THERMOREGULATORY RESPONSE TO RADIOFREQUENCY RADIATION

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Outline of talk

- Fundamentals of thermoregulation
- Sensitivity vs. capacity of thermoregulatory system
- Human thermoregulatory responses
- Contrasting RF with exercise and drug induced hyperthermia

THERMOREGULATION

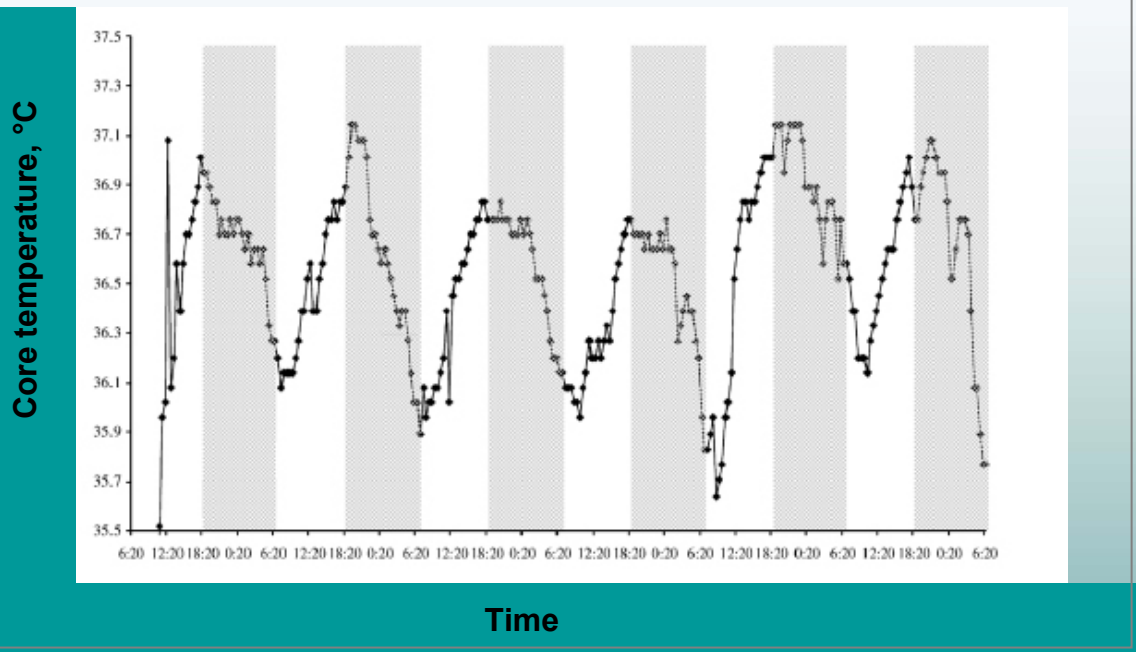
- The ability to regulate a relatively stable core temperature independent of changes in ambient temperature
- A unique autonomic regulatory system that relies on behavior and conscious awareness of the environment

THE STABILITY OF CORE TEMPERATURE: A COMPARATIVE PHYSIOLOGICAL PERSPECTIVE

30 gram mouse **7,000,000 gram African Elephant**

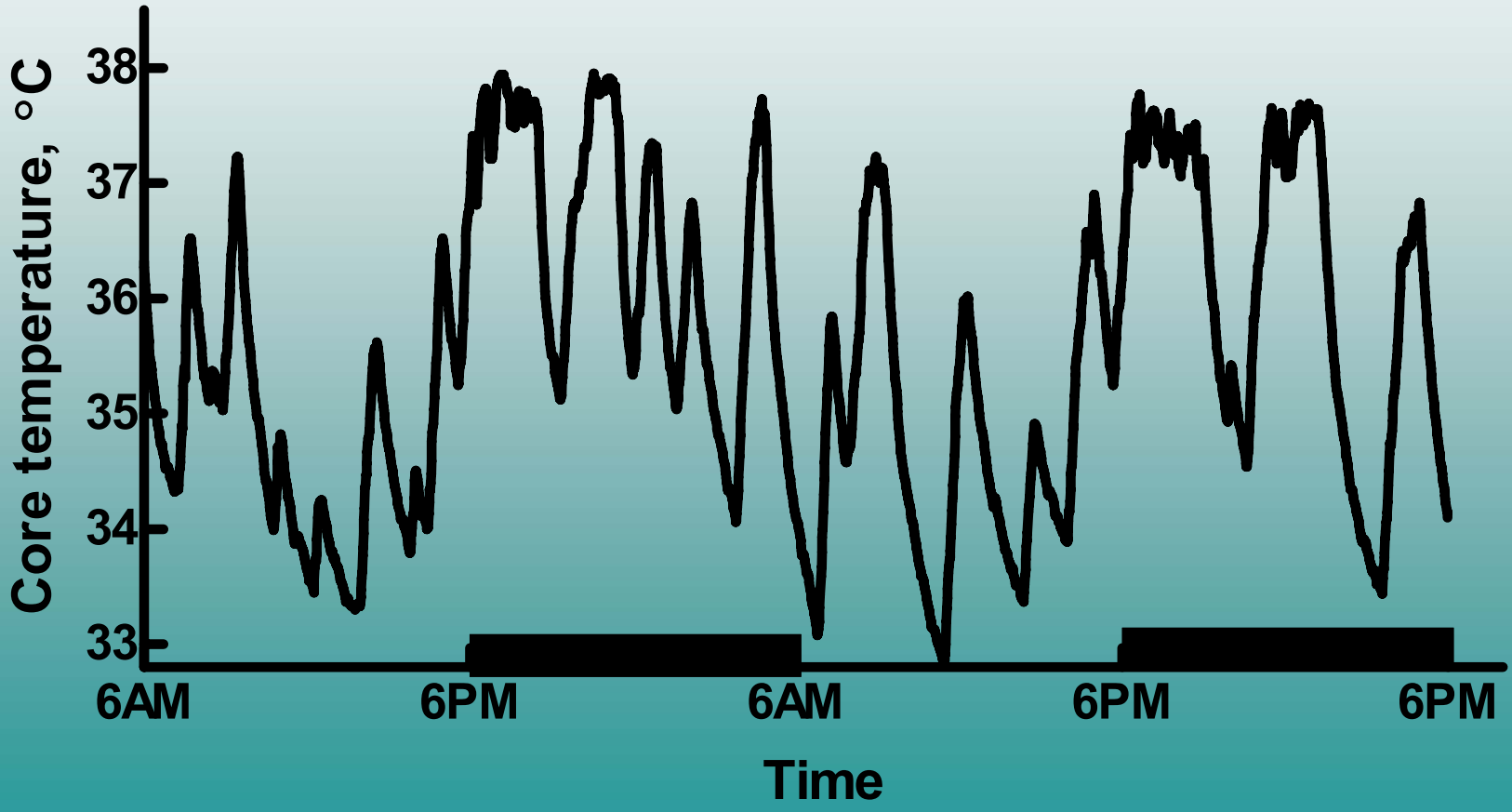
36.4 °C ← Mean core temperature → 36.2 °C

Five days of core temperature of an elephant



Kinaham et al. 2007

Two days of core temperature of a mouse



BODY HEAT BALANCE EQUATION

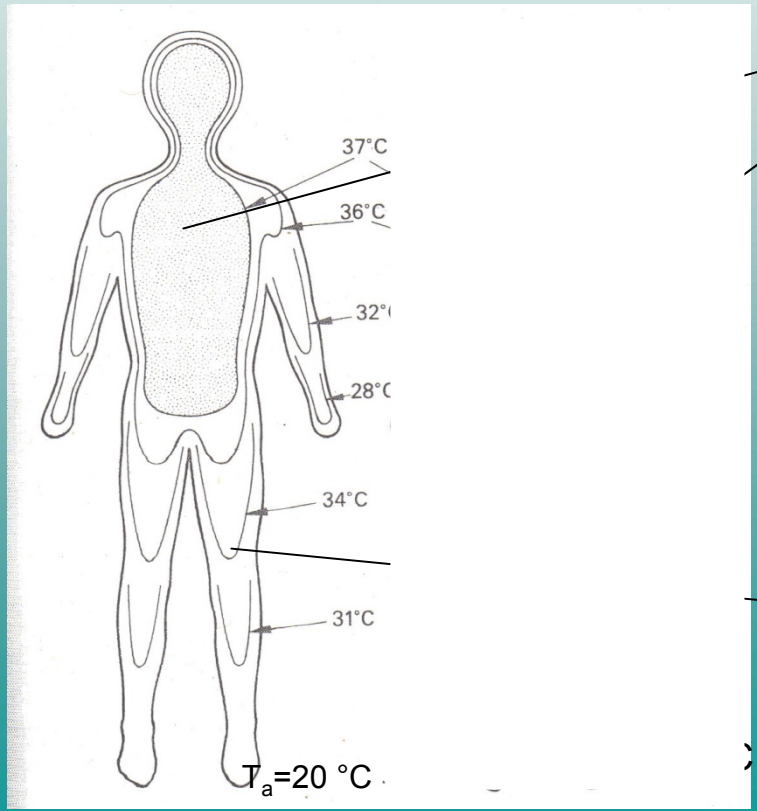
Heat storage (S) = Metabolic rate (M) – radiation (R)
convection (C)
conduction (K)
evaporation (E)

S=0 normothermia

S>0 = hyperthermia

S<0 = hypothermia

THE THERMAL CORE AND SHELL



S_{core}=M-H-REHL

H=conductive+convective heat transfer between core and shell

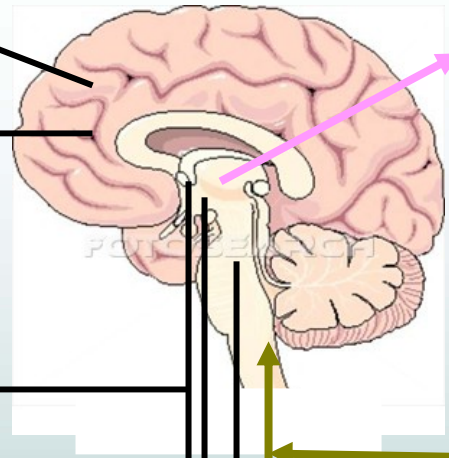
REHL=respiratory evaporative heat loss from lungs

A_{rf}=energy absorbed from RF

S_{core}=(M+A_{rf})-H-REHL

S_{shell}=A_{rf} +H-(E+C+K+R)

BASIC THERMOREGULATORY PATHWAYS



Preferred environment

TSH

ACTH

ADH

Pituitary

Thermal receptors to monitor core

evaporation

Sweat glands

ventilation

Respiratory

constrict

dilate

Skin blood vessels

piloerection

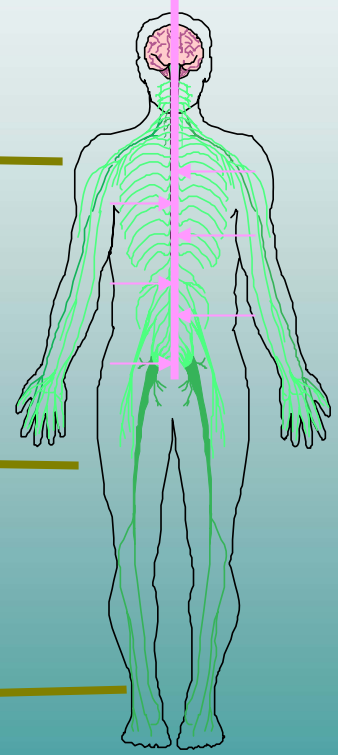
Hair follicles

adrenalin

Adrenal medulla

shivering

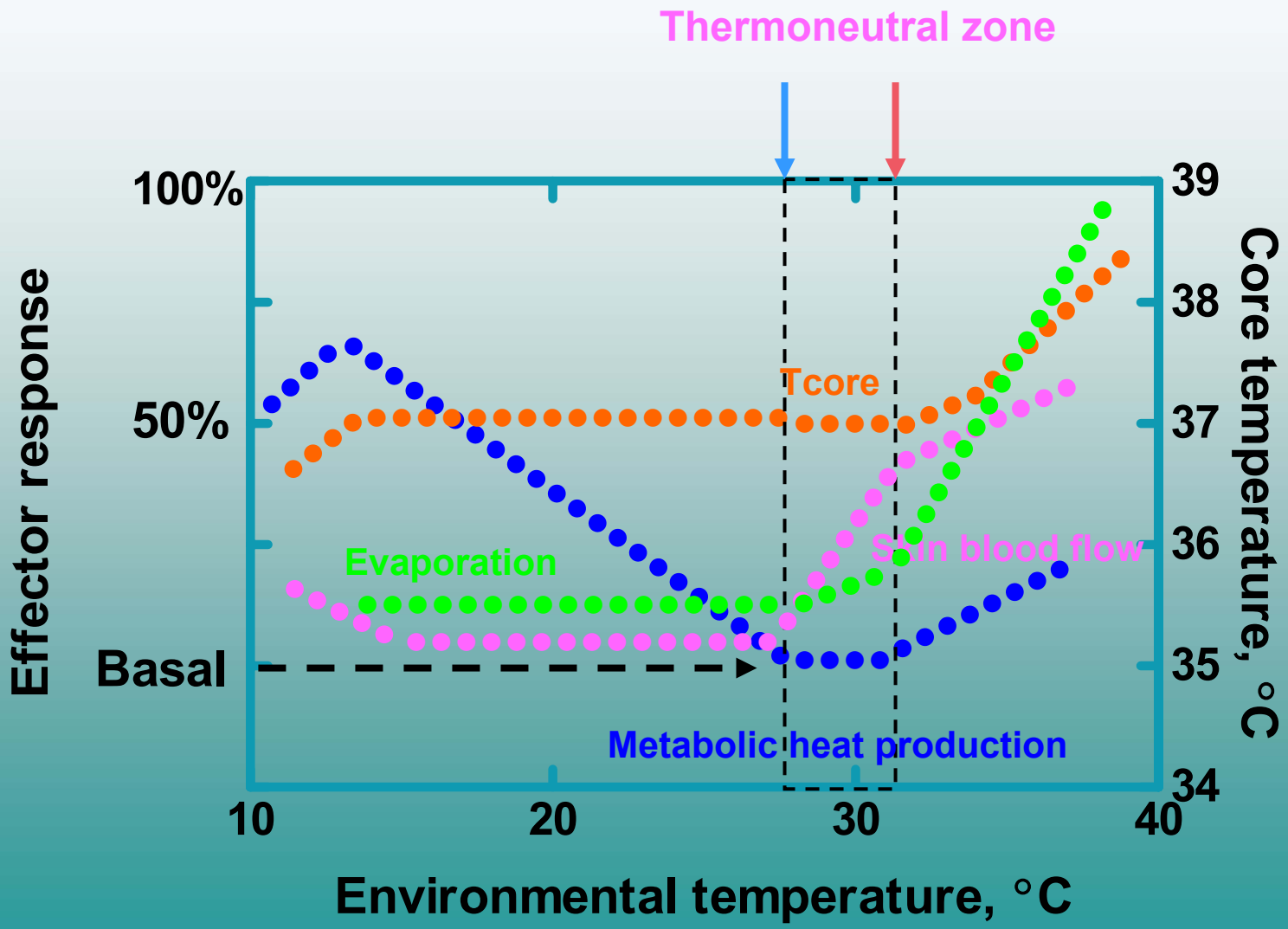
Skeletal muscle



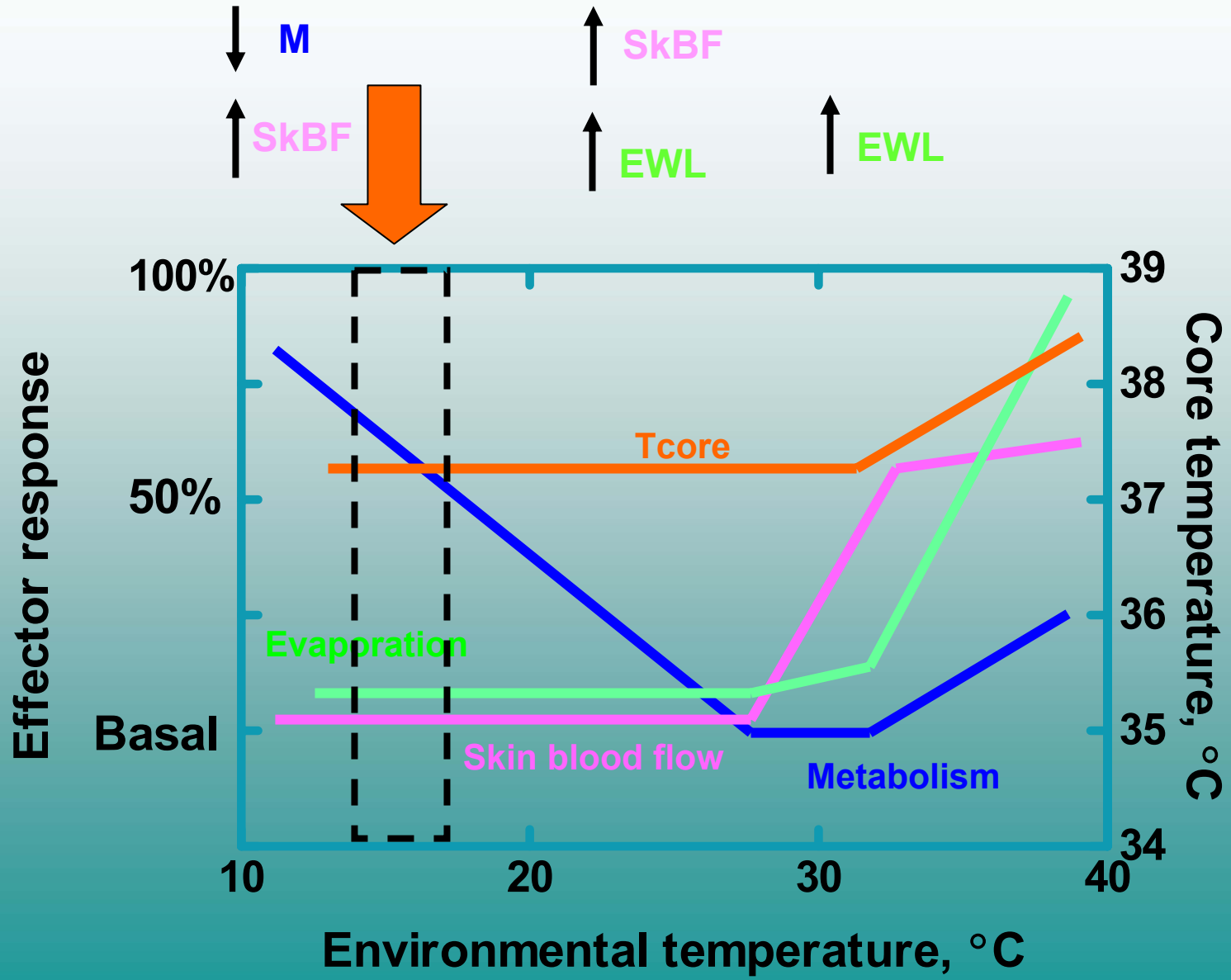
Cutaneous warm and cold receptors

COLD STRESS

THE THERMONEUTRAL PROFILE OF HOMEOTHERMS



THERMOREGULATORY OPTIONS TO RF EXPOSURE

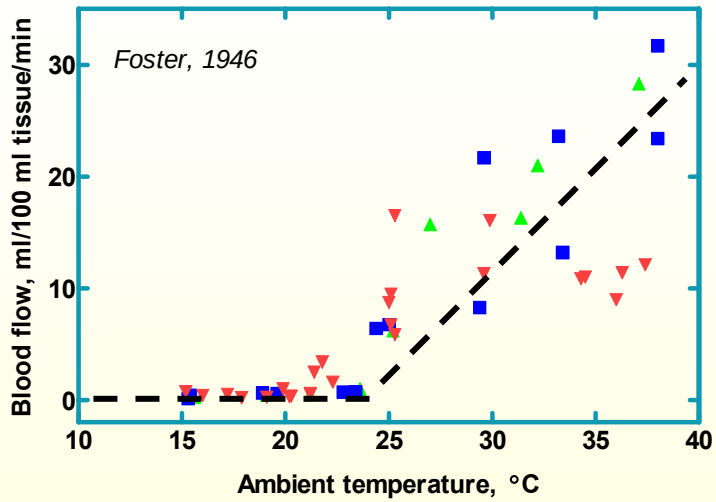


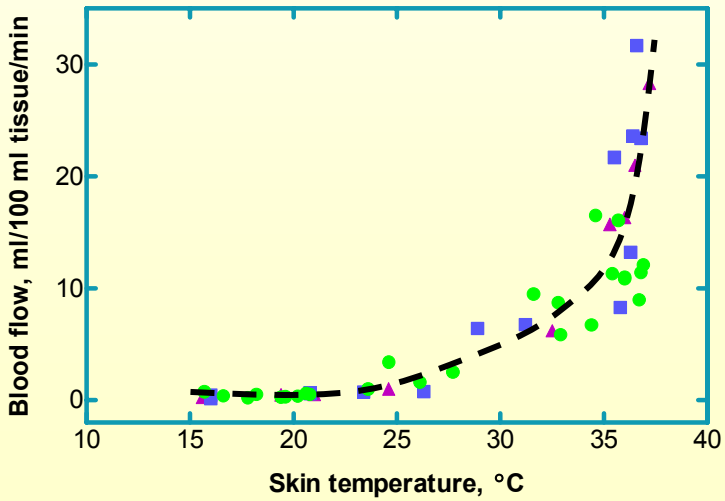
Basic characteristics of human thermoregulatory capacity in the cold

- Overall skin blood flow varies from ~150 to 2000 ml/min depending on temperature
- Below 25 °C, nude man is maximally vasoconstricted.
- Seminude man doubles metabolic rate by shivering after exposure for one hour

  to 5 °C.

Relationship between skin blood flow of the hand with ambient and skin temperature

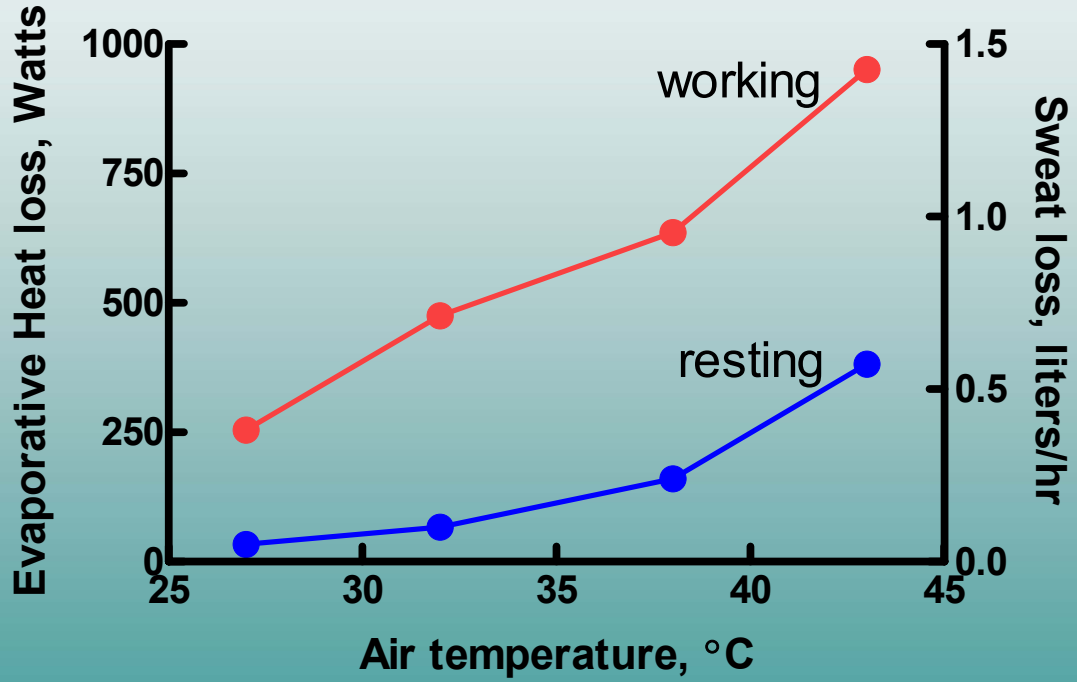




Basic characteristics of human thermoregulatory capacity in the heat

- Sweating activated during rest at air temperatures of 32-34 °C
- About 2.5 million sweat glands
- Total sweat duct area of 90 cm^2
- Working humans sweat output of 2 liter/hr for more than 5 hours (~1400 Watts)

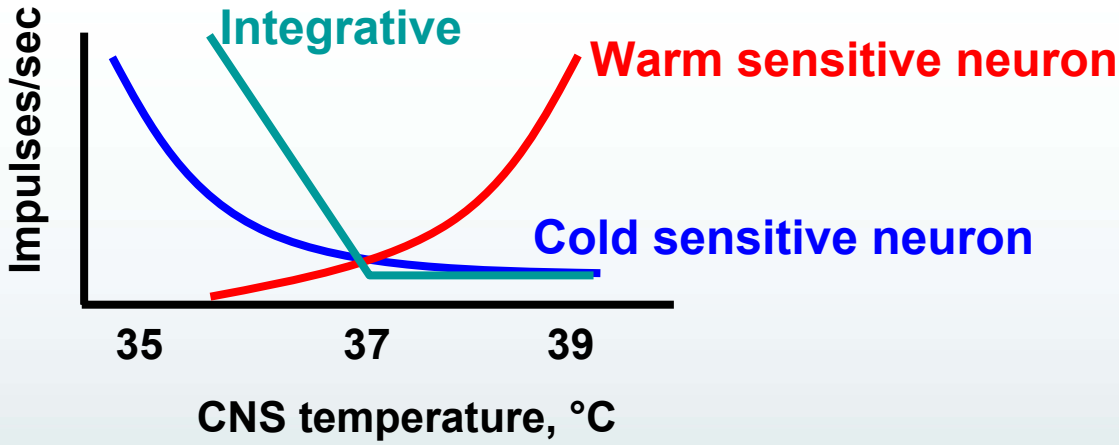
Sweating rates for clothed man during work and rest at various ambient temperatures*

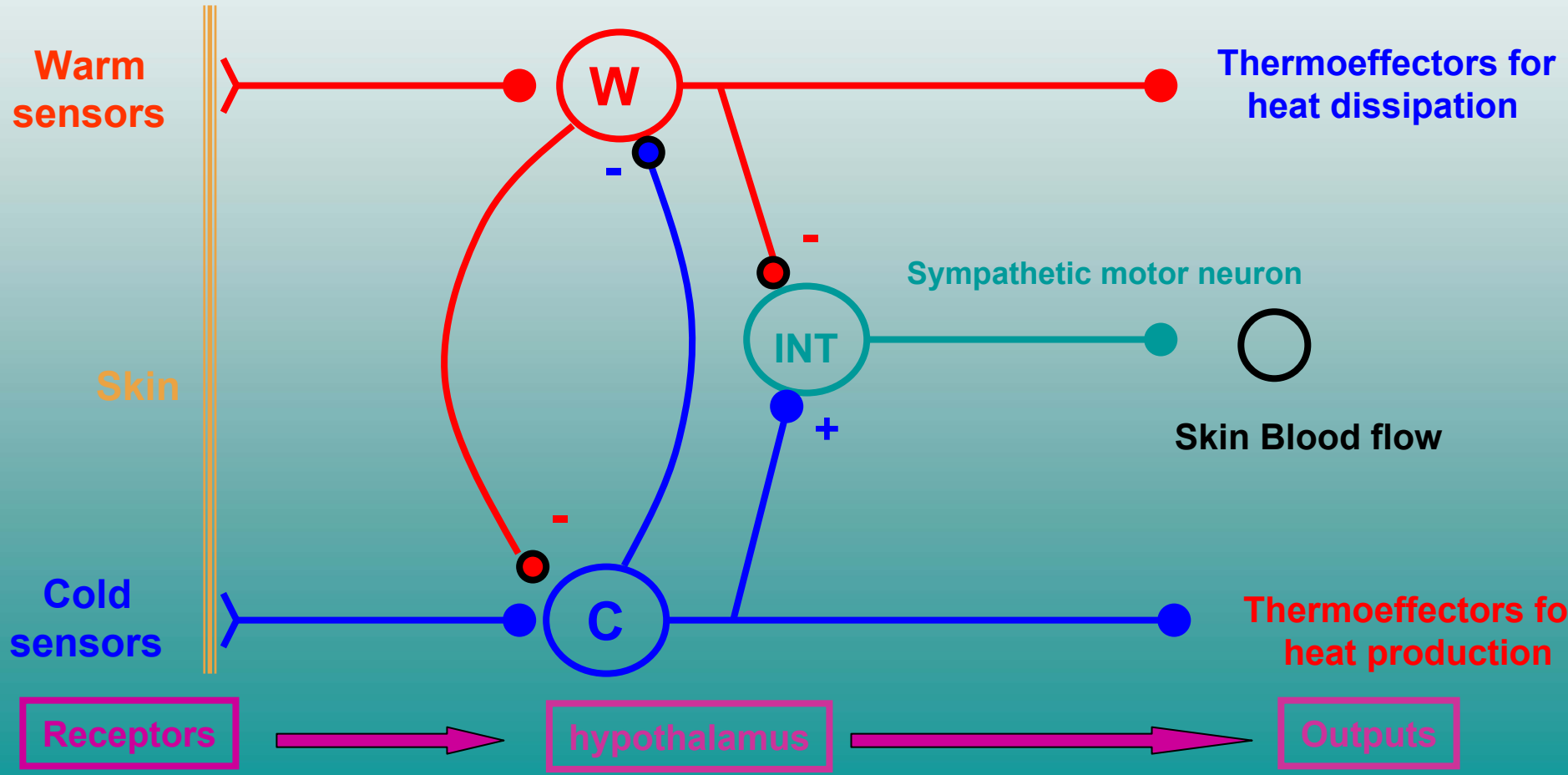


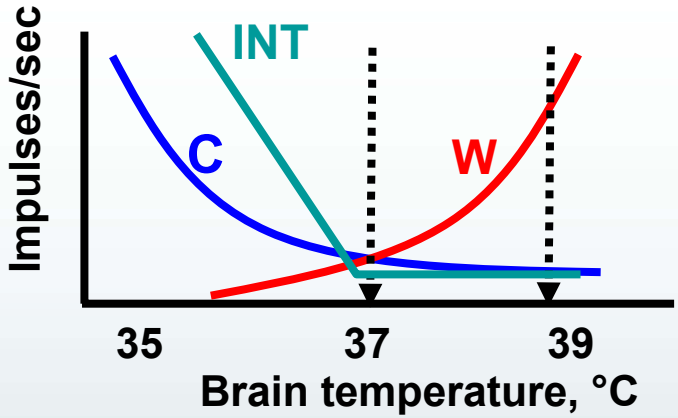
*Adolph, 1947

BASIC NEURAL MECHANISMS OF THERMOREGULATION

- Internal thermal sensitive neurons are driven by peripheral thermal stimulation


Impulses/sec
Integrative
Warm sensitive neuron
Cold sensitive neuron
35
37
39
CNS temperature, °C


Warm sensors
W
Thermoeffectors for heat dissipation
-
-
Sympathetic motor neuron
INT
Skin
+
Skin Blood flow
-
Cold sensors
C
Thermoeffectors for heat production
Receptors
hypothalamus
Outputs



FORCED HYPOTHERMIA

NORMOTHERMIA

Warm sensors

W

INT

C

Skin

Cold sensors

Sweating
Prefer cool temperature

Skin Blood flow

Shivering
Prefer warm temperature

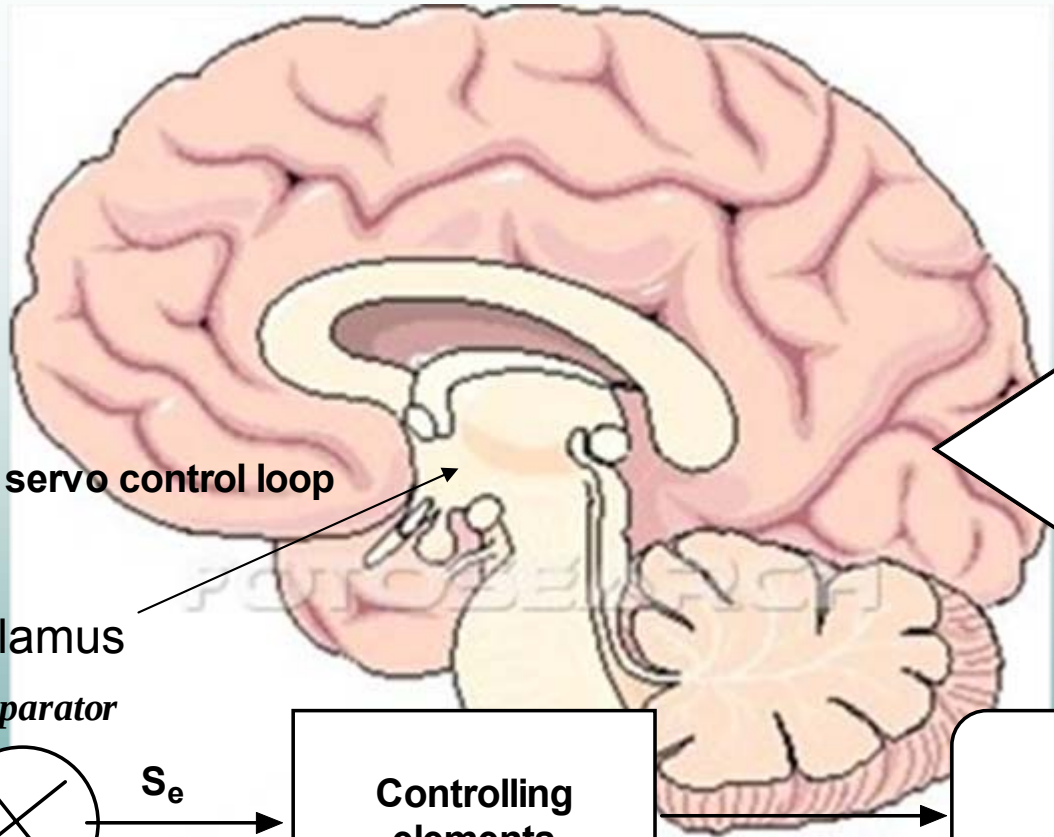
Hypothalamus

Outputs

Set-point and thermoregulation

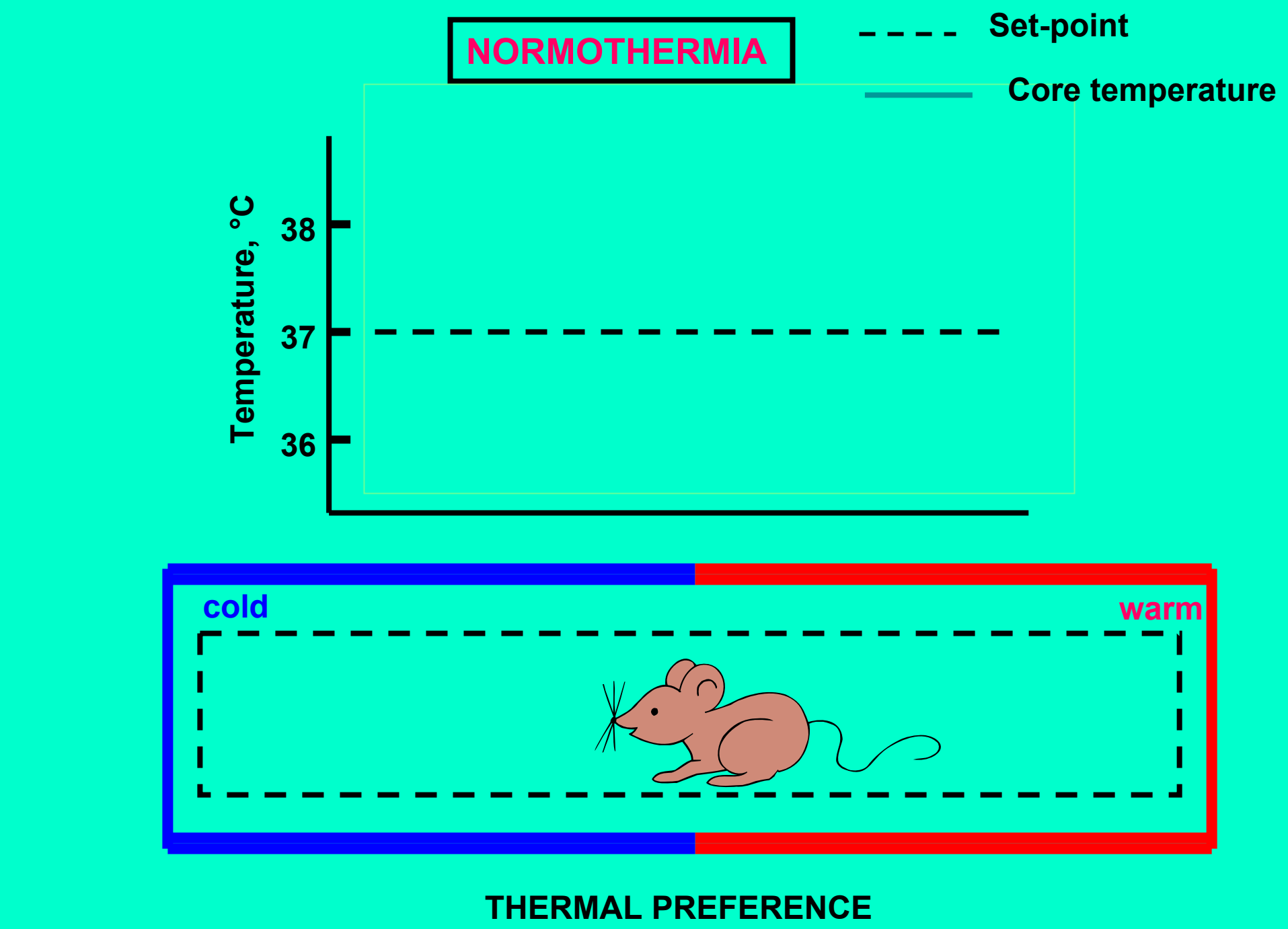
- Servo-loop thermoregulatory control remains a fundamental concept\
- Same concept can apply to local regulation of tissue temperature

Anterior hypothalamus-key site for thermoregulatory control

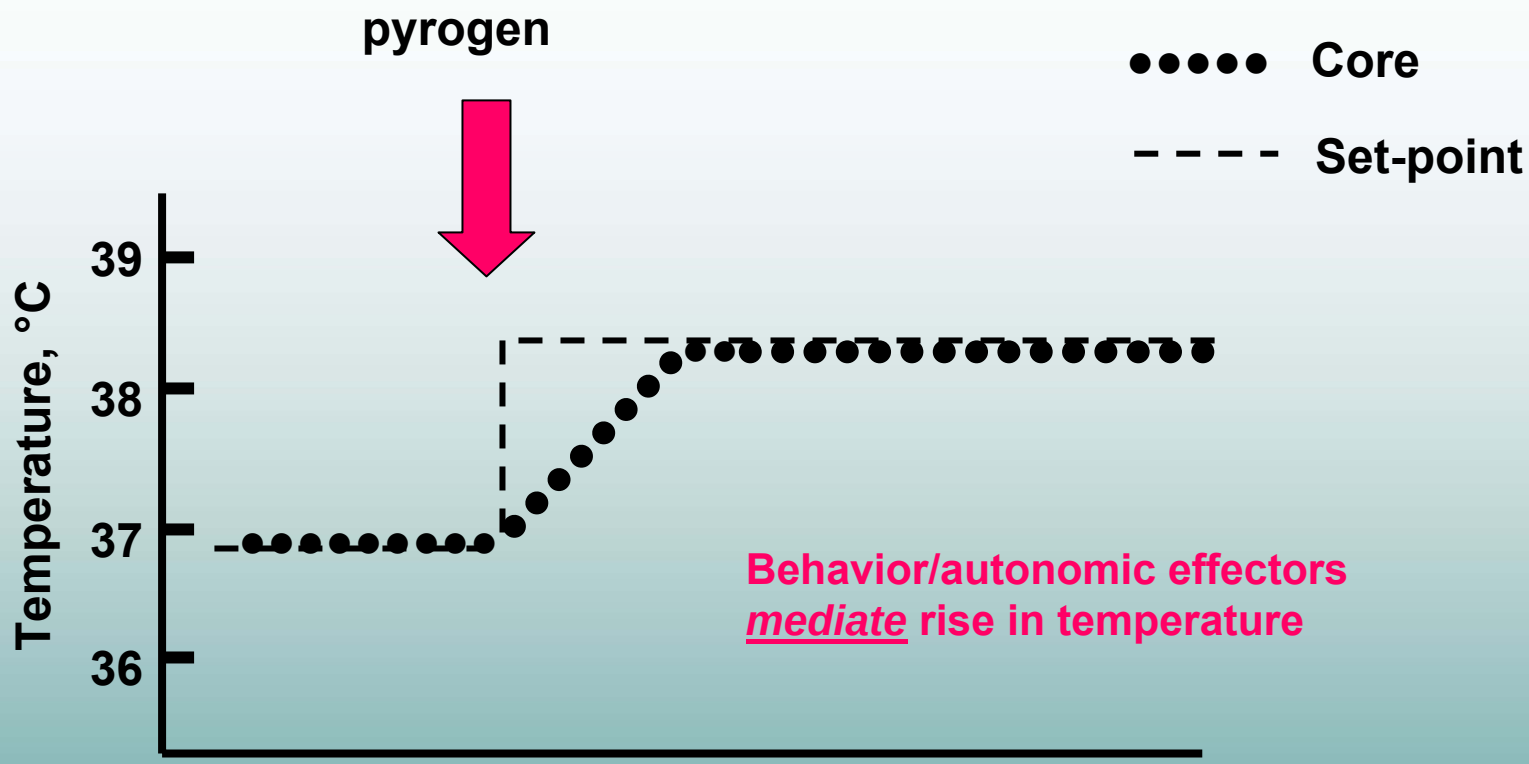


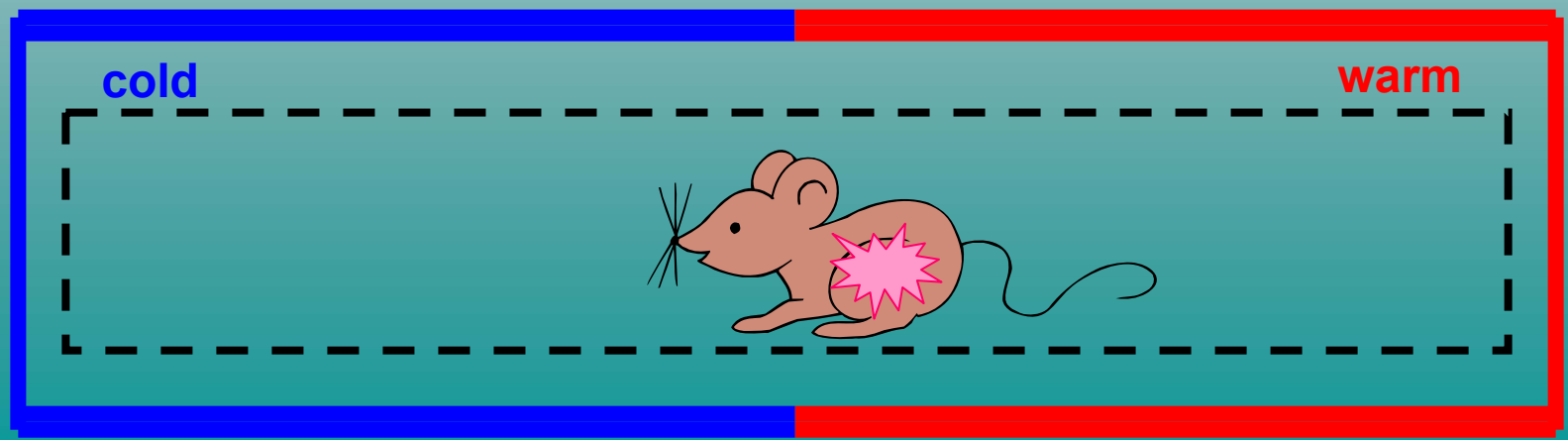
A Typical servo control loop

Anterior hypothalamus

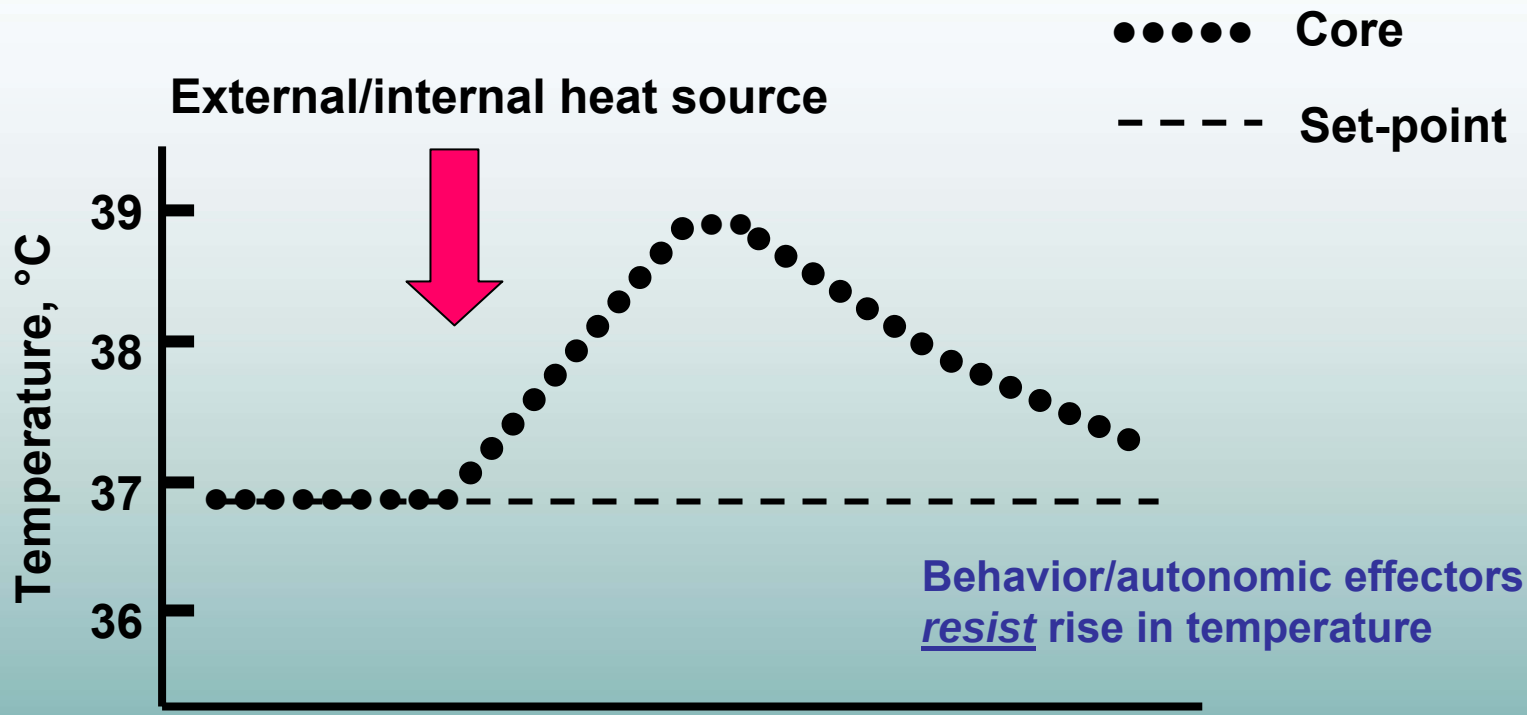

NORMOTHERMIA
Set-point
Core temperature
Temperature, °C
38
37
36
cold
warm
THERMAL PREFERENCE

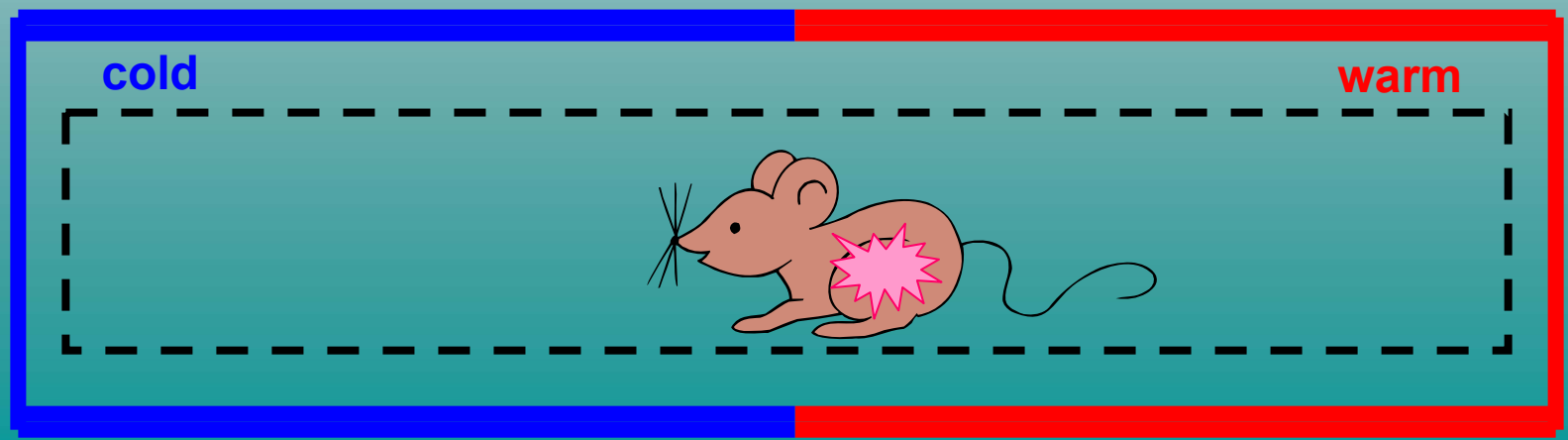
FEVER (REGULATED HYPERTHERMIA)



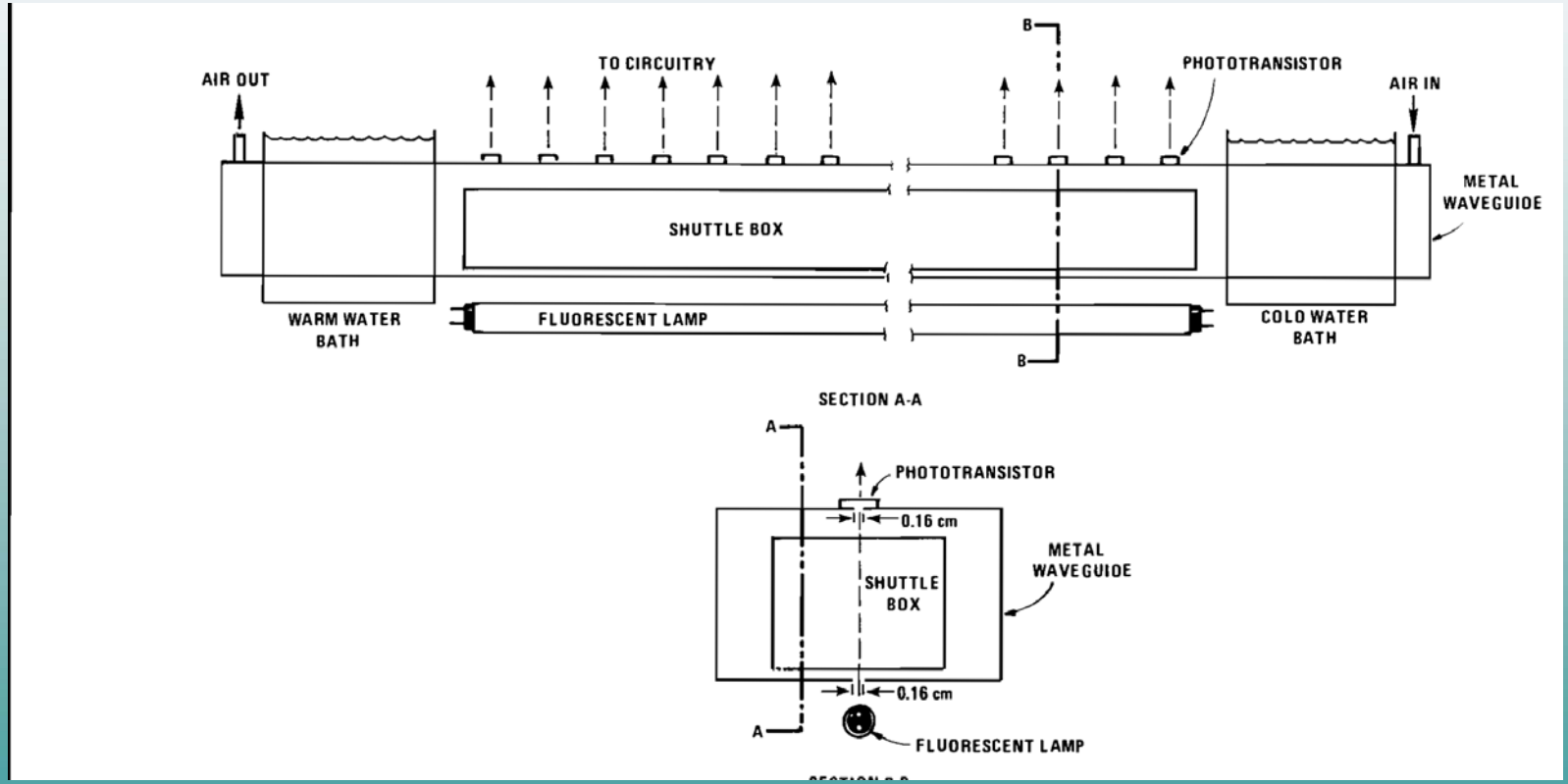


FORCED HYPERTHERMIA



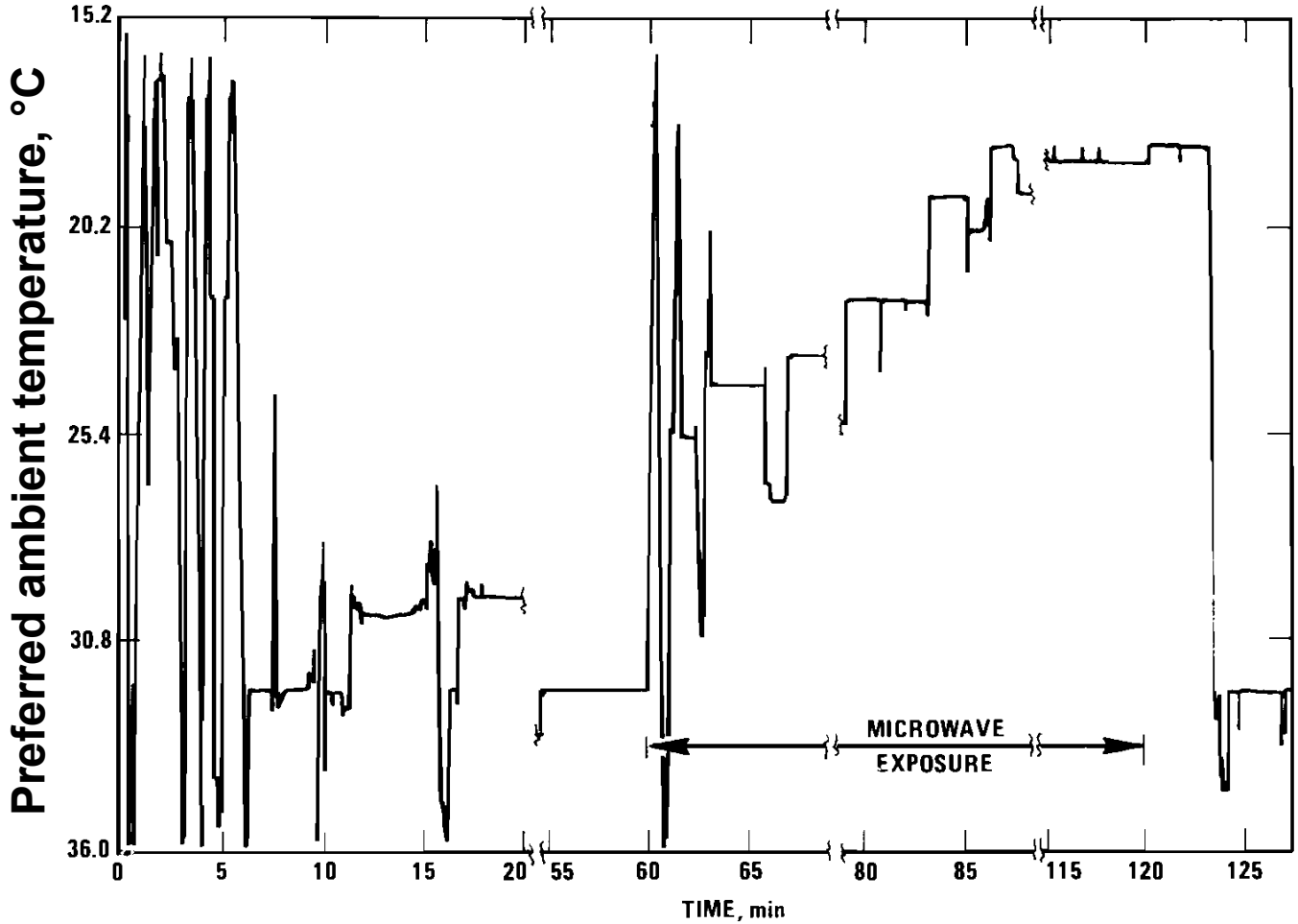


Temperature gradient to study thermoregulatory behavior of rodents exposed to 2450 MHz



Gordon et al. 1983

Behavioral thermoregulatory response of a mouse to 2450 MHz at whole body SAR of 24 W/kg



The two key questions in the study of thermoregulation and RF exposure

- SENSITIVITY

  What is the magnitude of the *error signal* required to activate heat dissipating behavioral and autonomic responses?

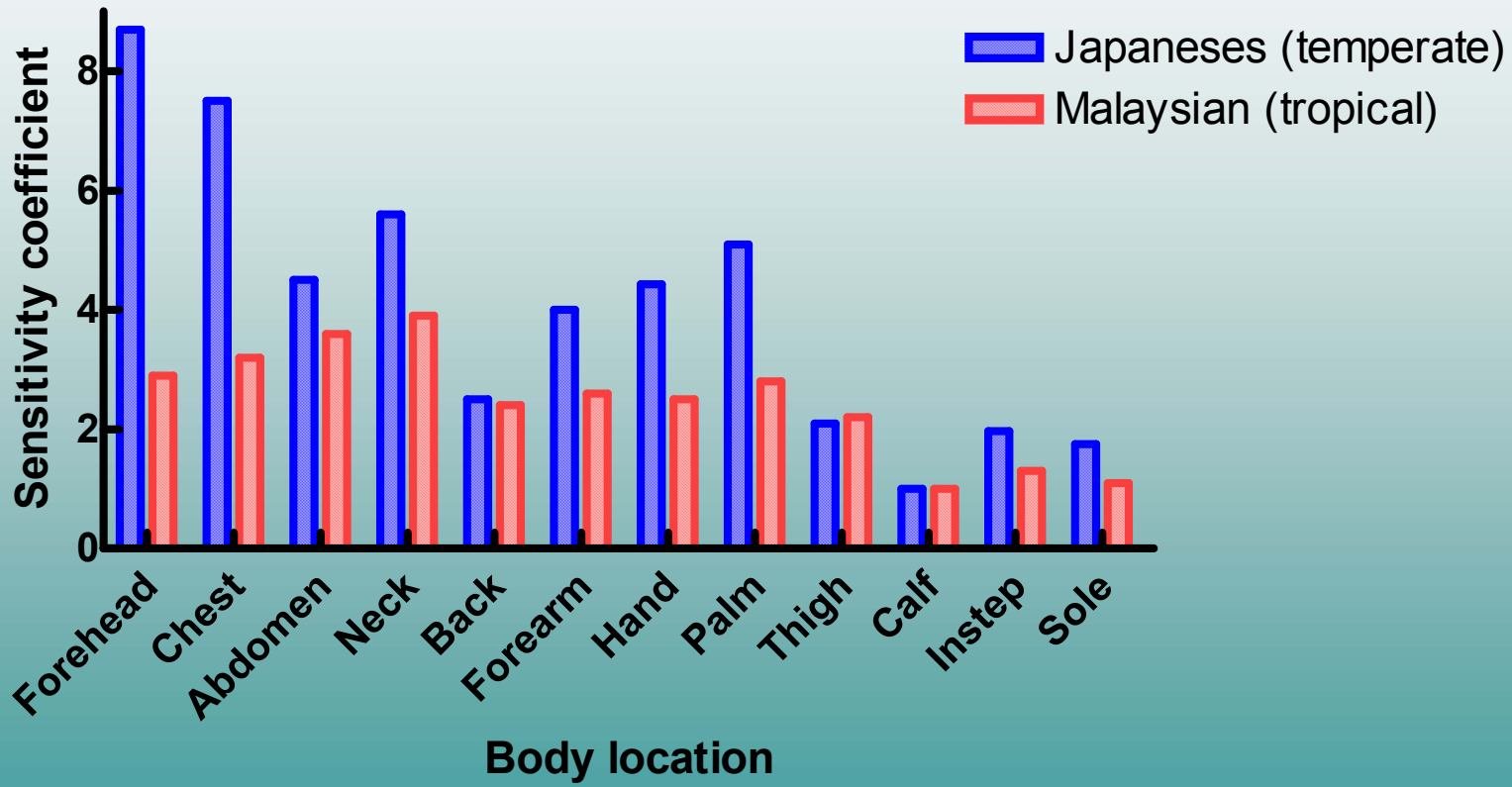
- CAPACITY

  How effective are heat dissipating *thermoeffectors* to maintain homeostasis?

Factors that can affect sensitivity

- RF frequency
- Ambient temperature (skin temperature)
- Age
- Rest vs. exercise
- Pre-existing conditions
- Genetic background
- Thermal adaptation

Thermal adaptation and warm sensation in humans adapted to temperate or tropical climate



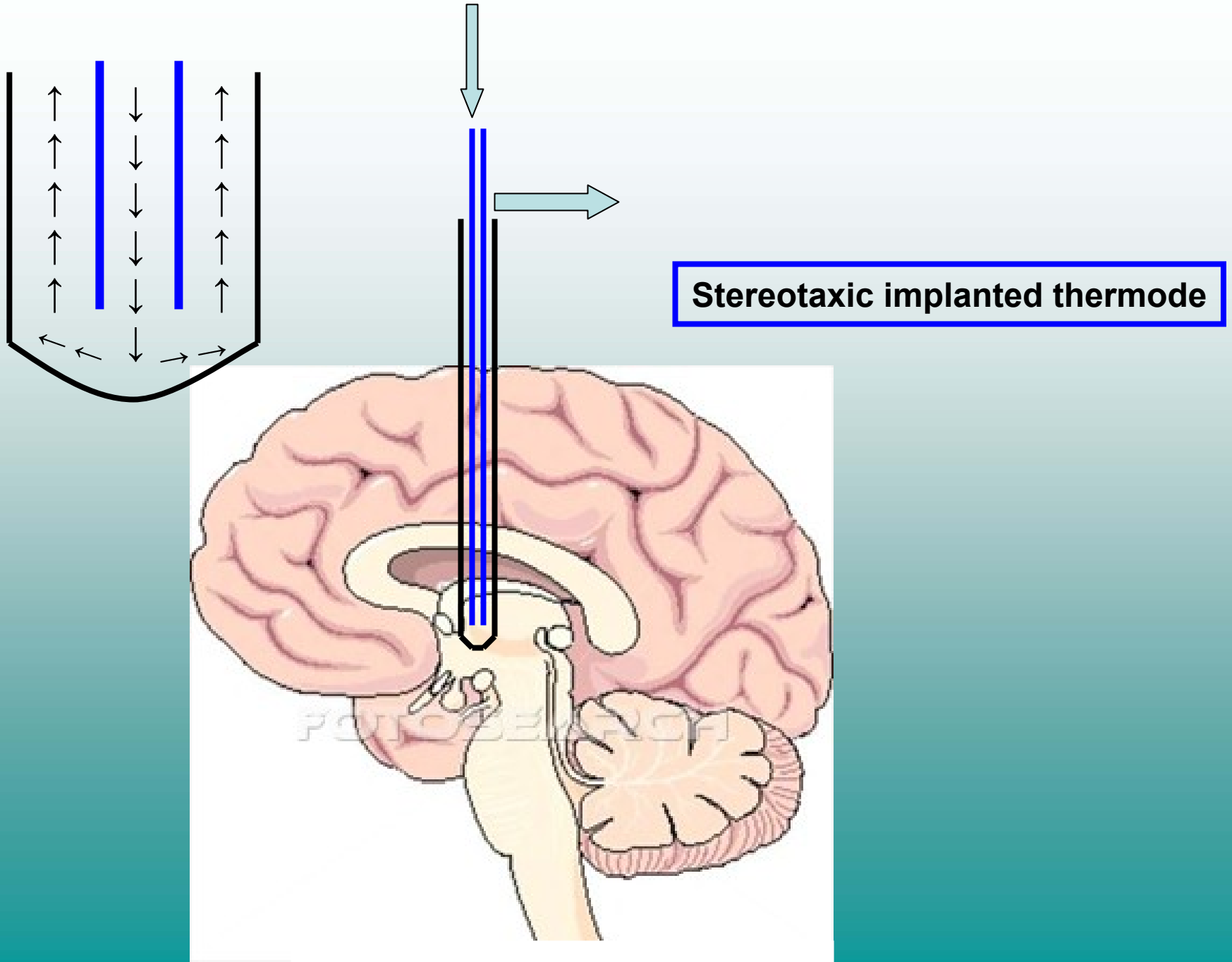
Lee et al. (2010)

Factors that could affect capacity to dissipate RF energy

- Age and health of subject
- Ambient temperature
- Relative humidity
- Acclimatization
- Genetic background

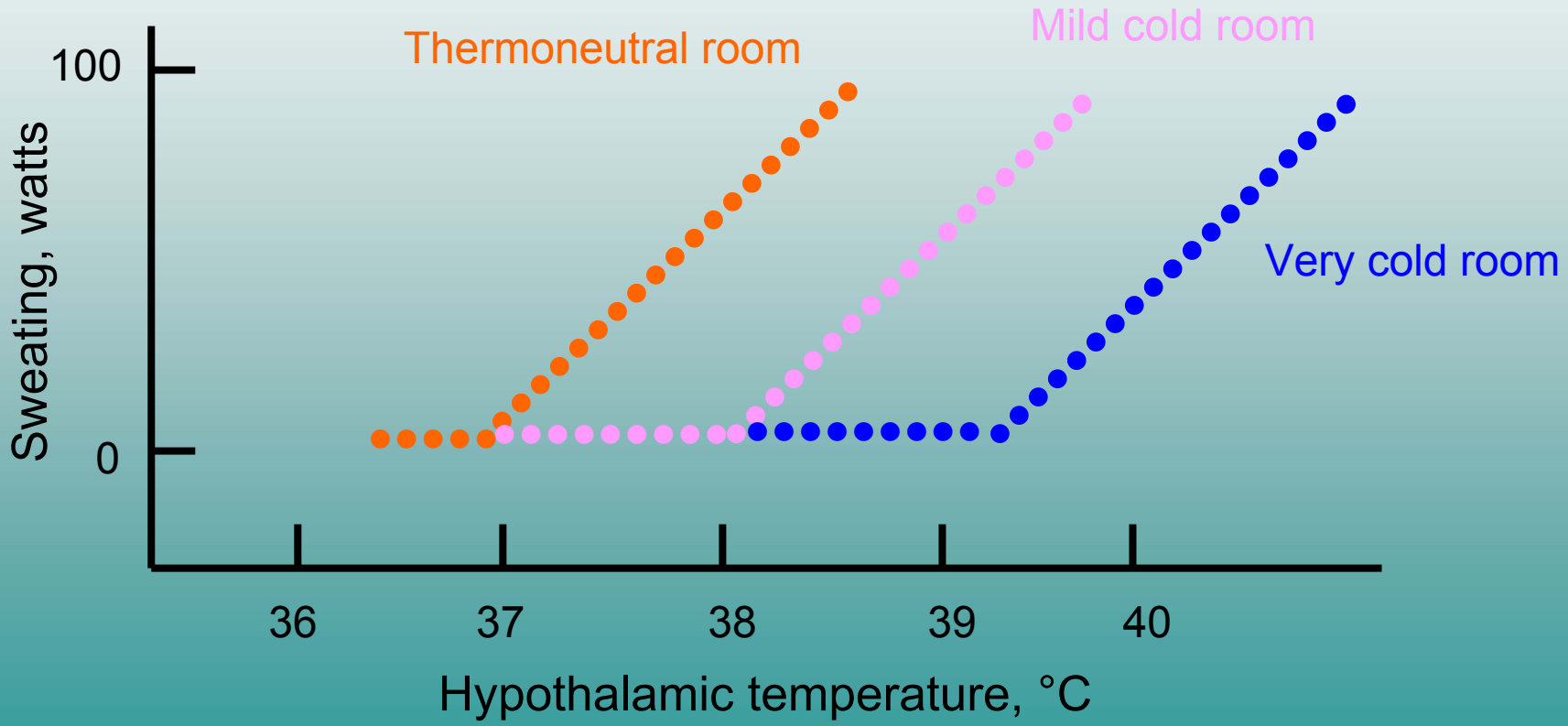
Understanding the thermal sensitivity of the CNS

- Receptors evolved in lower vertebrates to respond to change in body temperature
- Homeotherms respond to changes in skin/shell temperature
- Central receptors critical in exercise and fever
- Thermal sensitivity can be characterized with artificial stimulation

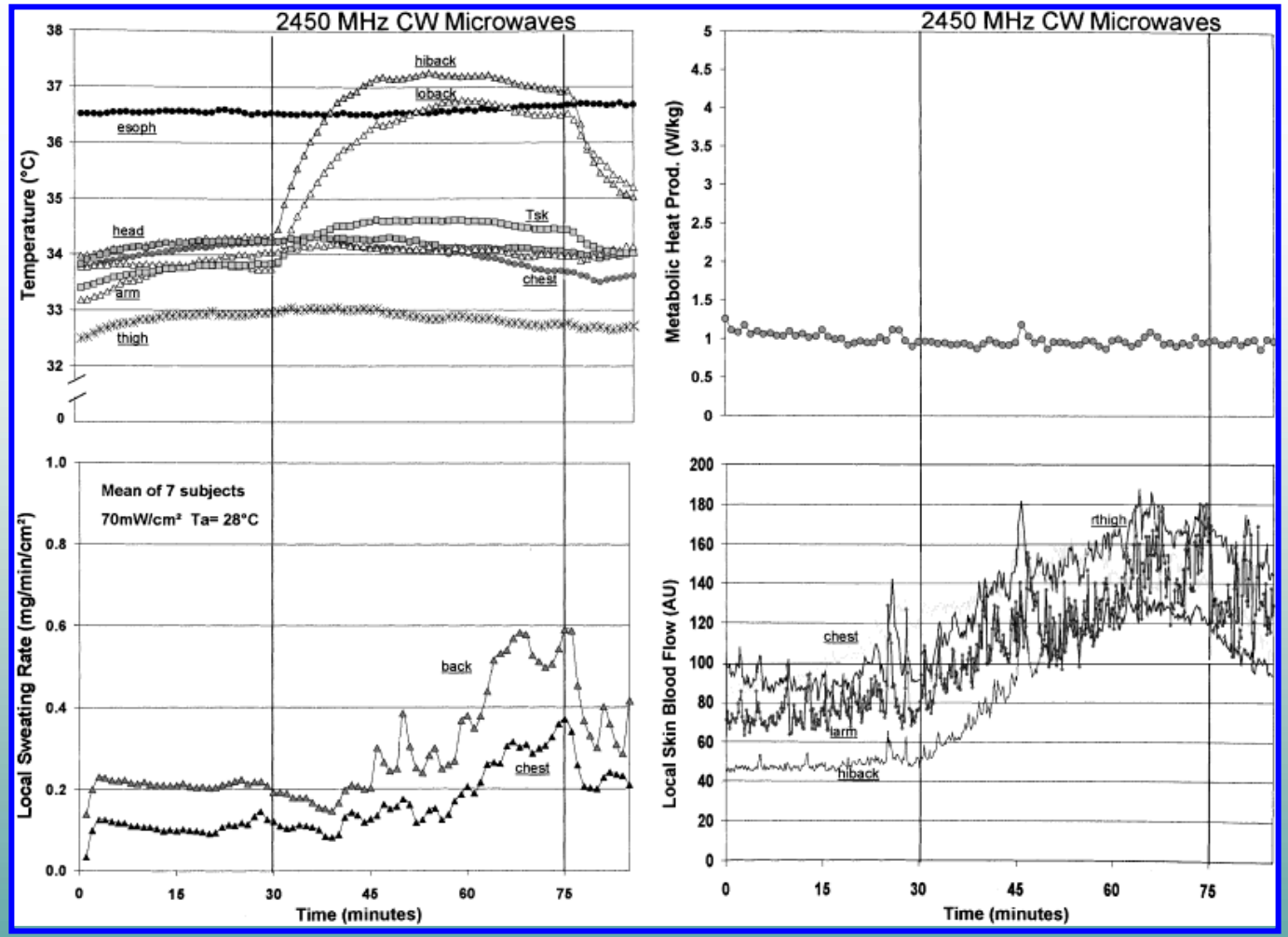

Stereotaxic implanted thermode

Predicted thermoregulatory response to hypothalamic heating

$$\text{Response (sweating)} = \alpha(T_{brain} - T_{set}) + \beta(T_{skin} - T_{set})$$



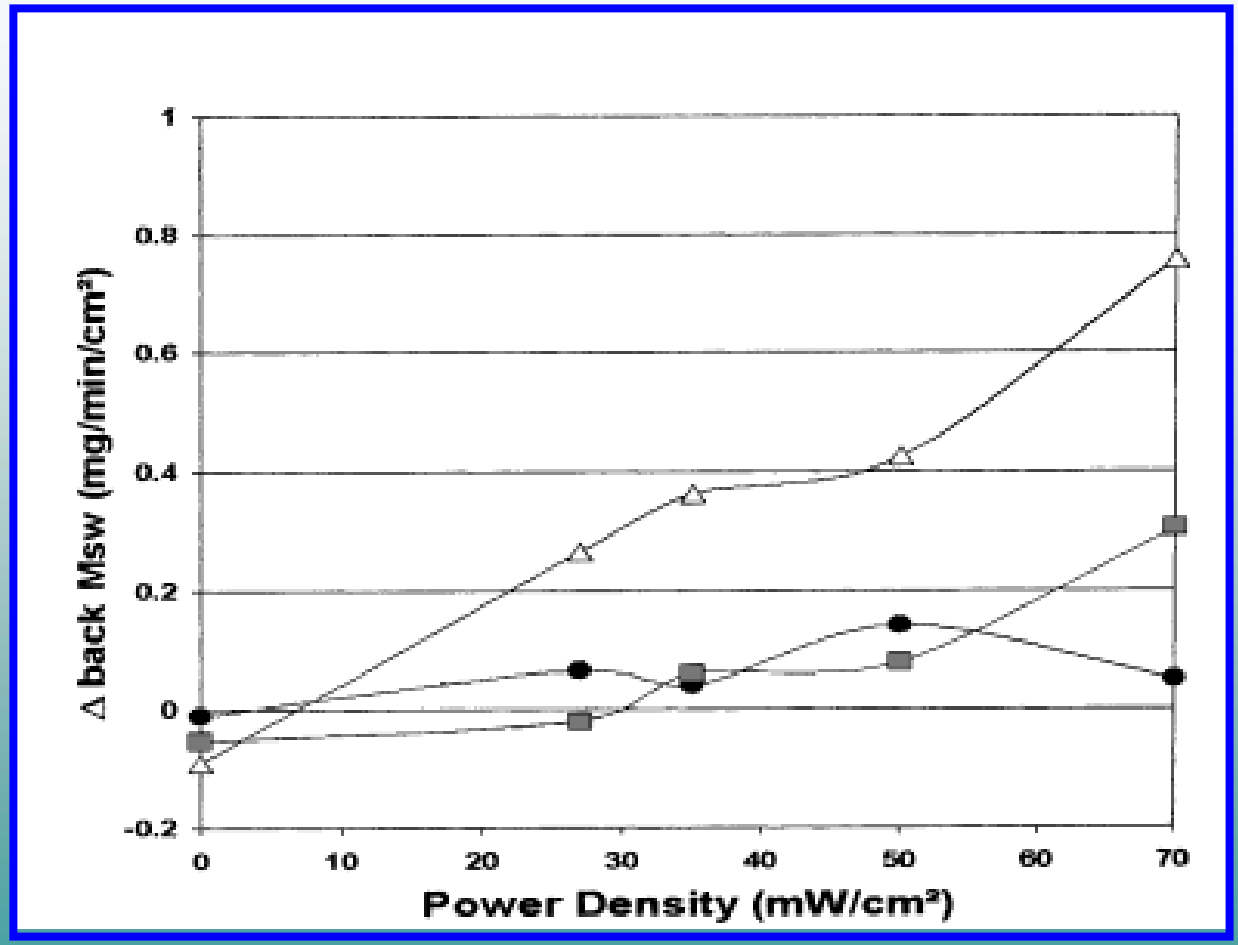
Thermoeffector responses to RF radiation in humans



Mean response of 7 volunteers to exposure to 2450 MHz (70 mW/cm2) at an ambient temperature of 28 °C (SAR≈1.0 W/kg). From Adair et al. (2001).

Mean response of 7 volunteers to exposure to 100 MHz (8 mw/cm^2) at an ambient temperature of 31 °C (SAR≈0.54 W/kg). From Adair et al. (2003).

Sweating response of seven human subjects to 2450 MHz exposure at three ambient temperatures

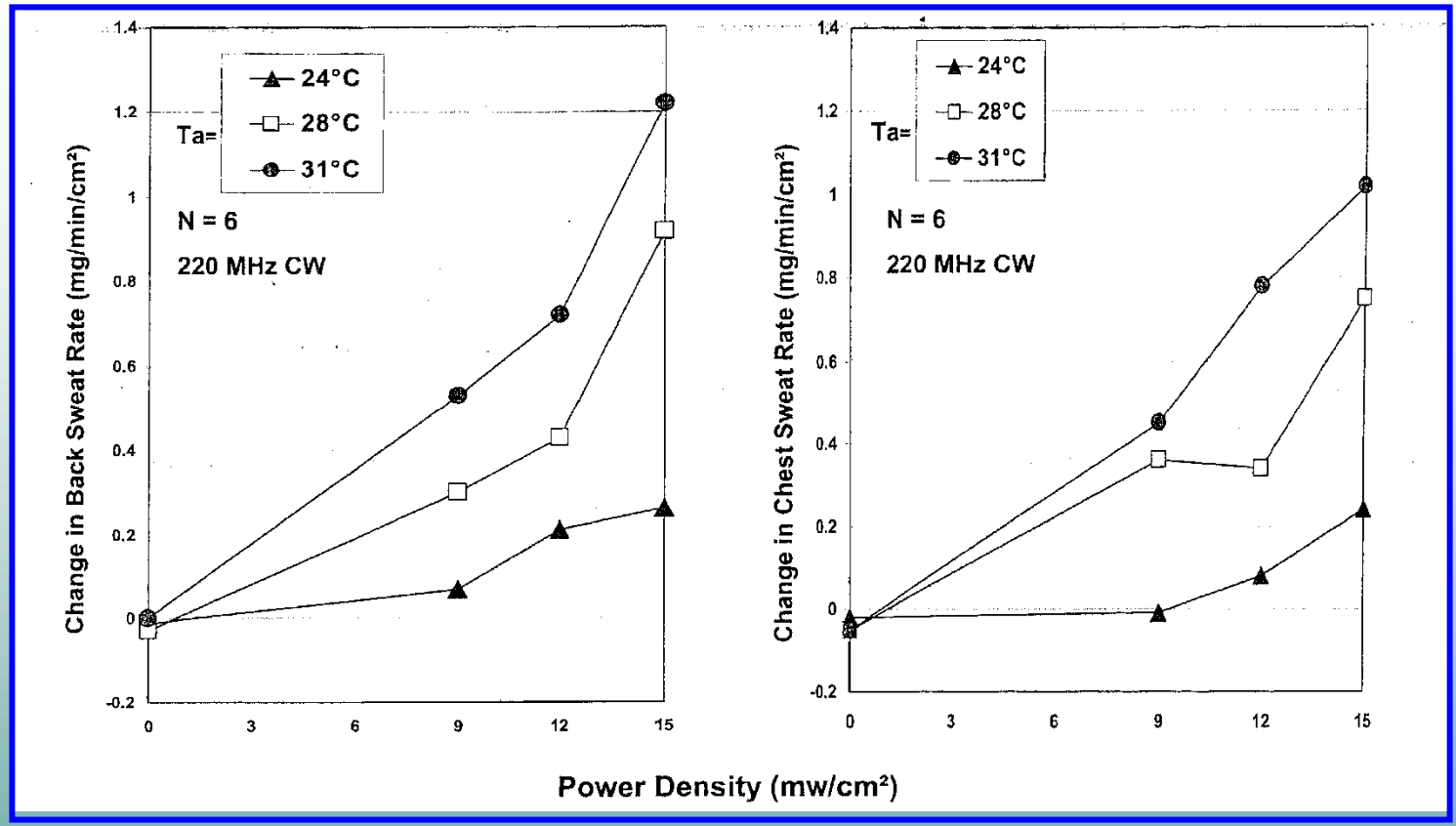


T_a=31 °C

T_a=28 °C

T_a=24 °C

Adair et al. 2001



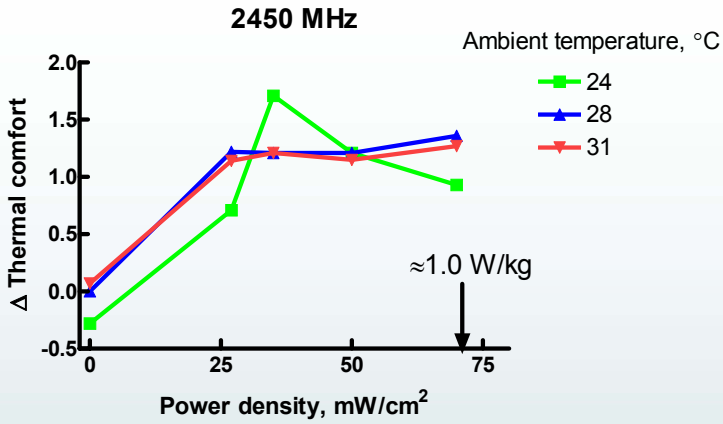
Sweating response at different ambient temperatures of humans exposed To 220 MHz RFR. Adair et al. 2005

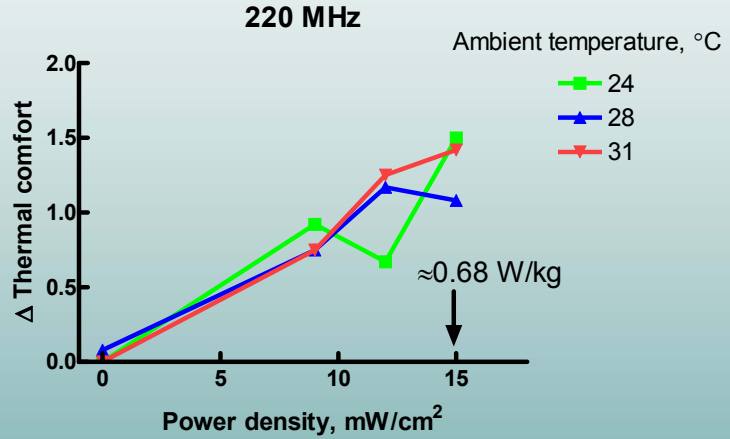
Thermoregulatory behavior

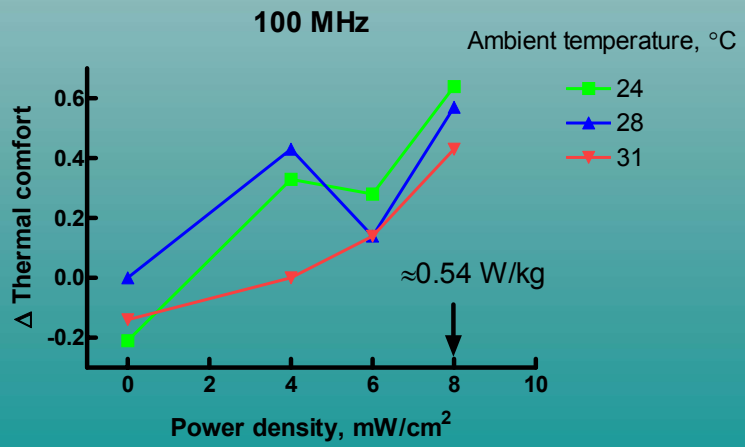
- Sensitive and effective thermoregulatory response
- Our first warning of impending thermal stress and heat-induced damage

Thermal comfort scale

Comfortable	0
Slightly uncomfortable	1
Uncomfortable	2
Very uncomfortable	3
Intolerable	4







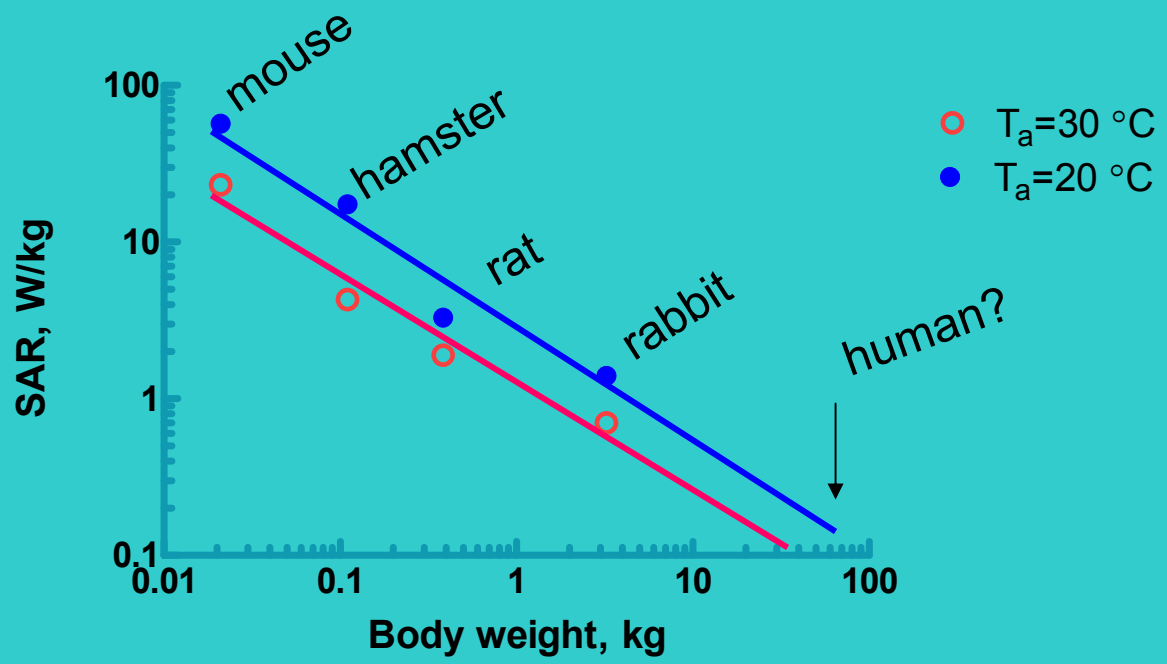
From Adair et al

CAPACITY TO THERMOREGULATE DURING EXPOSURE TO RF RADIATION

- Body size critical when dose of RF normalized to body weight
- Important in interspecies extrapolation

THRESHOLD SAR ASSOCIATED WITH ELEVATION IN CORE TEMPERATURE

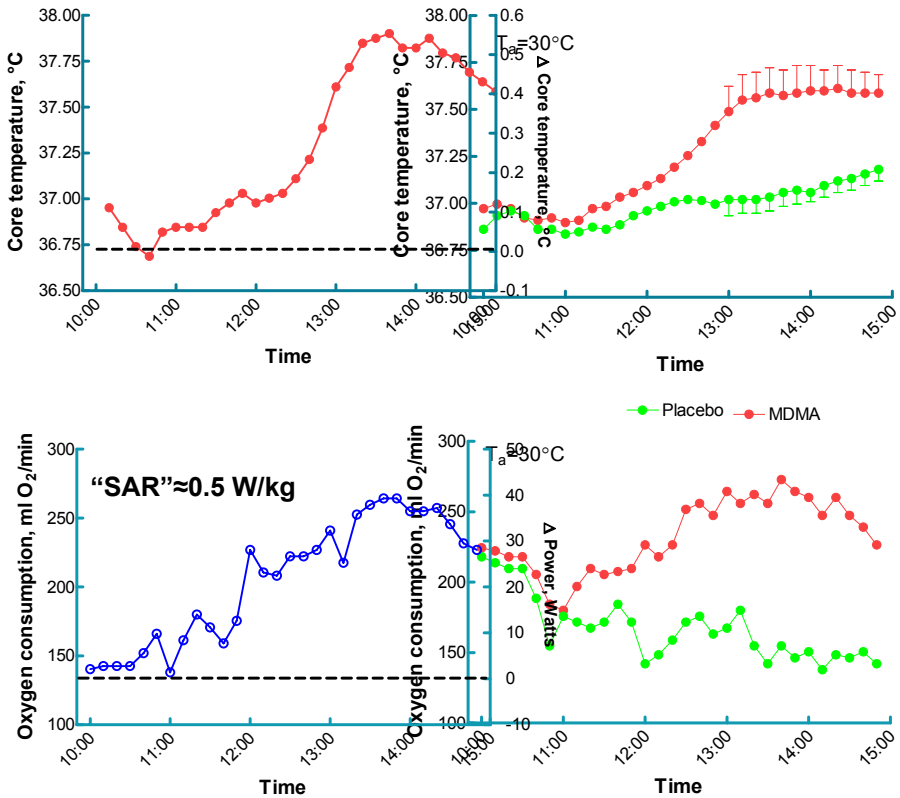
SAR ASSOCIATED WITH 1.0 °C RISE IN CORE TEMPERATURE



Comparing response to RF to other types of hyperthermia

- RF heat is a unique environmental stress
- Exercise-induced hyperthermia is a coordinated physiological response
- Drug- and fever-induced hyperthermia are also unique

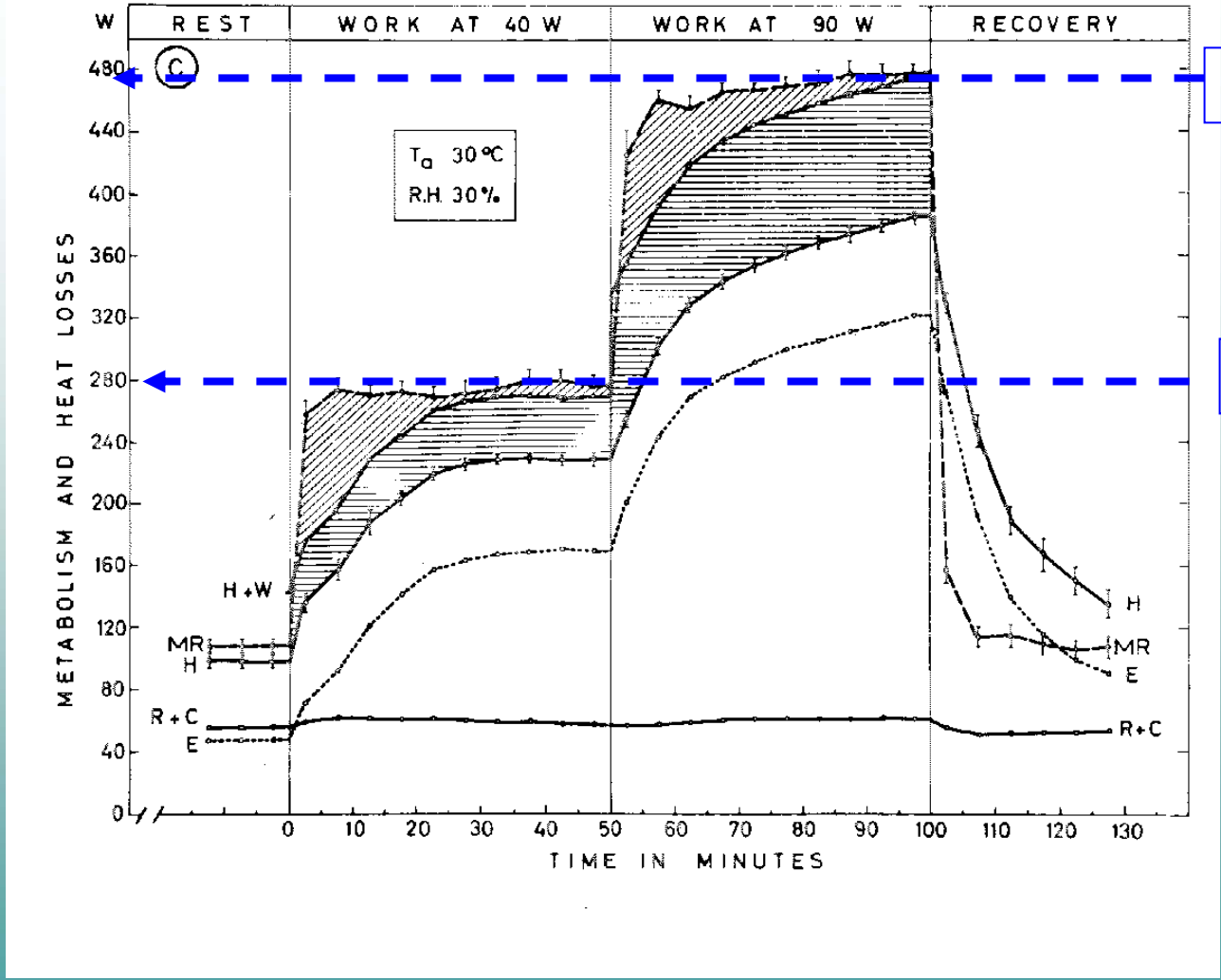
Drug-induced hyperthermia (MDMA; “ecstasy)
Relating metabolic heat production and hyperthermia



100 ml O_2/min~33.5 Watts

Freedman et al. 2008

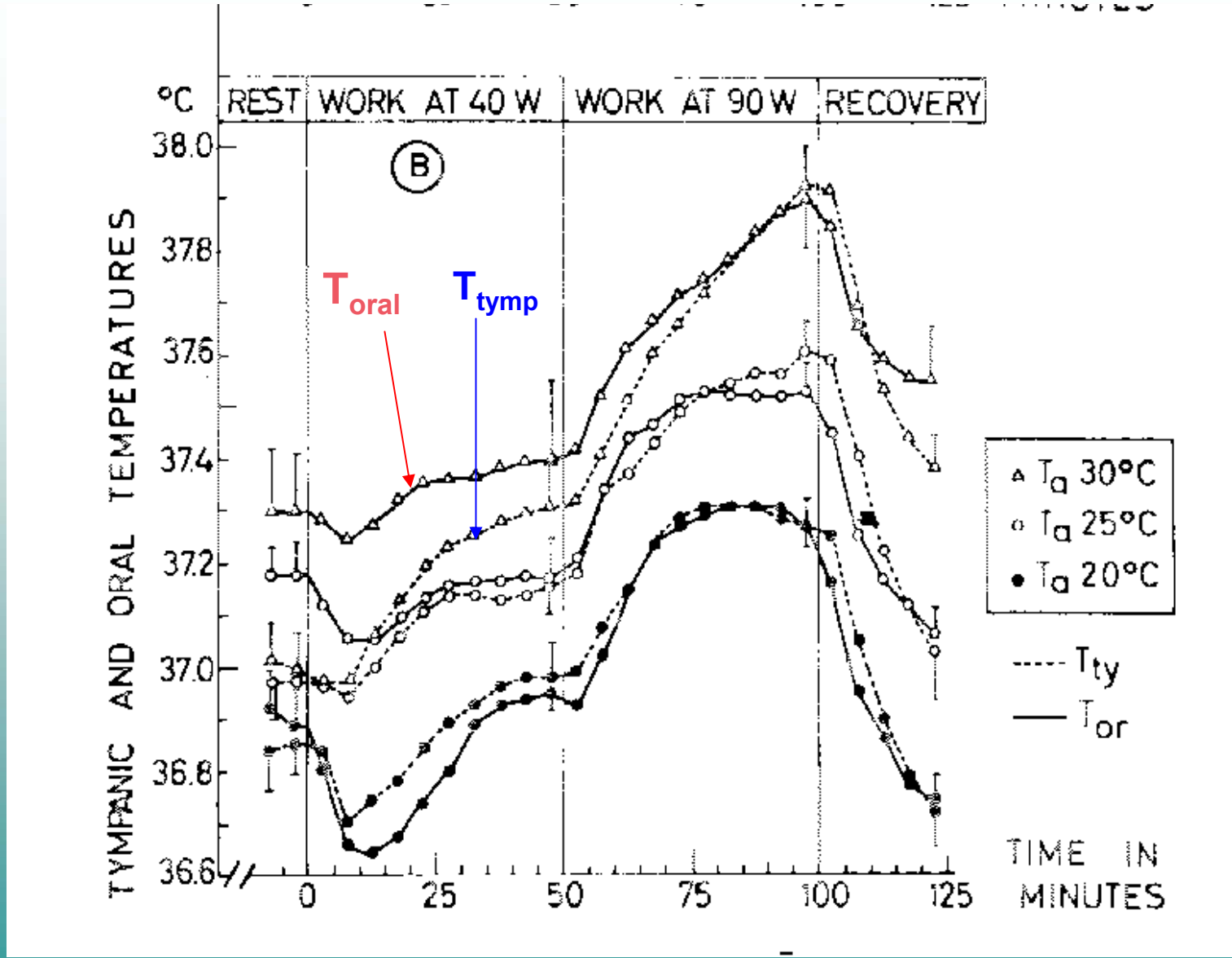
EXERCISE-INDUCED CHANGES IN CORE TEMPERATURE



"SAR"≈5.4 W/kg

"SAR"≈2.4 W/kg

Thermoregulatory response of 11 subjects during exercise on bicycle ergometer. Chappuis et al. 1976.


°C
REST
WORK AT 40 W
WORK AT 90 W
RECOVERY
B
38.0
37.8
37.6
37.4
37.2
37.0
36.8
36.6
TYMPANIC AND ORAL TEMPERATURES
T oral
T tymp
0
25
50
75
100
125
TIME IN MINUTES
Ta 30°C
Ta 25°C
Ta 20°C
Tty
Tor

Summary of thermal effects of various treatments in humans at ambient temperature of 30 °C

Treatment	"SAR"	ΔT_{core}
• Drug (MDMA)	0.5 W/kg	~0.6 °C
• Exercise	2.4 W/kg	~ 0.1 °C
• Exercise	5.4 W/kg	~ 0.5 °C
• 2450 MHz	1.0 W/kg	~0.15 °C
• 100 MHz	0.5 W/kg	~0.1 °C