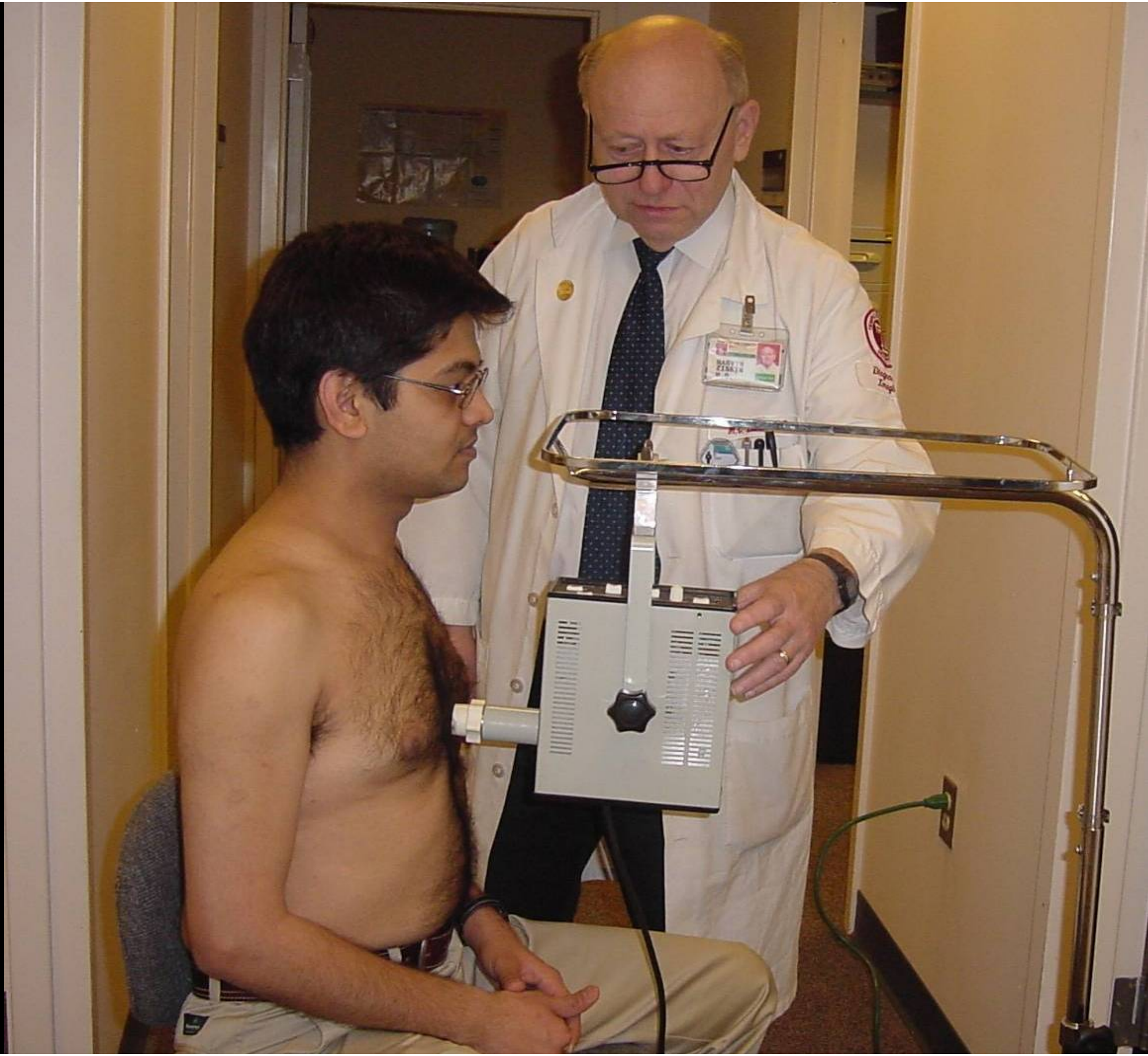
Osteoarthritis	Cancer
Esophagitis	Substance Abuse
Peptic Ulcer	Epilepsy
Duodenal Ulcer	Alcoholism
Hypertension	Psoriasis
Myocardial Infarct	Pain
Mental Disease	Prostatic Hypertrophy
Rheumatic Disease	Anemia

Ukrainian Clinical Studies 1993

Number of Centers	**325**
Number of Patients	**250,000**
Pathology	**Efficiency**
Nervous Diseases	**88.7%**
Digestive Diseases	**96.1%**
Respiratory Diseases	**96.7%**
Mental Diseases	**80.3%**
Blood Circulation	**92.7%**
“Women’s” Diseases	**87.0%**
Skin Disorders	**84.8%**
Rheumatic Diseases	**84.3%**
Infectious Diseases	**96.2%**

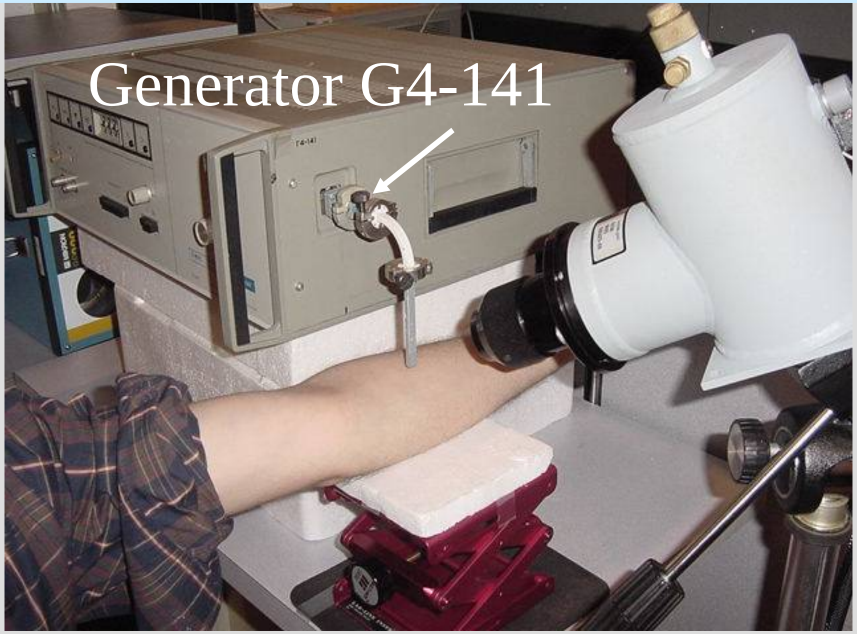
Millimeter Wave Therapy

- Typical Power Density
  10 – 20 mW/cm^2
- “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



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

Lower forearm



Index finger

Frequency: 42.25 GHz
Output power: 52 mW

Effect of Blood Perfusion on Heating

Experimental Techniques

- Vasodilating Cream to increase perfusion
- Blood Pressure Cuff to decrease perfusion
- Laser Doppler Probe to measure perfusion

Exposure

- 208 mW/cm^2 at 42.5 GHz
- Sites: Forearm and Finger
- Duration: 10 min

Effect of Blood Perfusion on Heating

Results

Forearm $\Delta T = 4.0\ °C$ by 10 min

Finger $\Delta T = 2.5\ °C$ by 2 min

Occlusion: $\Delta T = 2\ °C$ in exposed area

$\Delta T = -2\ °C$ in unexposed area

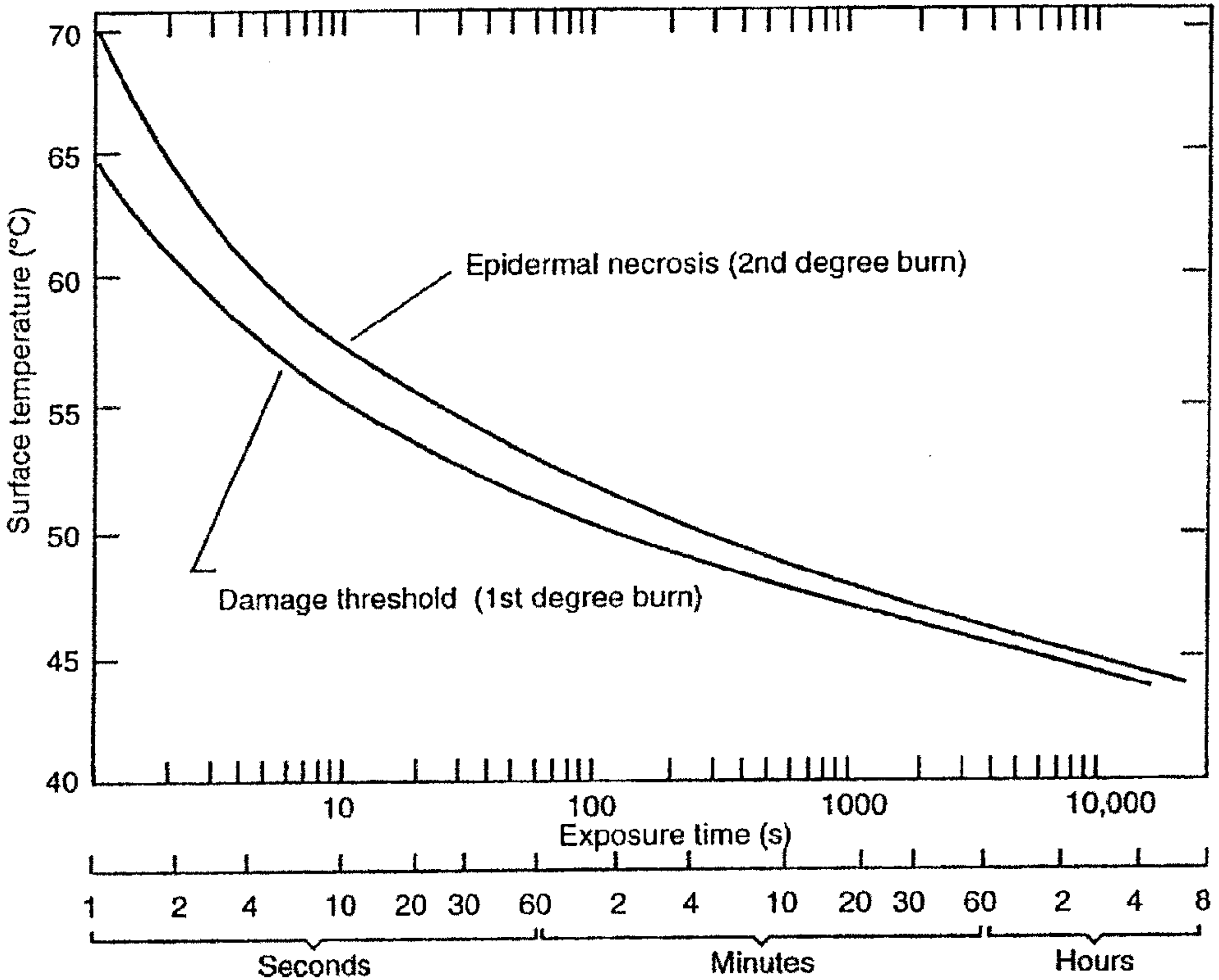
Vasodilation: Variable ΔT depending on Venous pattern

Effect of Blood Perfusion on Heating

Conclusions:

- ΔT greatly affected by blood flow
- Beam size is important
- Narrow beam
  - Caused shallow and low ΔT
  - Required 2D equations for good fit
- Broad beam
  - Caused deeper and higher ΔT
  - 1D equation provided good fit
- Bioheat Transfer Equation
  - Required $k_{eff} = (1 + \beta \cdot f) \cdot k$

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



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.

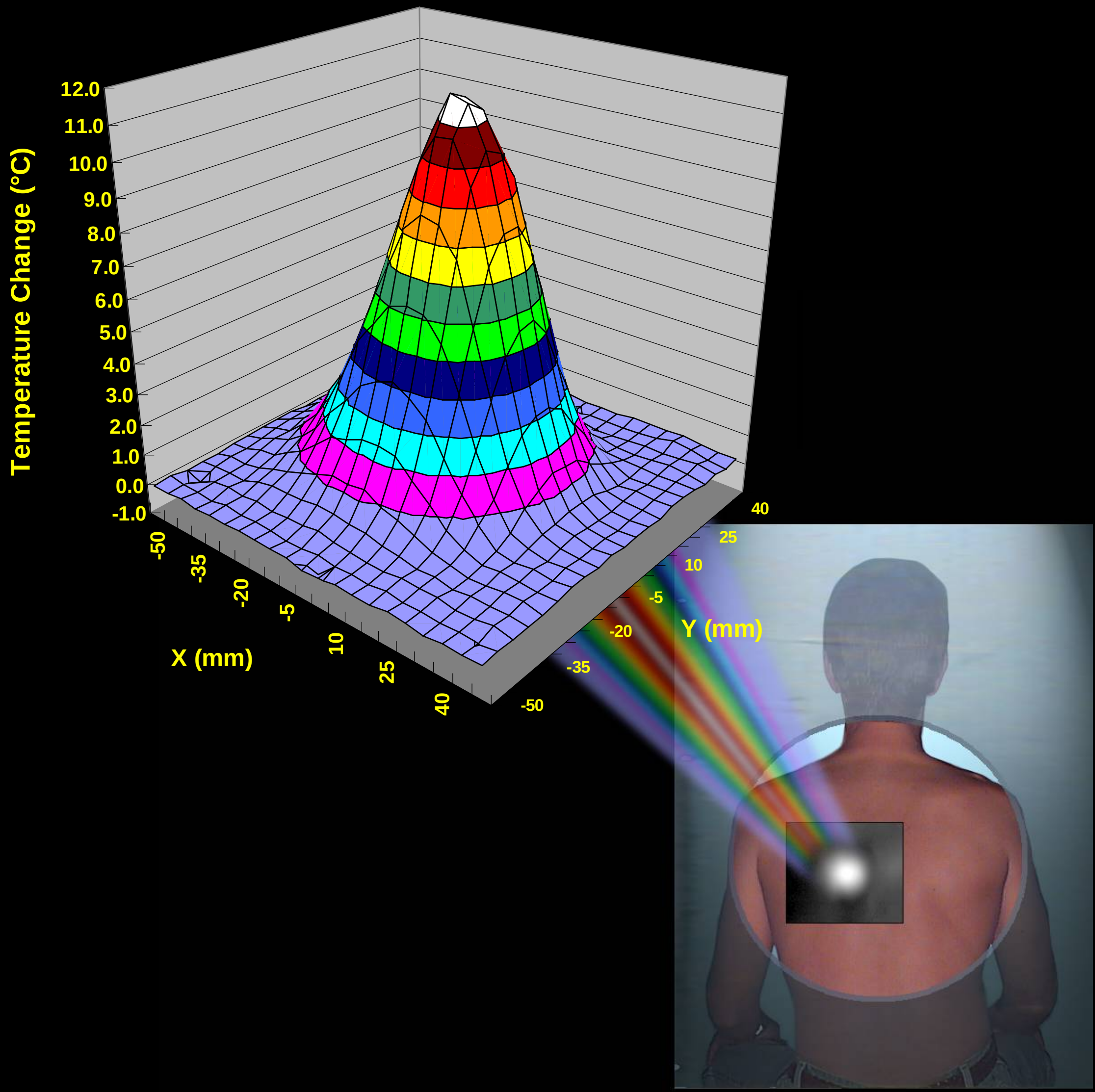
Health Phys. 78(3):259–267; 2000

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.

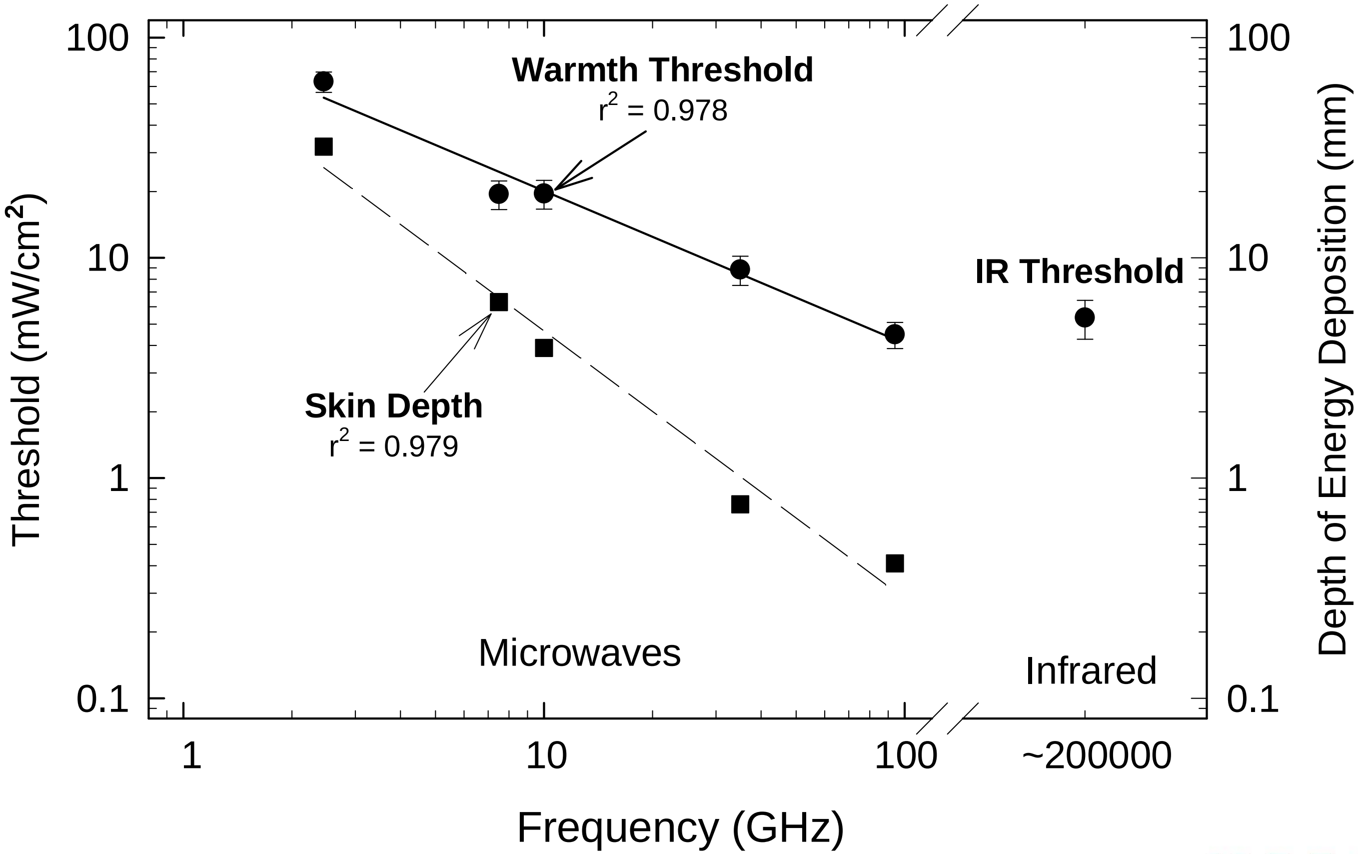
The threshold for thermal pain has been determined for microwave (3 GHz; Cook 1952b) and infrared irradiation (Cook 1952b; Hardy et al. 1952) in human subjects. The threshold for pain was found to be a

Infrared Thermography

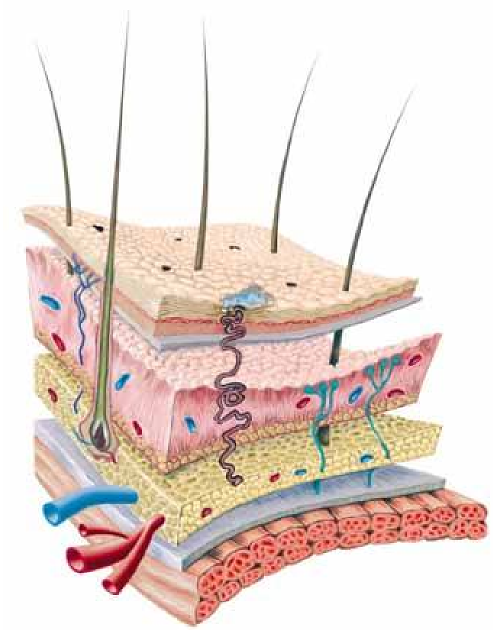


VERIDIAN

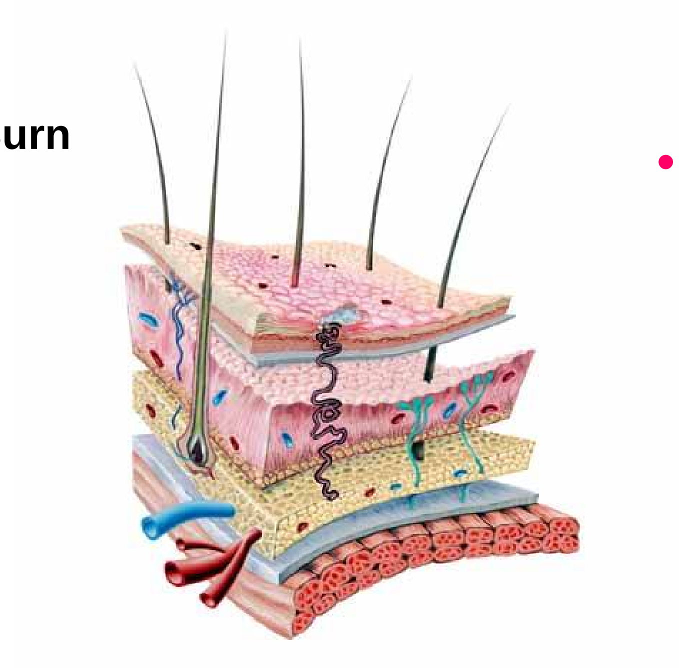
Warmth Detection Threshold and Penetration Depth: Variation with Microwave Frequency



Normal Skin

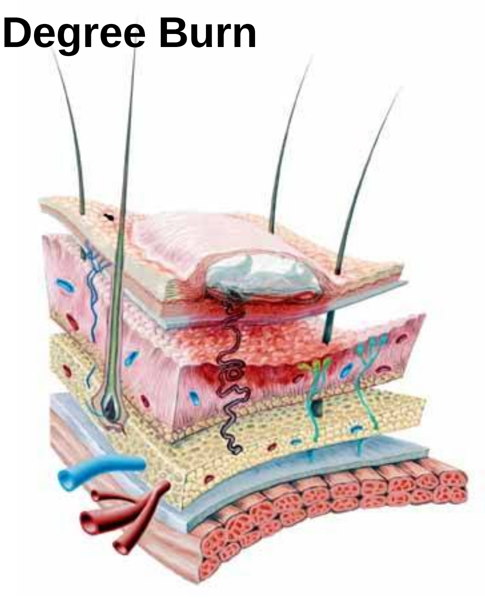


1st Degree Burn



- **First degree burn:**
  - **Epidermis is burned;**
  - **Reddening occurs and swelling is possible**
  - **Heals without scarring**

2nd Degree Burn



3rd Degree Burn

- **Second degree burn:**
  - **Epidermis and dermis are burned;**
  - **Intense red discoloring;**
  - **Severe pain, swelling, and blistering.**

- **Third degree burn:**
  - **All layers of skin burned => to fat, muscle, and possibly bone**
  - **May be severe pain, but sometimes extensive nerve damage results in little or no pain**
  - **Areas appear charred black or dry white**
  - **Areas cannot heal fast enough on their own to prevent infection**

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

Thank You