Chapter 7

Energy Metabolism and Body Temperature

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Section 1 Energy Metabolism

Section Outline

- Energy metabolism
- Factors affecting the metabolic rate
- Basal metabolism

Metabolism

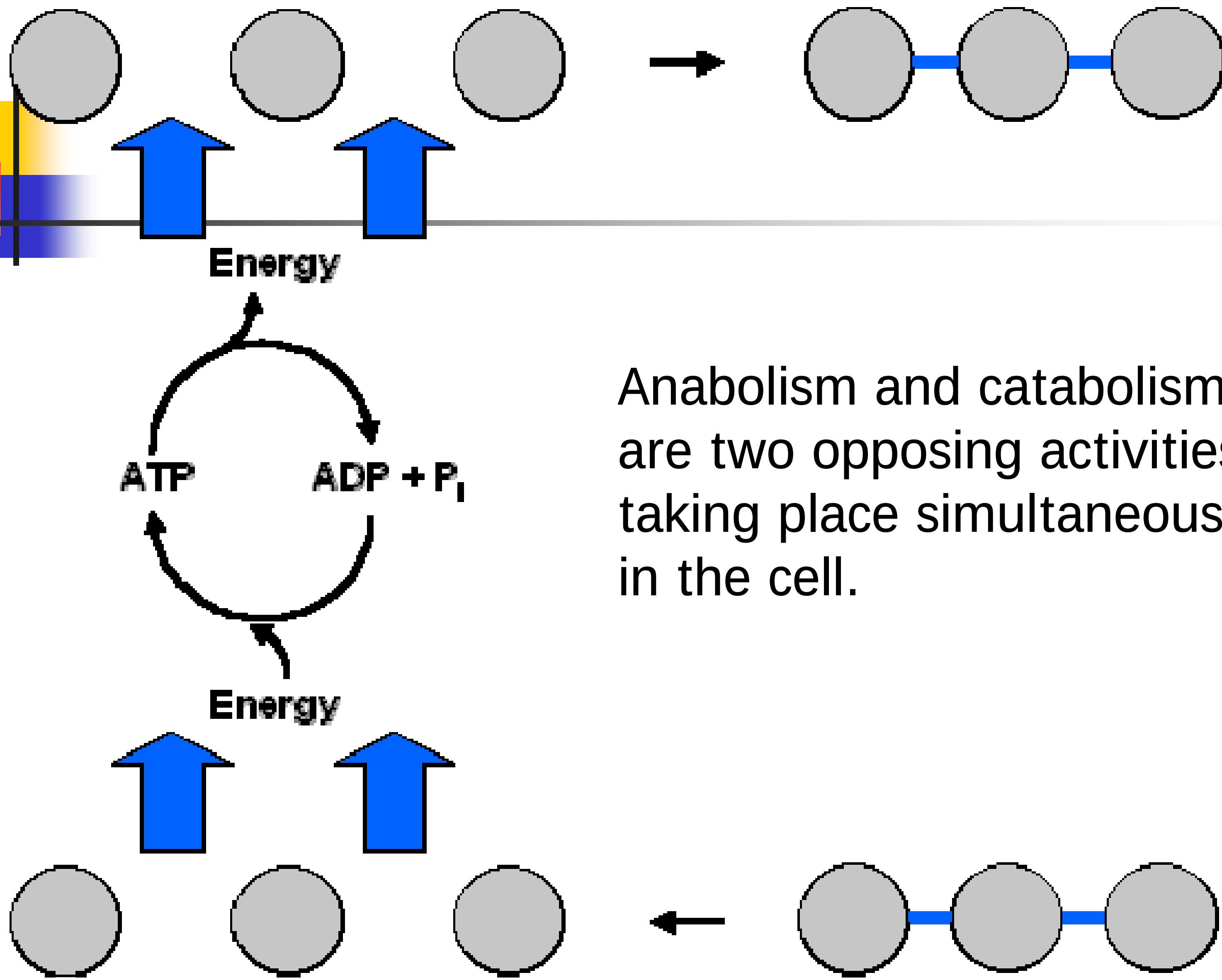
Material metabolism

Anabolism: take up energy

Catabolism: liberate energy

Energy metabolism

Anabolism(take up energy)

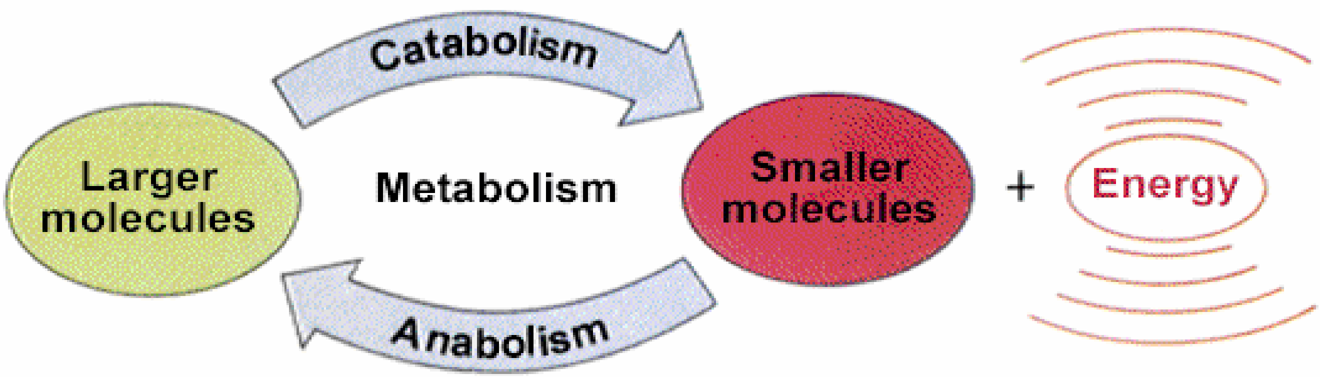


Anabolism and catabolism are two opposing activities taking place simultaneously in the cell.

Catabolism (liberate energy)

1.Energy metabolism

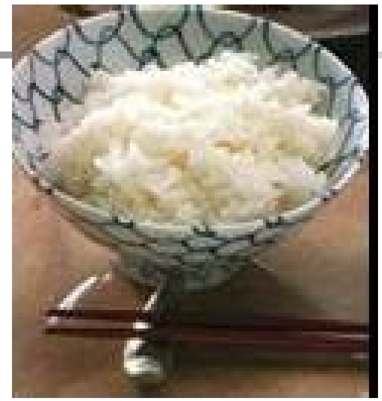
Energy metabolism: the production, storage, transformation, release and utility of energy during the process of material metabolism.



Energy sources

Carbohydrates: mainly glucose

70%



protein

Skeletization
cachexia

Fat

30%

Carbohydrate

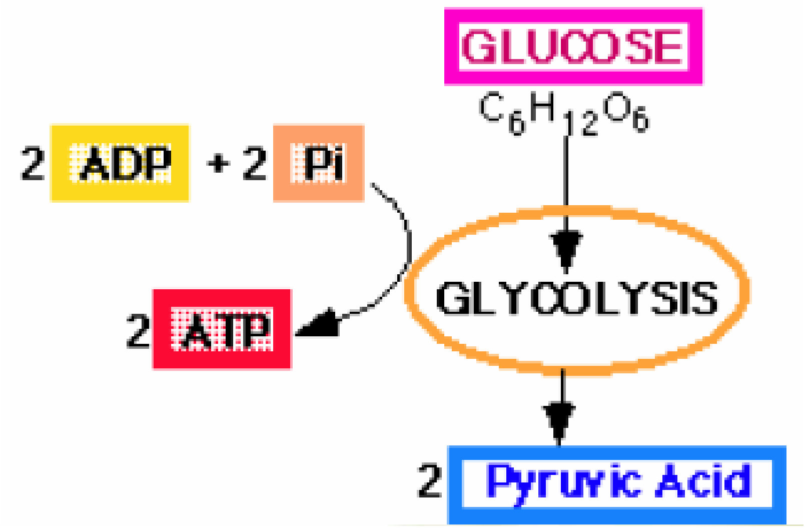
Glucose

Glucose: a major energy source

Enter into cells

Glucose 6-phosphate

- Polymerized into glycogen
- Catabolized
  - Aerobic oxidation: 38mol ATP/glucose
  - Glycolysis: 2mol ATP/glucose



Fat

Major form of energy storage

Alternative Energy Source

Proteins

Proteins are made up of amino acids.

In contrast to glucose and fatty acids, amino acids can be stored until needed.

Energy Transformation

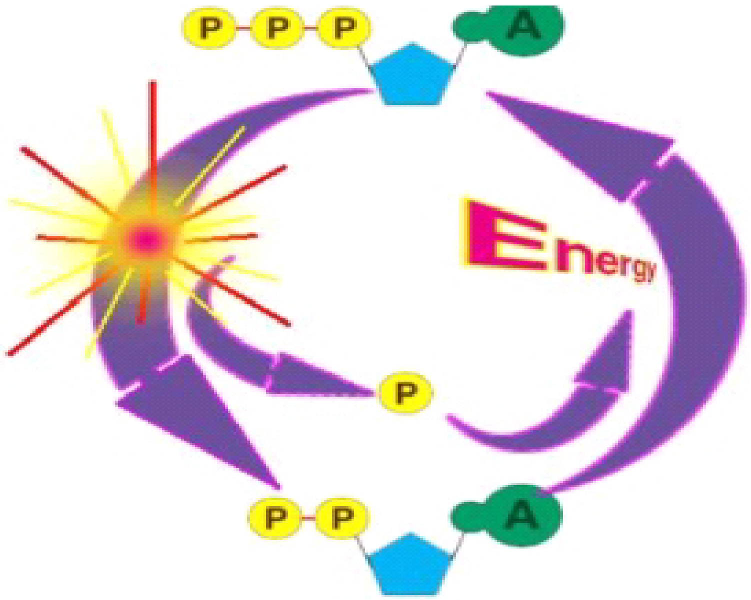
High-energy phosphate compounds

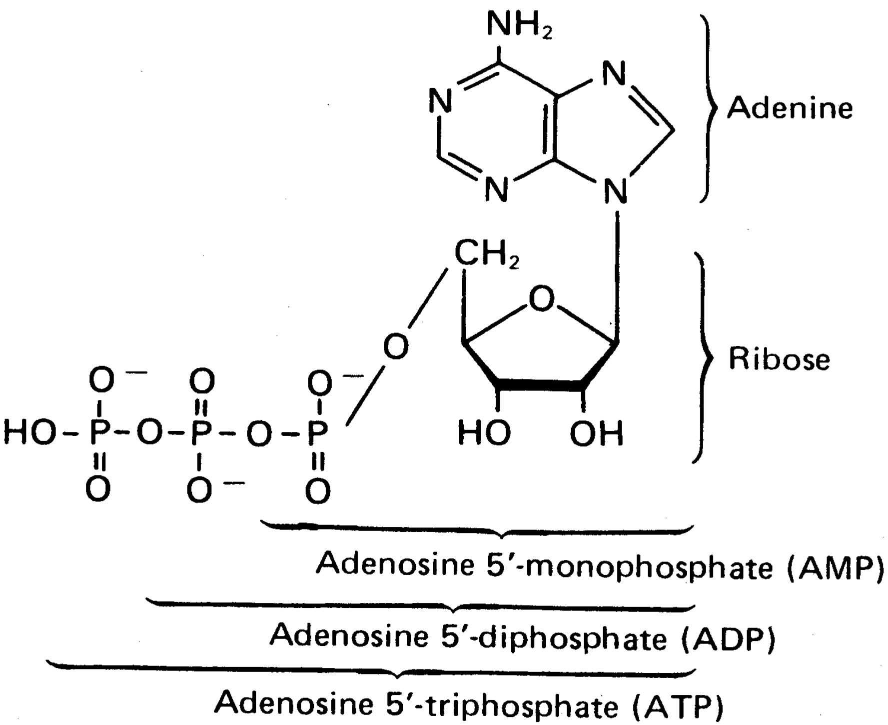
- Adenosine triphosphate (ATP)
- Creatine phosphate (CrP) (phosphorylcreatine)

ATP: “Energy Currency”

The key substance in energy transformationand utilization

- ATP is generated by combustion of carbohydrates, fats and proteins
- Energy from ATP can be used
  - Synthesis and growth
  - Muscular contraction
  - Glandular secretion
  - Nerve conduction
  - Active absorption





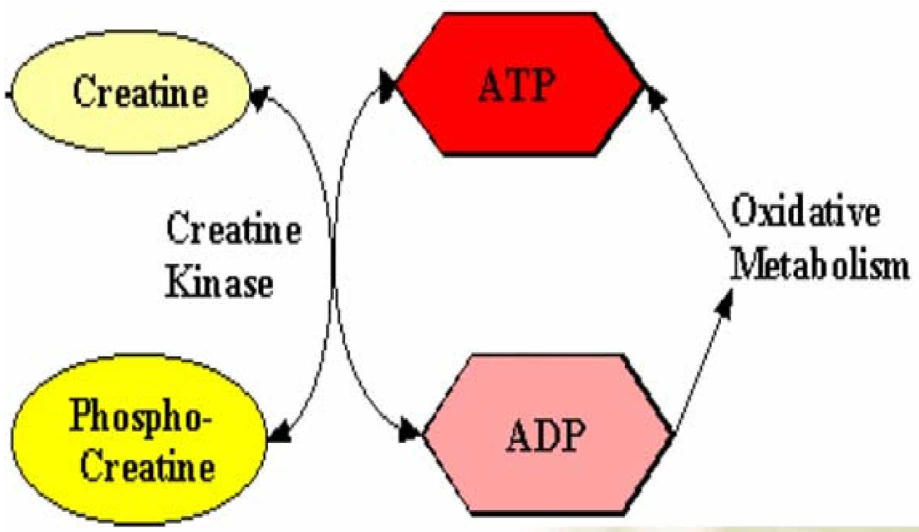
A combination of adenine, ribose and three phosphate radical.

Two phosphate radicals are connected with the reminder of the molecule by so called high-energy bonds. The amount of free energy in each of these high –energy bonds per mole of ATP is about 12,000 calories in the body.

It functions as an intracellular energy source.

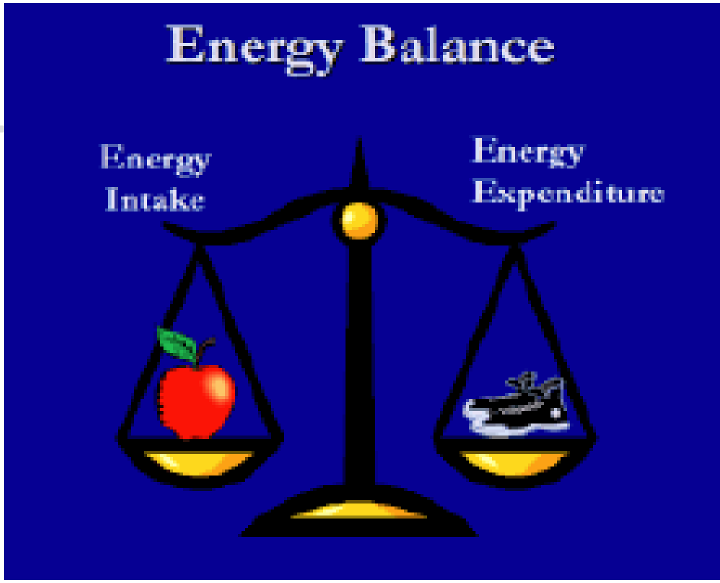
CrP: an ATP "buffer"

- Another energy-rich phosphate compound found in **muscle**
- **CrP** is an important **energy store for ATP**



This keeps the concentration of ATP at an almost constant high level as long as any Crp remains.

How to maintain a stable body weight



Storage=

Energy intake-energy output

Output:

- **Performing essential metabolic functions of the body**
- **Performing various physical activities**
- **Digesting ,absorbing, etc**
- **Maintaining body temperature**

obesity

Energy intake>energy expenditure

Abnormal feeding regulation
Psychogenic factors
Neurogenic abnormalities
Genetic factors
Childhood overnutrition

What is fat?

Your 'body mass index' or BMI is a measure of body fat based on height and weight. A BMI of:

- under 20 = underweight
- 20-25 = normal
- 25-30 = overweight
- 30+ = obese

$$BMI = Weight/(Height)^2 (Kg/m^2)$$

For example:

A 70kg person with a height of 180cm

$$BMI = \frac{70}{(1.8)^2} = 21.6 \ (Kg/m^2)$$

2. Metabolic Rate

(1) Metabolic rate

Total energy expenditure per unit time.

Usually expressed as the heat production per hour, per square body surface area ($kJ/m^2 \cdot h$).

(2) Measurement of energy metabolism

Laws of Thermodynamics

In the closed system, energy is neither created nor lost.

$$\Delta E = H + W$$

ΔE Internal energy liberated

H heat

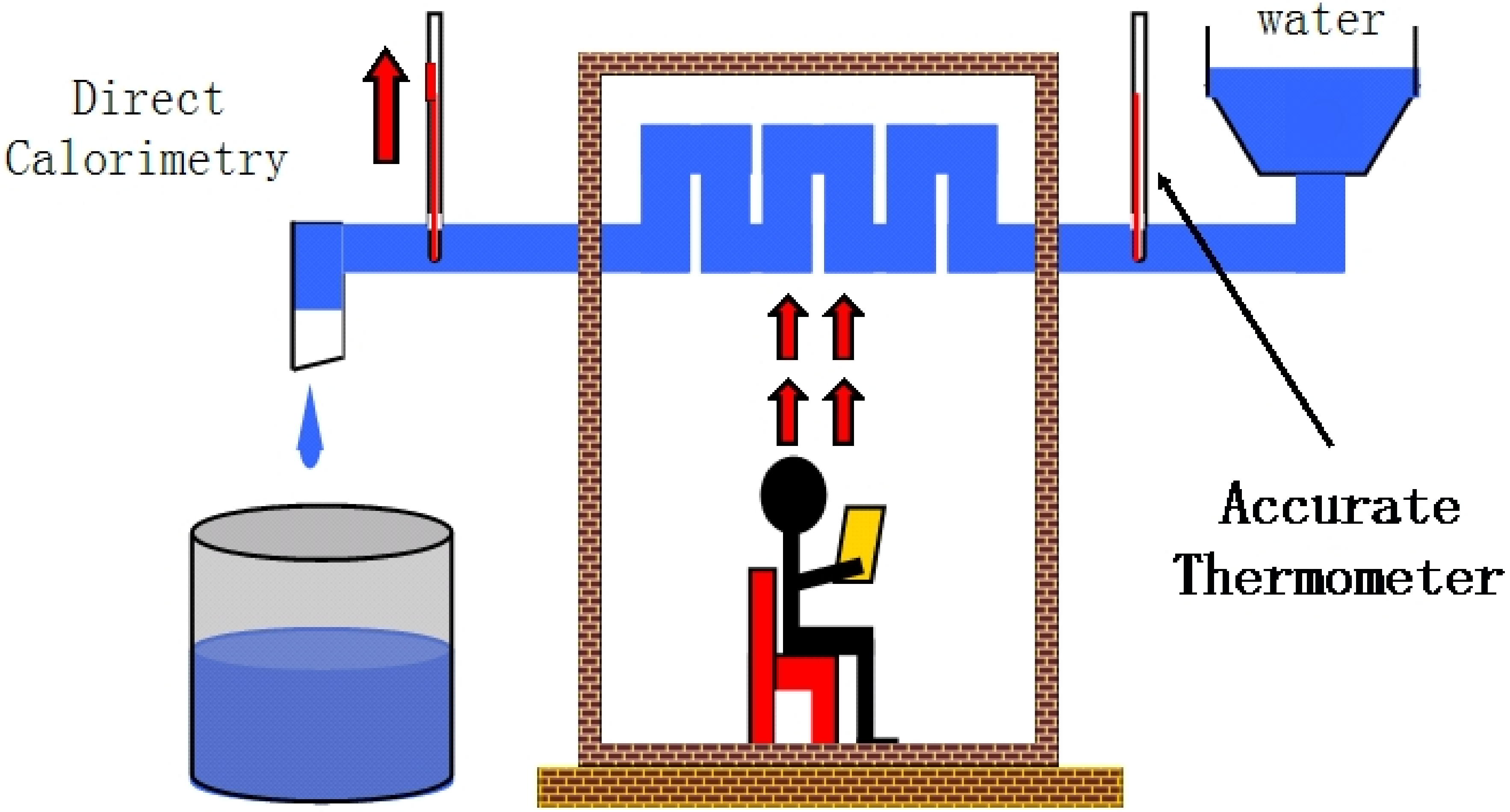
W Energy used to perform work

A person ordinarily is not performing any external work, the whole body metabolic rate can be determined by simply measuring the total quantity of heat liberated from the body in a given time.

Measurement of metabolic rate

- **Direct calorimetry**
- **Indirect calorimetry**

Direct calorimetry



Insulation airtight room

Indirect calorimetry

In a normal chemical reaction, the quantity of products are proportionable to the quantity of the substrate, this is called **constant proportional law**.

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + \triangle H$$

1)Thermal equivalent

The number calories produced by 1gm of food stuff, when it is completely oxidized ,is called thermal equivalent of the food.

- Oxidized in the body: biologic thermal equivalent
- Burnt outside the body: physical thermal equivalent

The thermal equivalent of the three nutrition substance (kJ/g)

Nutrition substance	physical thermal equivalent	biologic thermal equivalent
Carbohydrate	17.15	17.15
Protein	23.43	17.99
fat	39.75	39.75

Proteins could not be oxidized totally in the body.

2)Thermal equivalent of oxygen

The amount of calories produced by per liter of oxygen.

When 1 liter of oxygen is metabolized with glucose, 5.01 cal are released; with fat, 4.70 cal; and with protein, 4.60 cal.

3)Respiratory quotient (RQ)

The ratio of the volume of carbon dioxide (CO_2) produced to the volume of oxygen (O_2) consumed per unit of time

$$RQ = \frac{CO_2 \text{ produced (ml)}}{O_2 \text{ consumed (ml)}}$$

$C_6H_{12}O_6 + 6O2 \longrightarrow 6CO_2 + 6H_2O$ (glucose)

$2C_{51}H_{98}O_6 + 145O_2 \longrightarrow 102CO_2 + 98H_2O$ (tripalmitin)

- Carbohydrate: 1.0
- Fat: 0.70
- Protein: 0.8
- Average diet: 0.85 (0.70-1.0)

4)non-protein respiratory quotient (NPRQ)

Because oxidization to supply energy is not the major function of the protein, generally, the energy mainly comes from the catabolism of carbohydrate and fat.

Usually, the RQ is calculated by **the ratio of CO_2 production to O_2 consumption on the basis of approximate proportion of mixed carbohydrate and fat**, which is called non-protein respiratory quotient (NPRQ).

NPRQ	carbohydrate （%）	fat （%）	thermal equivalent of oxygen
0.707	0.00	100.0	19.61
0.71	1.10	98.9	19.62
0.72	4.76	95.2	19.67
0.73	8.40	91.6	19.72

0.80	33.4	66.6	20.09
0.81	36.9	63.1	20.14
0.82	40.3	59.7	20.19
0.83	43.8	56.2	20.24
0.84	47.2	52.8	20.29
0.85	50.7	49.3	20.34
0.86	54.1	45.9	20.40

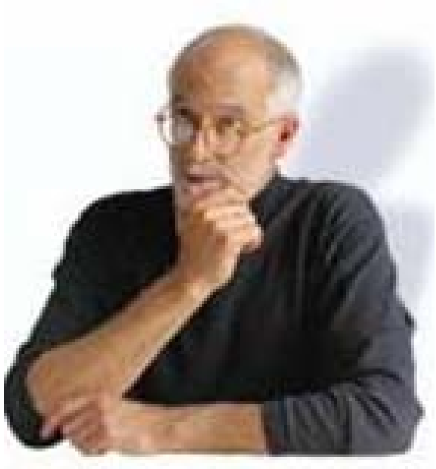
Different composition

Measuring the metabolic rate

- Measurement of O_2 consumption and CO_2 production.
- Measurement of urea nitrogen----protein oxidized and the heat produced by protein.
- Calculation of O_2 consumption and CO_2 production of non-protein nutrition----NPRQ----heat produced by non-protein nutrition
- Total heat = heat produced by protein + heat produced by non-protein nutrition

3. Factors affecting energy metabolism

- Muscular exertion
- Emotional state
- Specific dynamic action, SDA
- Environmental temperature
- Other factors affecting energy metabolism



（1） Muscular exertion

Exercise→O_2 consumption↗→metabolic rate ↗

Energy expenditure during different types of activity for a 70 kg person

FORM OF ACTIVITY	ENERGY Kcal/h
Lying still, awake	77
Sitting at rest	100
Typewriting rapidly	140
Dressing or undressing	150
Walking on level, 4.3 km/h (2.6 mi/h)	200
Bicycling on level, 9 km/h (5.5 mi/h)	304
Walking on 3 percent grade, 4.3 km/h (2.6 mi/h)	357
Sawing wood or shoveling snow	480
Jogging, 9 km/h (5.3 mi/h)	570
Rowing, 20 strokes/min	828

Oxygen debt

Physiological state produced by vigorous exercise, in which the lungs cannot supply all the oxygen that the muscles need. In other words, the lungs and bloodstream pumped by the heart, cannot supply sufficient oxygen for aerobic respiration in the muscles.

In such a situation the muscles can continue to break down glucose to liberate energy for a short time using anaerobic respiration. This partial breakdown produces lactic acid, which results in a sensation of fatigue when it reaches certain levels in the muscles and the blood.

（2） Emotional state

- The O_2 consumption of brain is 20 times of muscle.
- There is no difference between sleep and consciousness.
- But at some emotional states (fear,vexation, agitation), energy production increase.

Anxiety
Fear

- Tension of muscles ↗
- Hormones release ↗
    - Thyroid hormone
    - Epinephrine
    - Norepinephrine

→ Metabolic rate ↗

（3） Specific dynamic action of food （SDA）

Specific dynamic action of a food is the obligatory energy expenditure that occurs during its assimilation into the body.

- Protein: 30%
- Carbohydrate: 6%
- Fat: 4%
- Mixed diet: 10%

（4）Environmental temperature

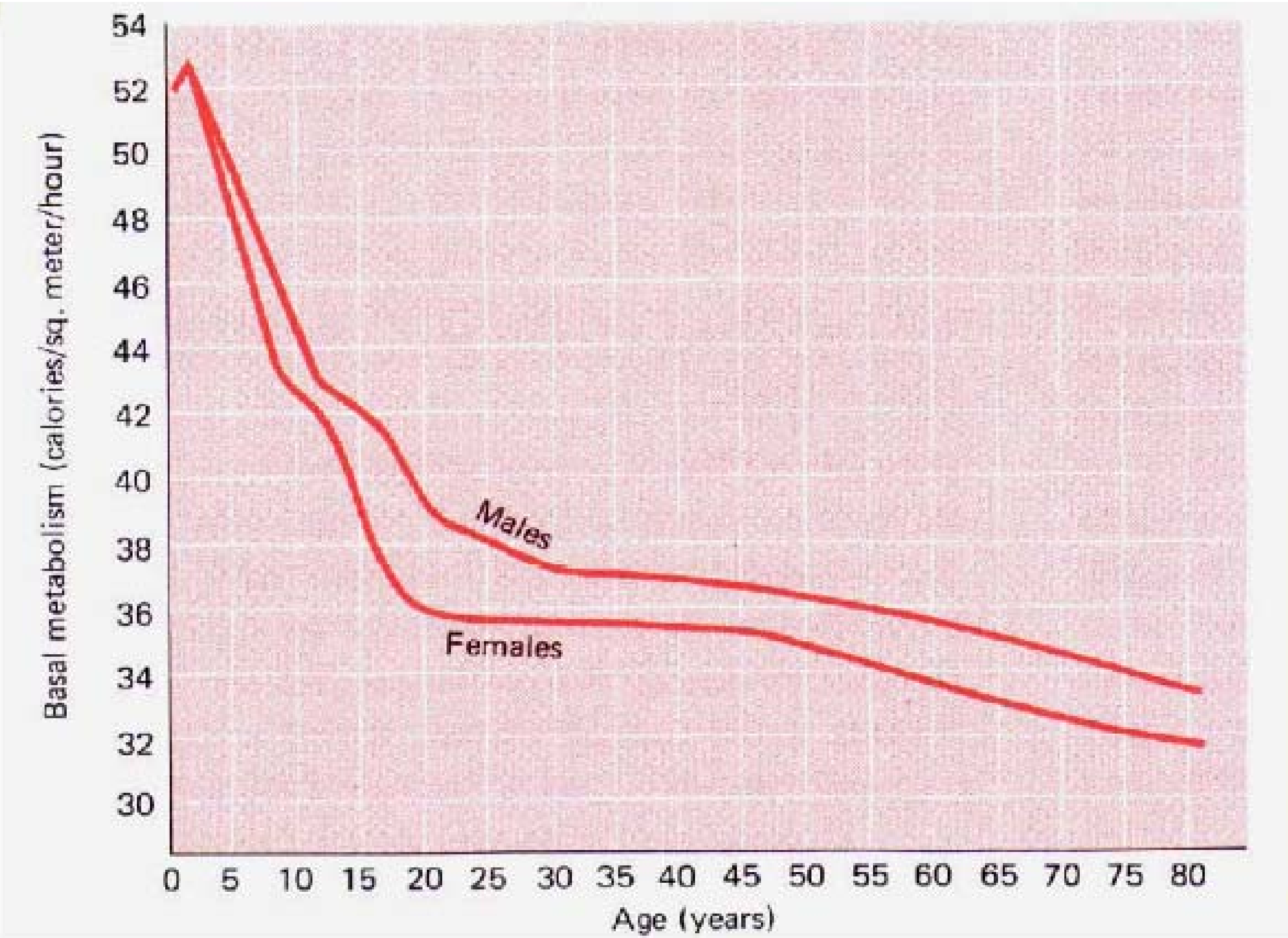
- **20~30° steady**
- **<20 ° shivering→metabolic rate ↗**
- **>30 ° acceleration of metabolic process →metabolic rate ↗**

↓

chemical reactions in the body

（5） Other factors

- Age
- Hormones
- Body temperature
- Sleep


Basal metabolism (calories/sq. meter/hour)
54
52
50
48
46
44
42
40
38
36
34
32
30
Males
Females
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Age (years)

4、Basal metabolism

- **Basal metabolism means energy metabolism under basal condition.**
- **Basal metabolic rate (BMR) means basal metabolism per unit of time (kJ/m^2h).**
- **BMR is expressed as the energy metabolism per unit of time, per square of body surface. KJ/(m2.h)**

Stevenson formula

Body Surface Area (m^2) =

0.0061 x Height (cm) +0.0128 x Weight (kg)-0.1592

（1） Basal conditions:

a. Must not have eaten any food for at least 12 hours

b. After a night of restful sleep

c. No strenuous exercise

d. Eliminate all psychic and physical factors

e. The room temperature is between 20-25 ℃

Basal metabolic rate(BMR): The metabolic rate determined at rest in a room at a comfortable temperature in the thermoneutral zone 12-14 hours after the last meal.

（2） Measurement

The averaged normal value of BMR (kJ / $m^2 \cdot h$)

Age	11-15	16-17	18-19	20-30	31-40	41-50	>50
Male	195.5	193.4	166.2	157.8	158.6	154.0	149.0
Female	172.5	181.7	154.0	146.5	146.9	142.4	138.6

For convenience, the BMR is usually expressed as a percentage increase or decrease above or below the standard normal values.

$$\frac{\textbf{Measured value} - \textbf{standard value}}{\textbf{Standard value}} \times 100\%$$

For example

One man, 20 years old, O_2 consumption is:15L/h,

body surface area:1.5 m^2

NPRQ=0.82; Thermal equivalent of oxygen: 20.19 KJ/L

BMR:

$20.19\ KJ/L \times 15L/h \div 1.5\ m^2 = 201.9\ KJ/(m^2.h)$

The standard BMR for a man of 20 years old is 157.8 KJ/(m2.h), so the BMR is (201.9- 157.8) ÷ 157.8 × 100%=28% above standard.

Expressed as +28%.

（3） Significance of BMR

- normal range : ±10-15%
- pathologic significance: >±20%
- hyperthyroidism： ＋ 25～80％
- hypothyroidism ： － 20～40％
- The BMR increases about 13% for every 1 rise in body temperature.

Summary

- Energy metabolism refers to the production, storage, transform, release and utility of energy during the process of material metabolism.
- ATP functions as an “energy currency” in metabolism.
- The metabolic rate is the amount of energy liberated per unit of time.
- Strenuous exercise is the factor that causes the most dramatic effect on metabolic rate.
- BMR is usually measured under so-called basal conditions.

Section 2 Body temperature and temperature regulation

- **Body temperature**
- **The balance between heat production and heat loss**
- **Thermoregulation**

Poikilothermal

(cold-blooded) animals

Homeothermic animals

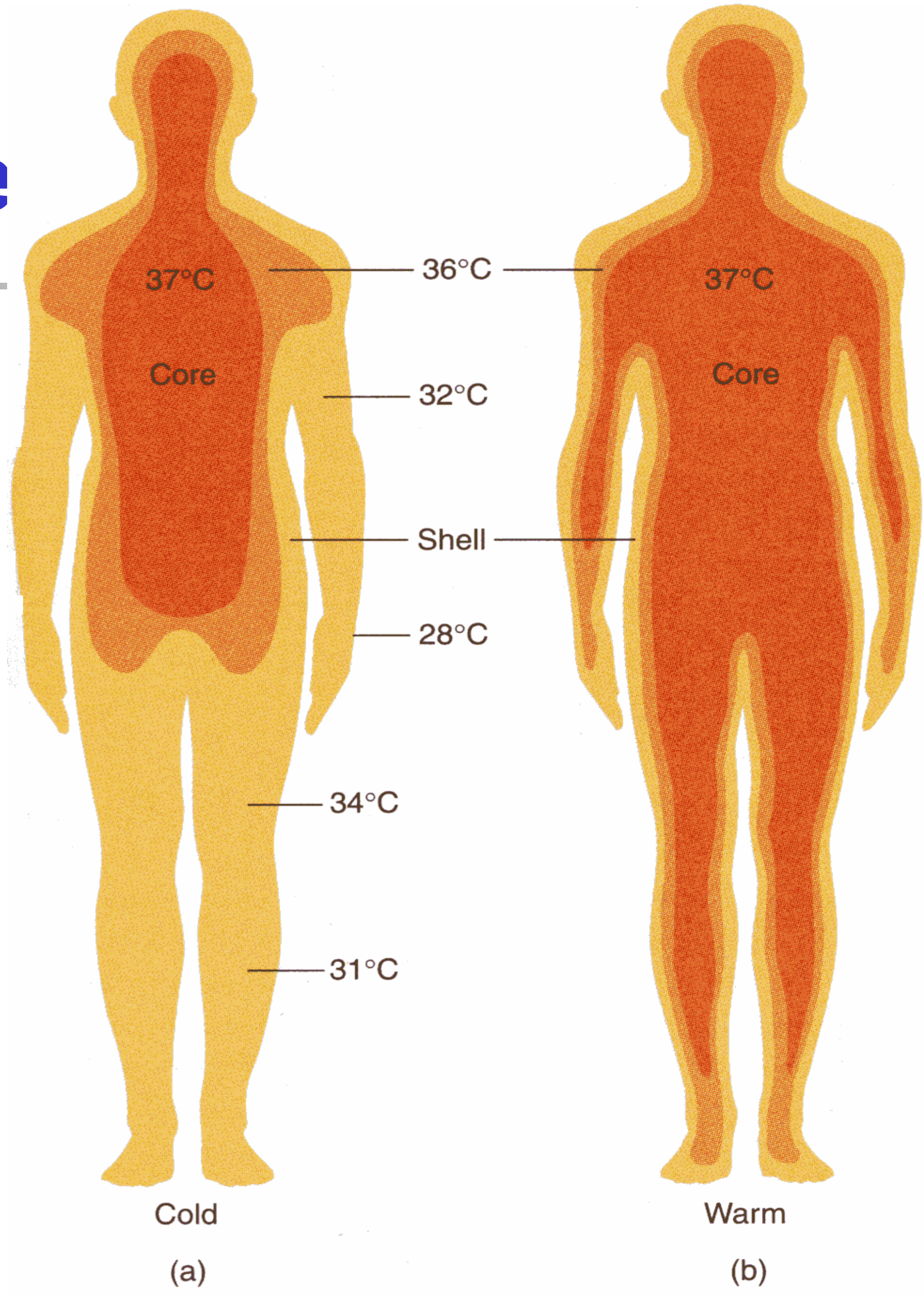
一、Body tempe

1. Shell temperature

- **Shell temperature**
- **Core temperature**

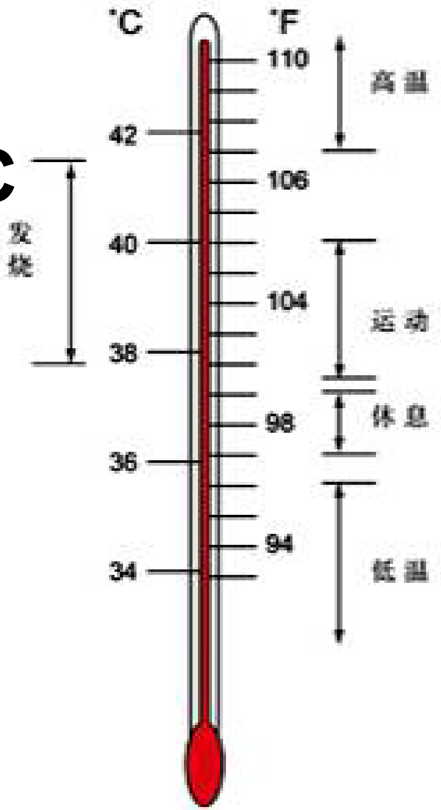
a: 20° C

b: 35° C



Body temperature means the average core temperature.

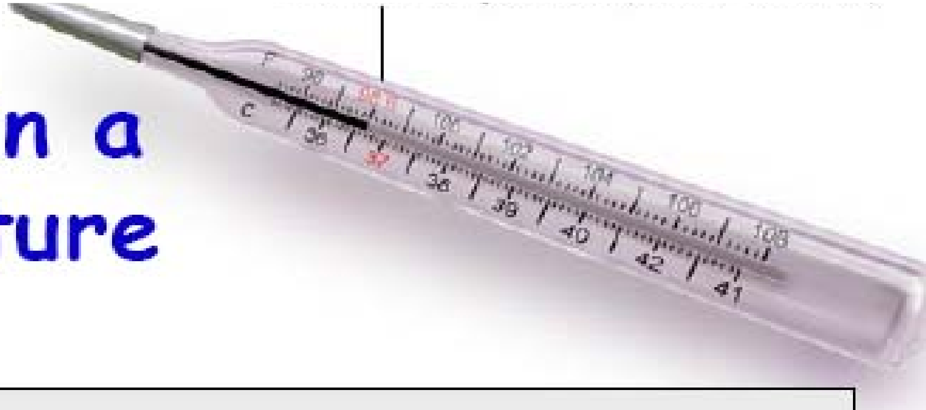
- Axillary temperature: 36.0～37.4° C
- Oral temperature: 36.7～37.7 ° C
- Rectal temperature: 36.9～37.9 ° C



- **Esophagus (食管):** the temperature in the middle of the esophagus is the same as the temperature in the right atria（右心房）so that in some experiment it is often used as an index of the core temperature.

- **Tympanic (鼓膜):** the temperature of the tympanic is similar to the temperature in hypothalamus（下丘脑）, it is often used as the temperature in brain in research.

Important to maintain a stable body temperature

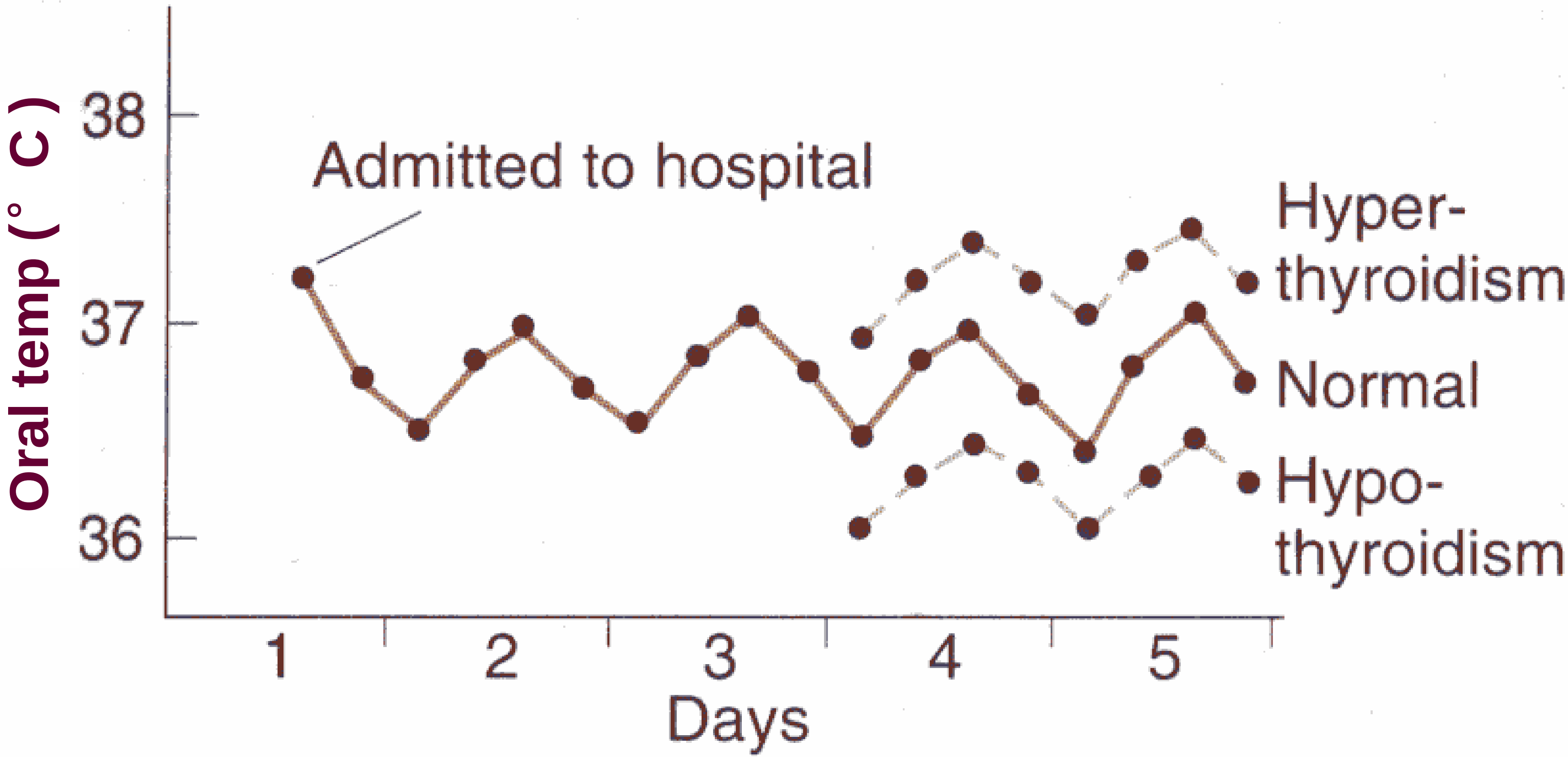


Core Temperature (℃)	Symptoms
28	muscle failure
30	loss of body temperature control
33	loss of consciousness
37	normal
42	central nervous system breakdown
44	death

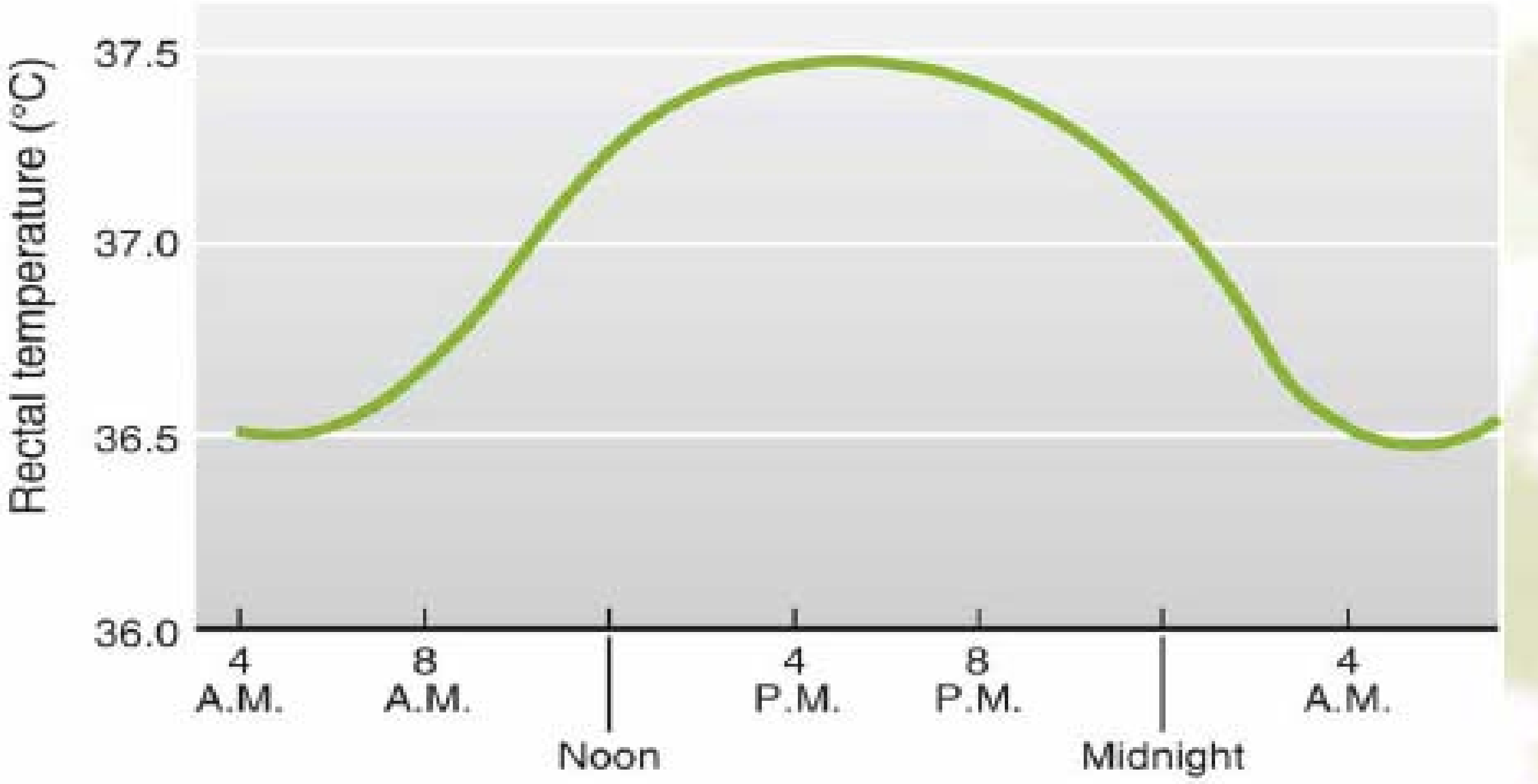
1.2 Arrangement of body temperature

- Circadian rhythm
- Sex
- Age
- Others

Circadian rhythm



Typical temperature chart of a hospitalized patient who does not have a febrile disease. Note the slight rise in temperature, due to excitement and apprehension, at the time of admission to the hospital, and the regular circadian temperature cycle.

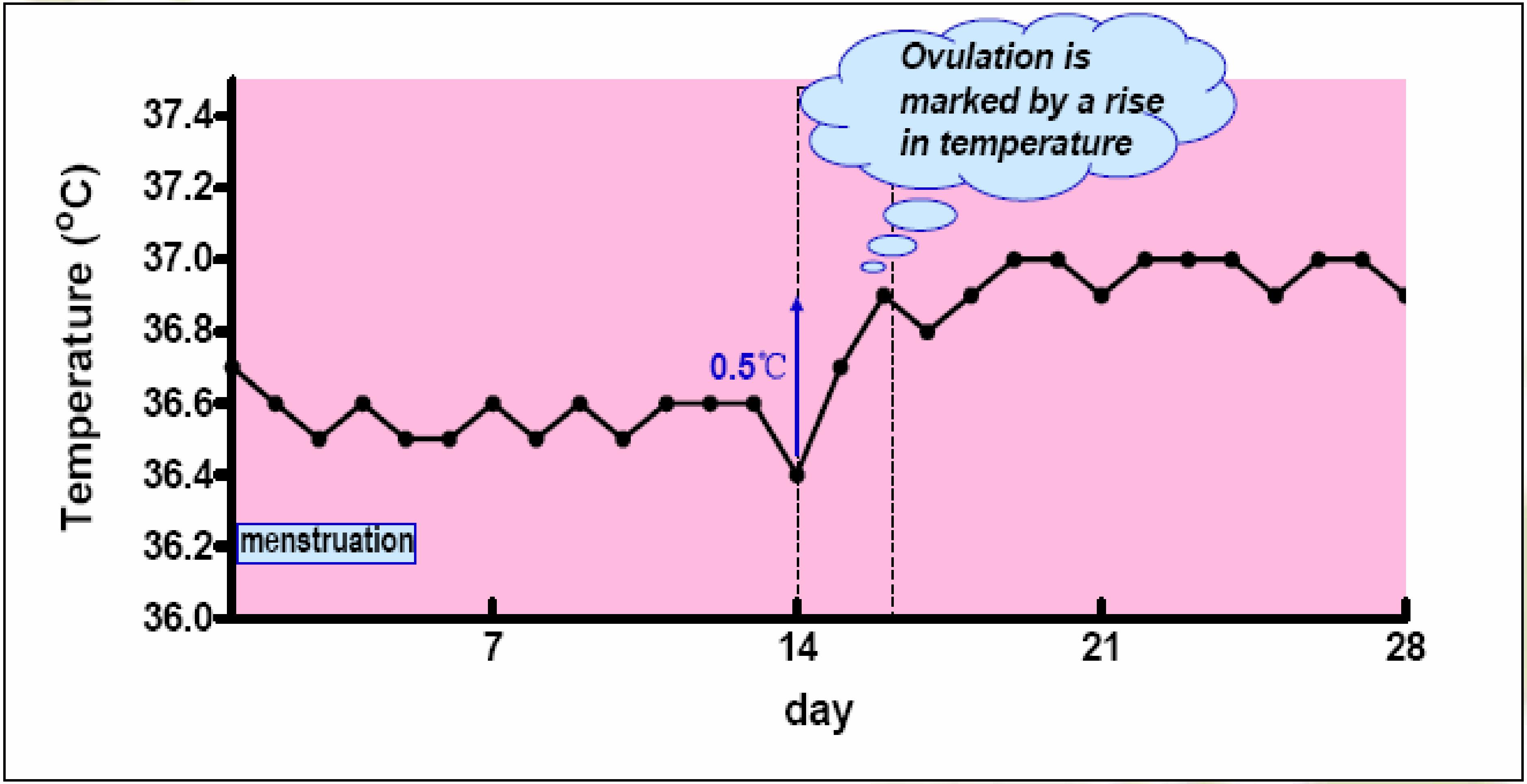


Lowest at 6:00 am, highest at 6:00 pm (< 1^0C)

Suprachiasmatic nucleus in the hypothalamus hyperthyroidism

Sex

Adult female > male (0.3ºC)



In women, an additional monthly cycle of temperature variation is characterized by a rise in basal temperature at the time of ovulation

Age

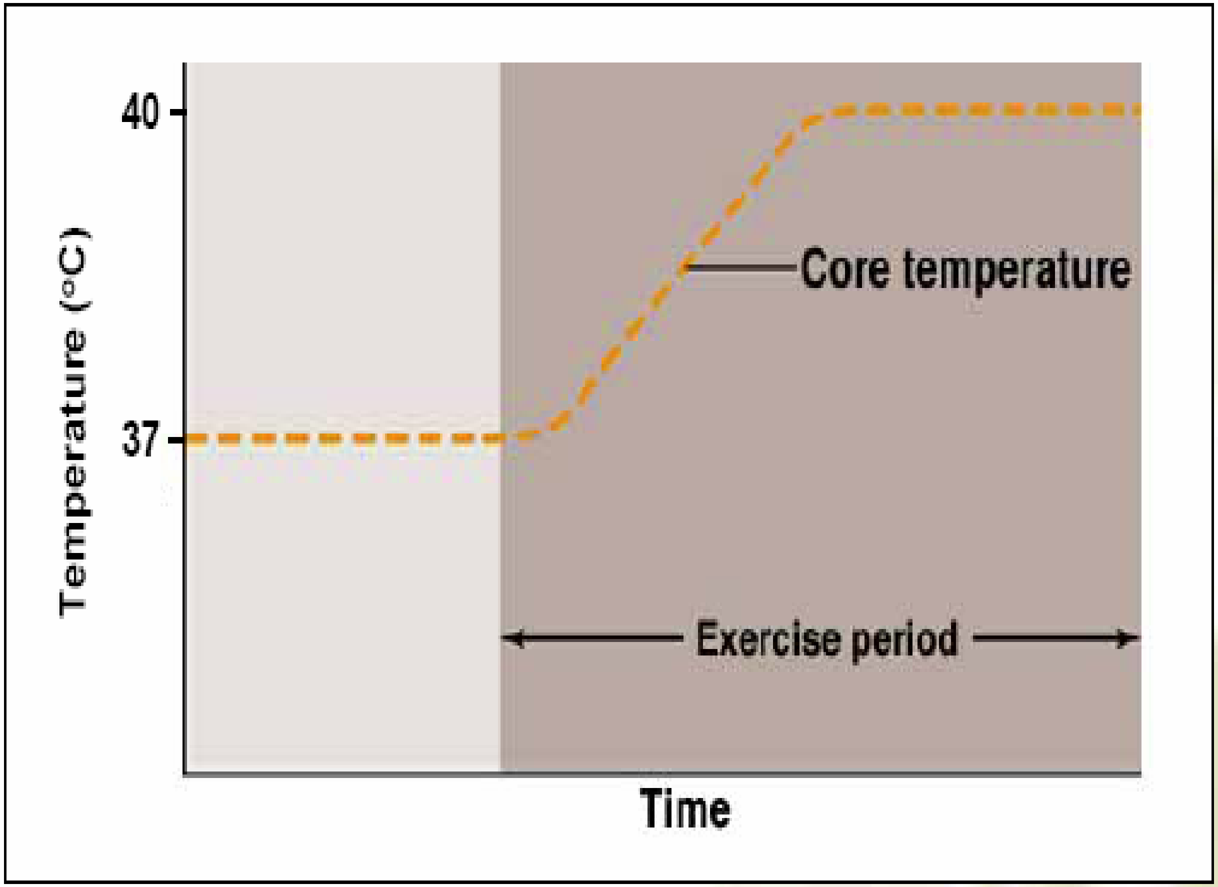
- A newborn child has a slightly higher temperature than an adult, and the body temperature of a young child is more variable due to the higher metabolic rate.
- The old persons have lower body temperature due to the decreased metabolic rate.

Body temperature

	age	6:00	9:00	12:00	15:00	18:00	21:00	24:00	average
mother	43	**36.2** ℃	**36.8** ℃	**37.0** ℃	**37.1** ℃	**36.9** ℃	**36.9** ℃	**36.8** ℃	**36.8** ℃
father	45	**36.3** ℃	**36.5** ℃	**36.9** ℃	**37.0** ℃	**36.8** ℃	**36.7** ℃	**36.6** ℃	**36.7** ℃
child	15	**36.4** ℃	**36.7** ℃	**37.1** ℃	**37.3** ℃	**37.0** ℃	**36.9** ℃	**36.8** ℃	**36.9** ℃

Others:

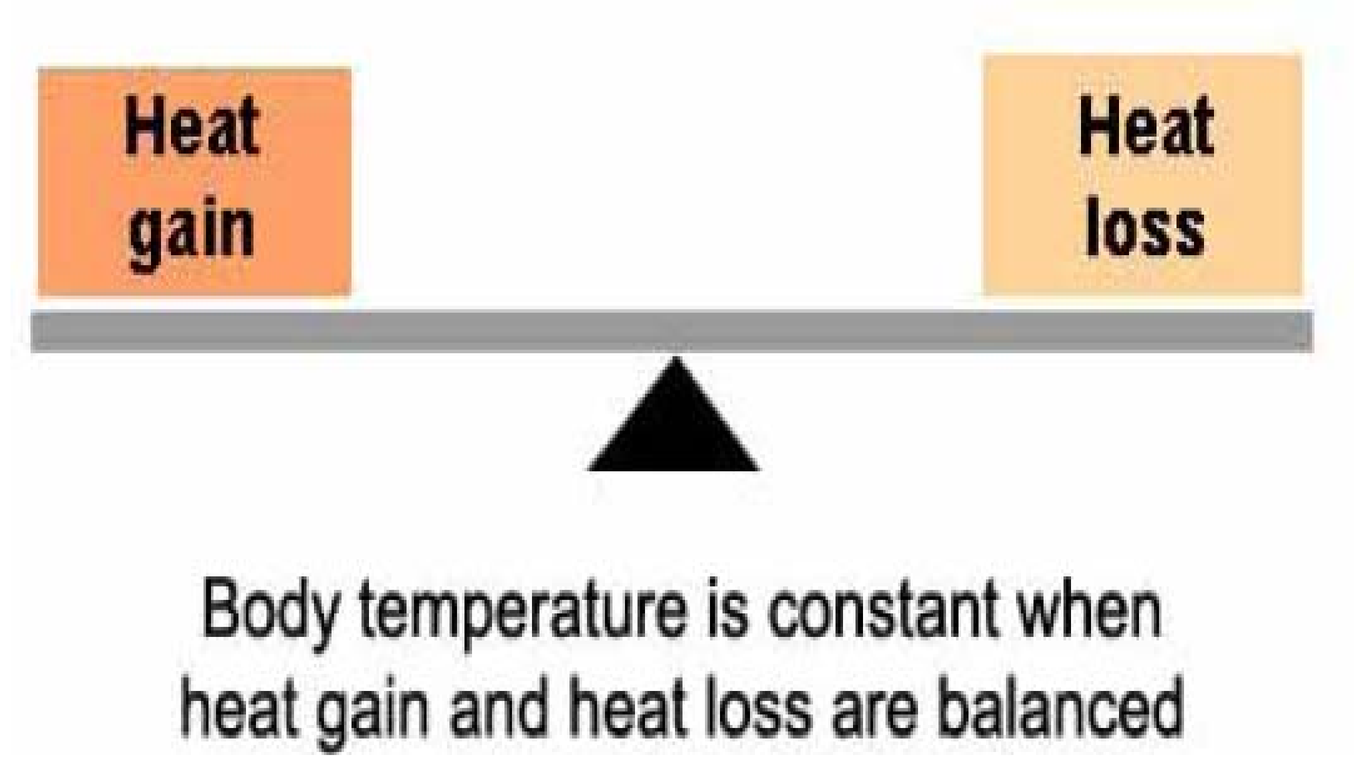
- exercise



- emotion
- eating
- environmental temperature

2. Balance of body heat

- Heat production (Thermogenesis)
- Heat loss (Thermolysis)



2.1 Heat production

A principal by-product of the metabolism

- Basal metabolism
- Extra metabolism caused by
  - Muscular activity
  - Hormones (thyroxine)
  - Sympathetic nervous system
  - Dietary intake

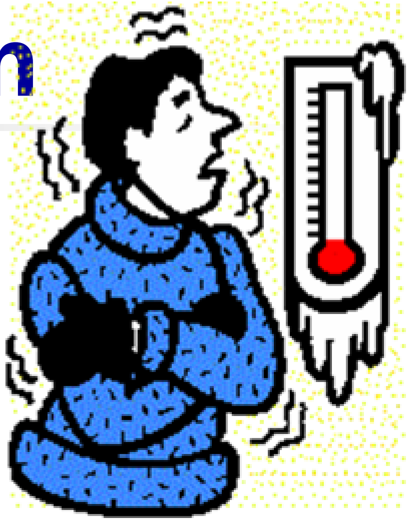
Main organs of heat production

- At rest: viscera (liver)
- During exercise: skeletal muscles

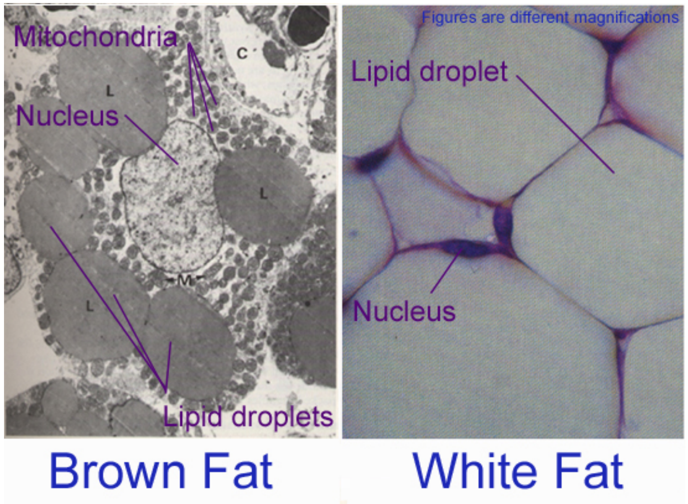
❖ Main organs of heat production in the body

	Percentage in Body Weight	heat production (%)	
		at rest	working
Brain	2.5	16	1
viscera (especially liver)	34	56	8
Skeletal muscle	56	18	90
Others	7.5	10	1

Form of heat production



- shivering thermogenesis
- non-shivering thermogenesis



Shivering thermogenesis

- Primary controlled by hypothalamus
- Rhythmic, oscillating skeletal muscle contractions

The first muscle changes in response to a decrease in core body temperature are a gradual and general increase in skeletal muscle contraction.

Shivering constitutes the major control of heat production for temperature regulation. Muscle contractions during shivering may increase the metabolism rate of the body about 4-5 times.

Non-shivering thermogenesis

Mediated by sympathetic stimulation and thyroid hormone

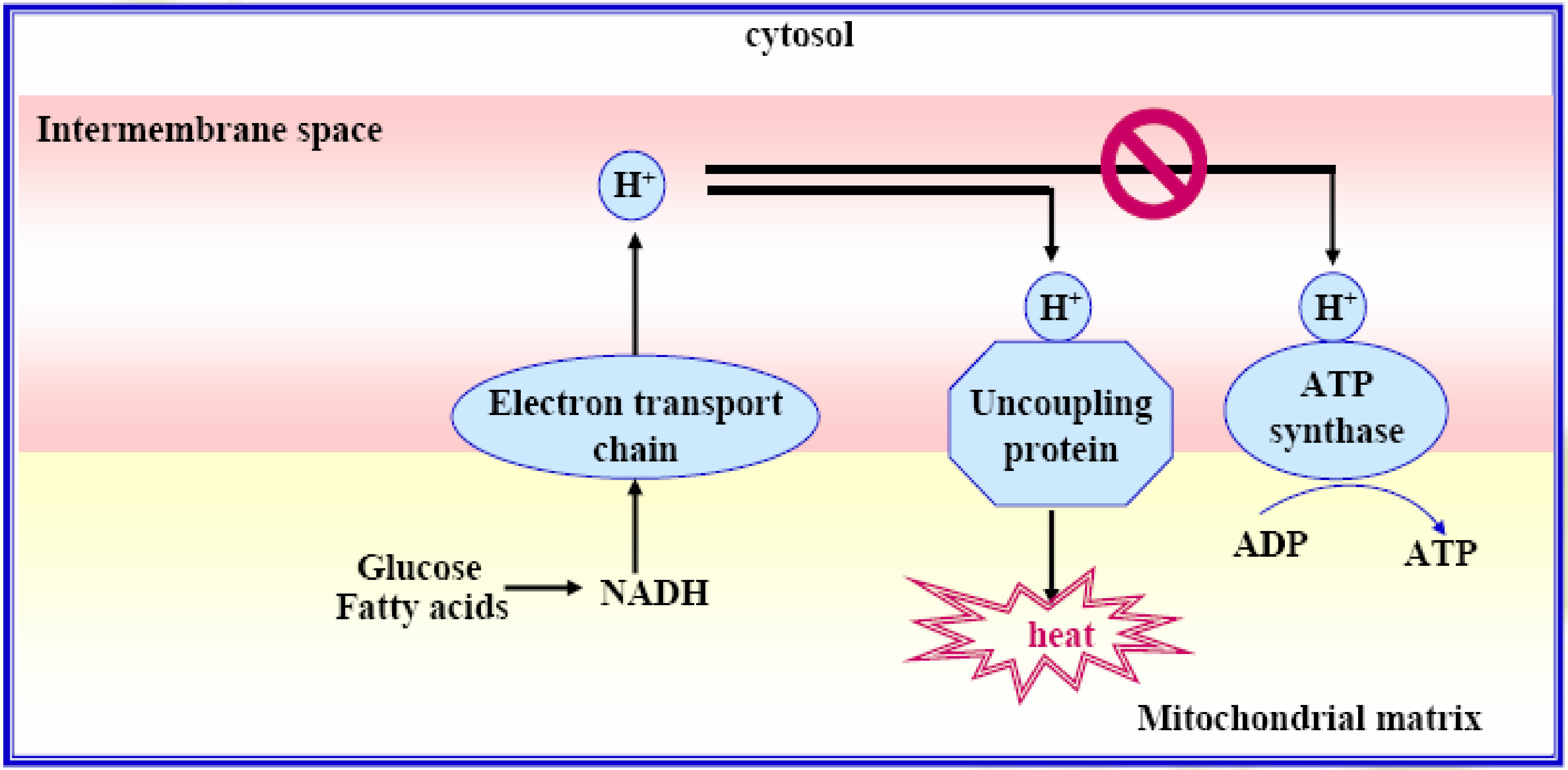
Observed in the following natural cituations

- In small children
- In cold adaptation
- In hibernating animals

brown adipose tissue. It has a high rate of metabolis

Non-shivering thermogenesis

Brown adipose tissue



Regulation of heat production

Cold
- Thermal muscle tone, shivering
- Brown fat tissue
- Thyroid hormone, epinephrine, norepinephrine

→ Metabolic rate ↗

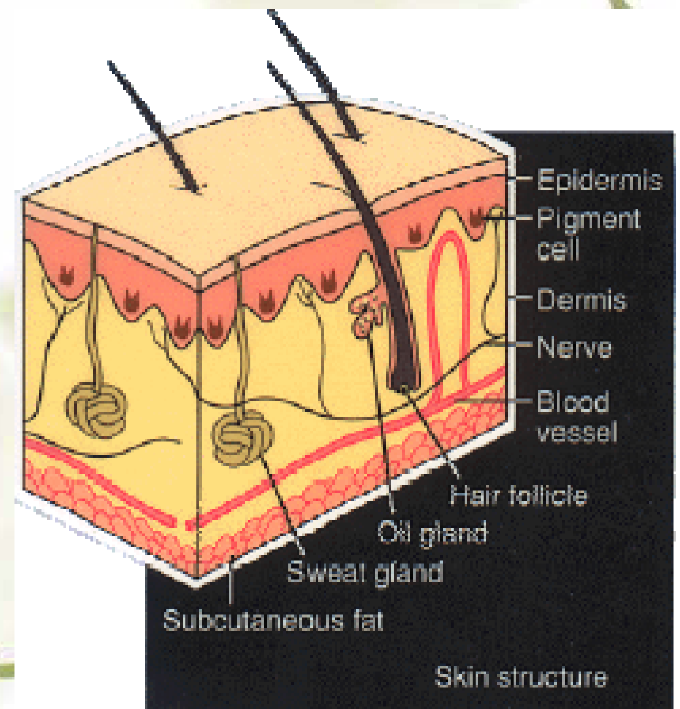
↓

Heat production ↗

2.2 Thermolysis

Deep organs → Skin → Air and other surrounding

Heat transfer

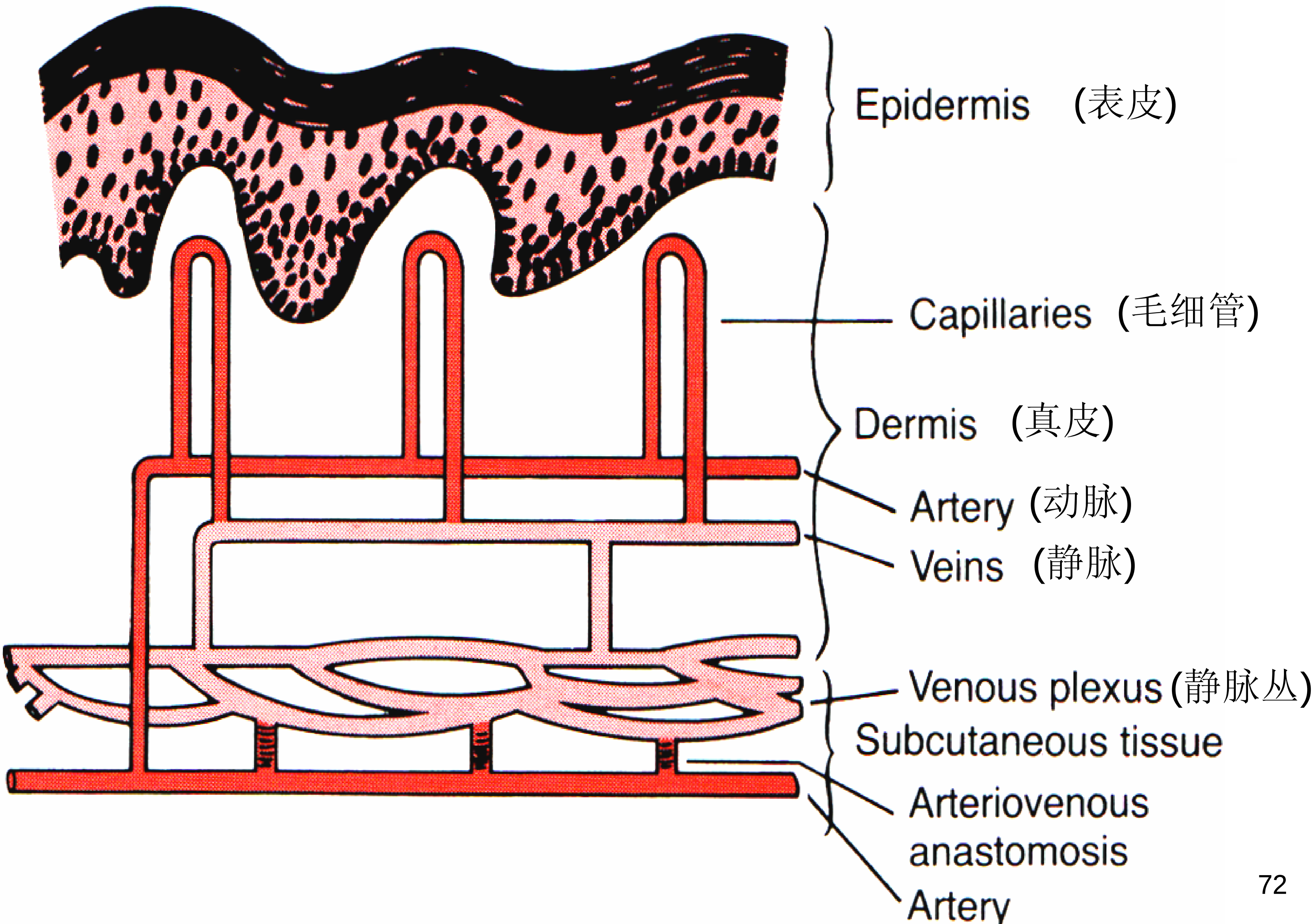


Factors affecting the heat loss

- **How rapidly heat can be conducted from the body core to skin.**

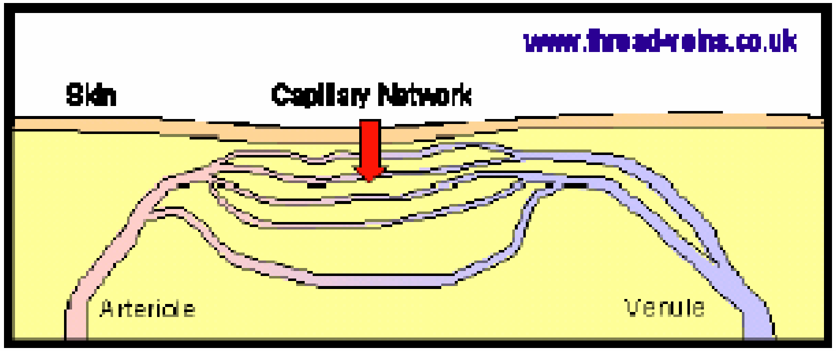
- **How rapidly heat can be transferred from the skin to the surroundings.**

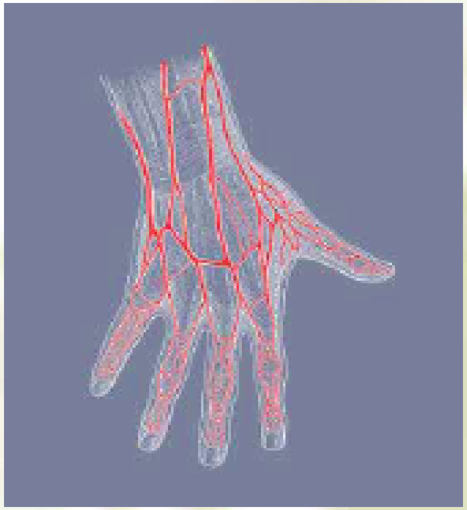
Heat transfer from core to skin

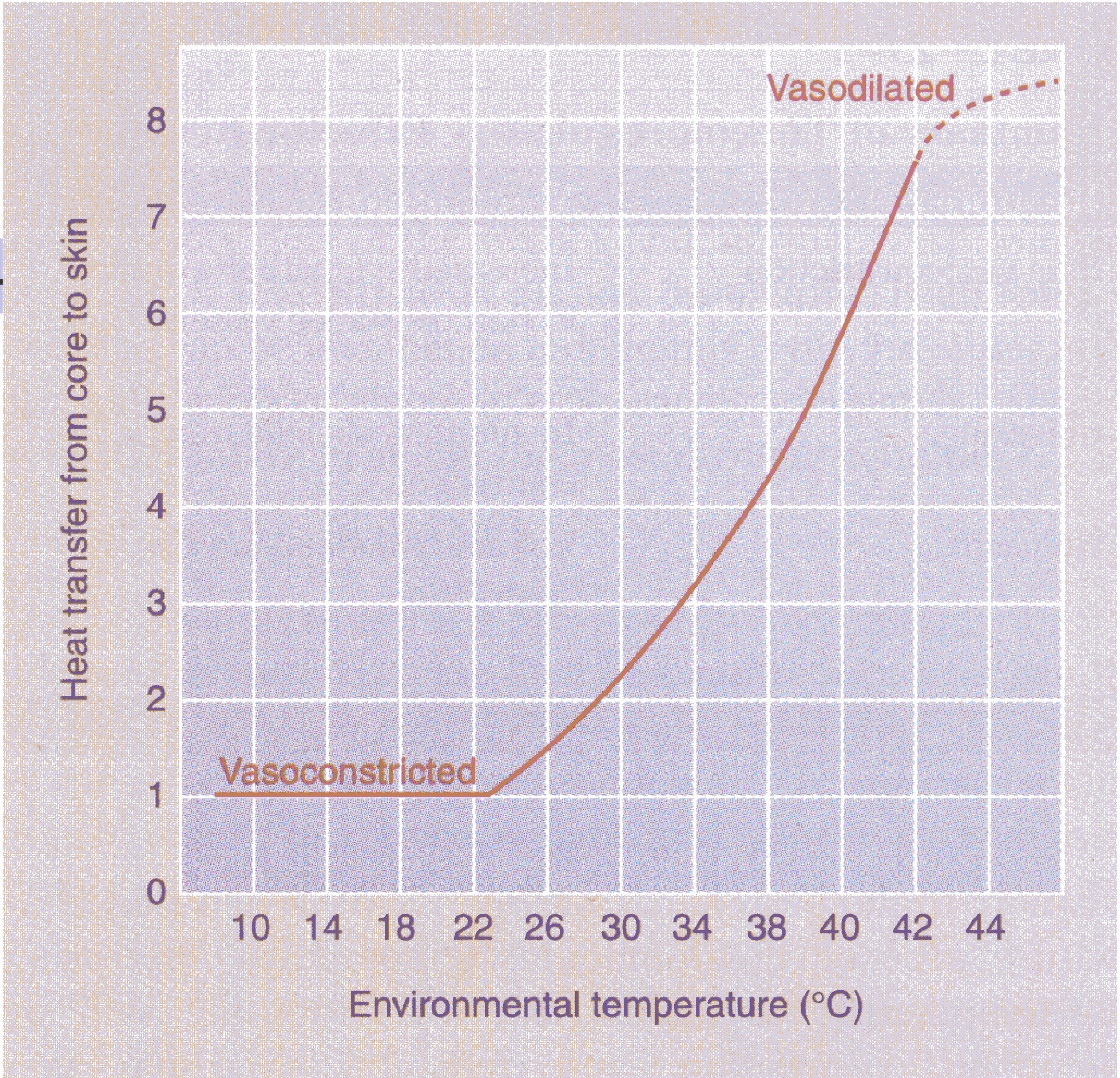


Heat transfer from core to skin

- flow of blood
- controlled by the sympathetic nervous system







Vasodilated
Vasoconstricted
Heat transfer from core to skin
0
1
2
3
4
5
6
7
8
10
14
18
22
26
30
34
38
40
42
44
Environmental temperature (°C)

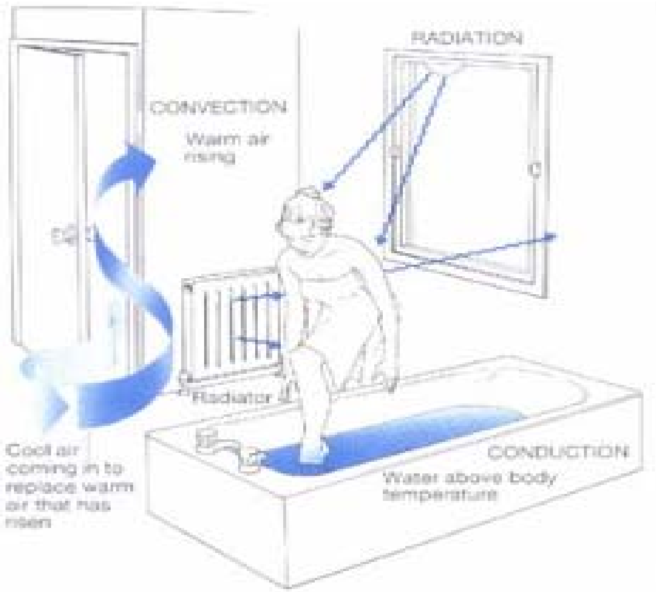
Heat is lost from the skin

Forms of thermolysis

- **Radiation** (辐射)： 60％
- **Conduction** (传导)
- **Convection** (对流)
- **Evaporation** (蒸发散热)

Radiation

Radiation is transfer of heat by **infrared electromagnetic radiation** from one subject to another at a different temperature with which it is not in contact.

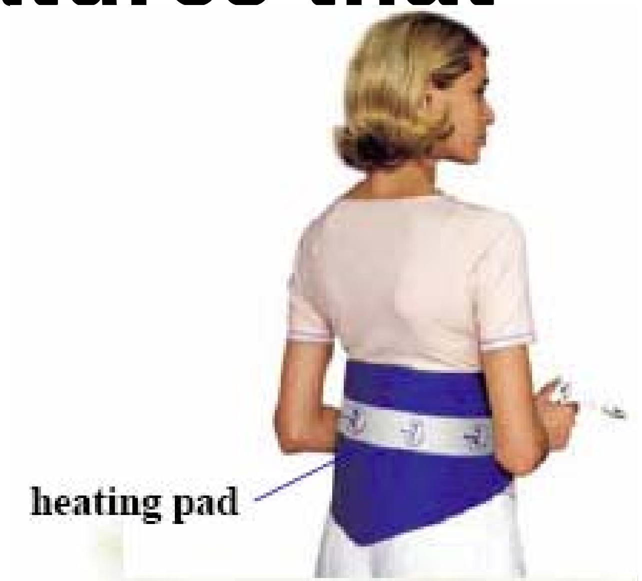


Affecting factors

- temperature difference between the skin surface and surrounding object
- the effective radiation area of the body surface

Conduction

Conduction is heat exchange between objects or substances at different temperatures that are in contact with one another.



- **15% of heat conducted to the air.**
- **Affecting factors**

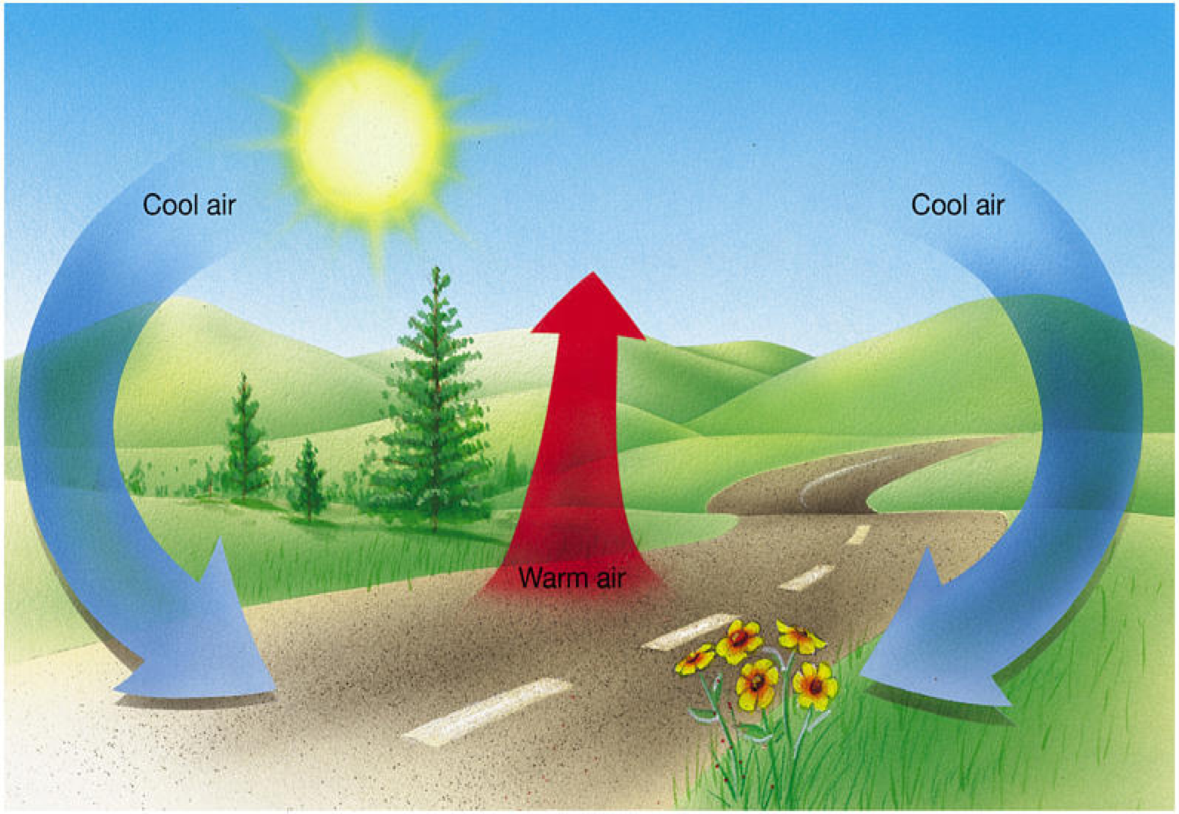
  - temp. difference between two objects in contact.

  - heat conduction rate in the materials.

Convection

Convection is heat exchange by the movement of air molecules.

Affecting factors：wind velocity



Convection is always occurring because warm air is less dense and therefore rises, but it can be greatly facilitated by external forces such as wind or fans. A small amount of convection almost always occurs around the body because of the tendency for the air adjacent to the skin to rise as it becomes heated.

Evaporation

- **Evaporation is transferring heat by vaporization of water on the skin and mucous membrane of the mouth and respiratory passages.**
- **Vaporization of 1 g of water removes about 0.6 kcal of heat.**

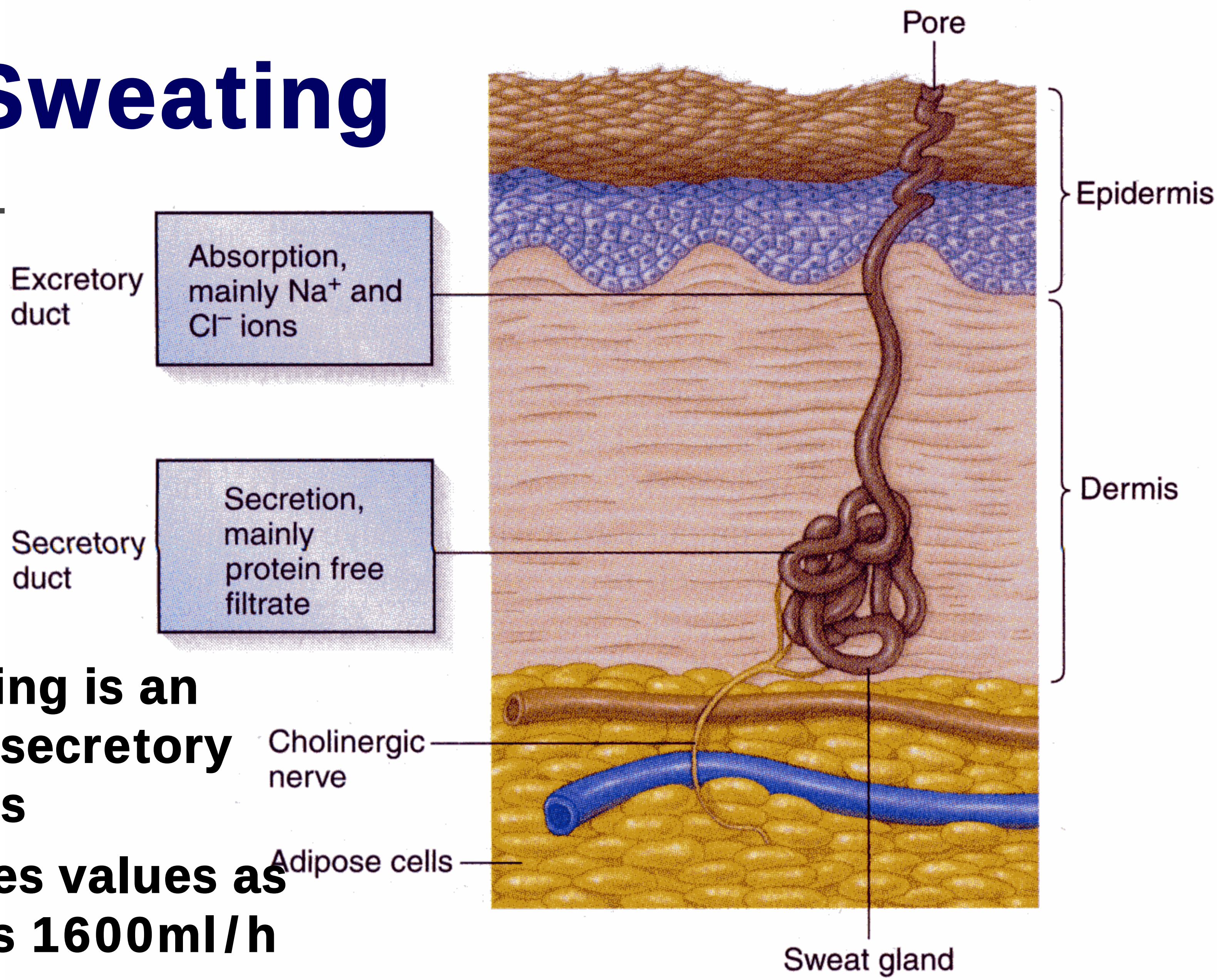
Evaporation

- **The only effective mechanism of heat loss when the environmental temperature is above skin temperature.**
- Evaporation takes place in two forms:
  - **Insensible perspiration**
  - **Sweating**

Insensible perspiration

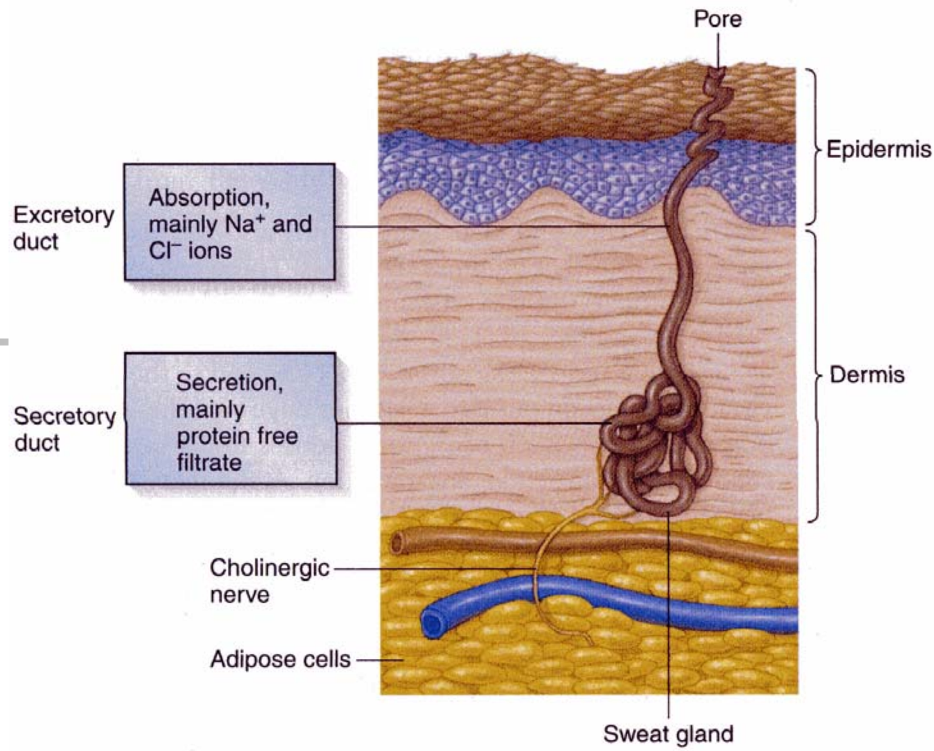
- Insensible perspiration means a certain amount of water is vaporized at all times.
- Insensible perspiration: 50ml/h; 1000ml/24h
- Insensible perspiration from skin: 600~800ml/24h
- Panting

Sweating



- **Sweating is an active secretory process**
- **Reaches values as high as 1600ml/h**

Sweating

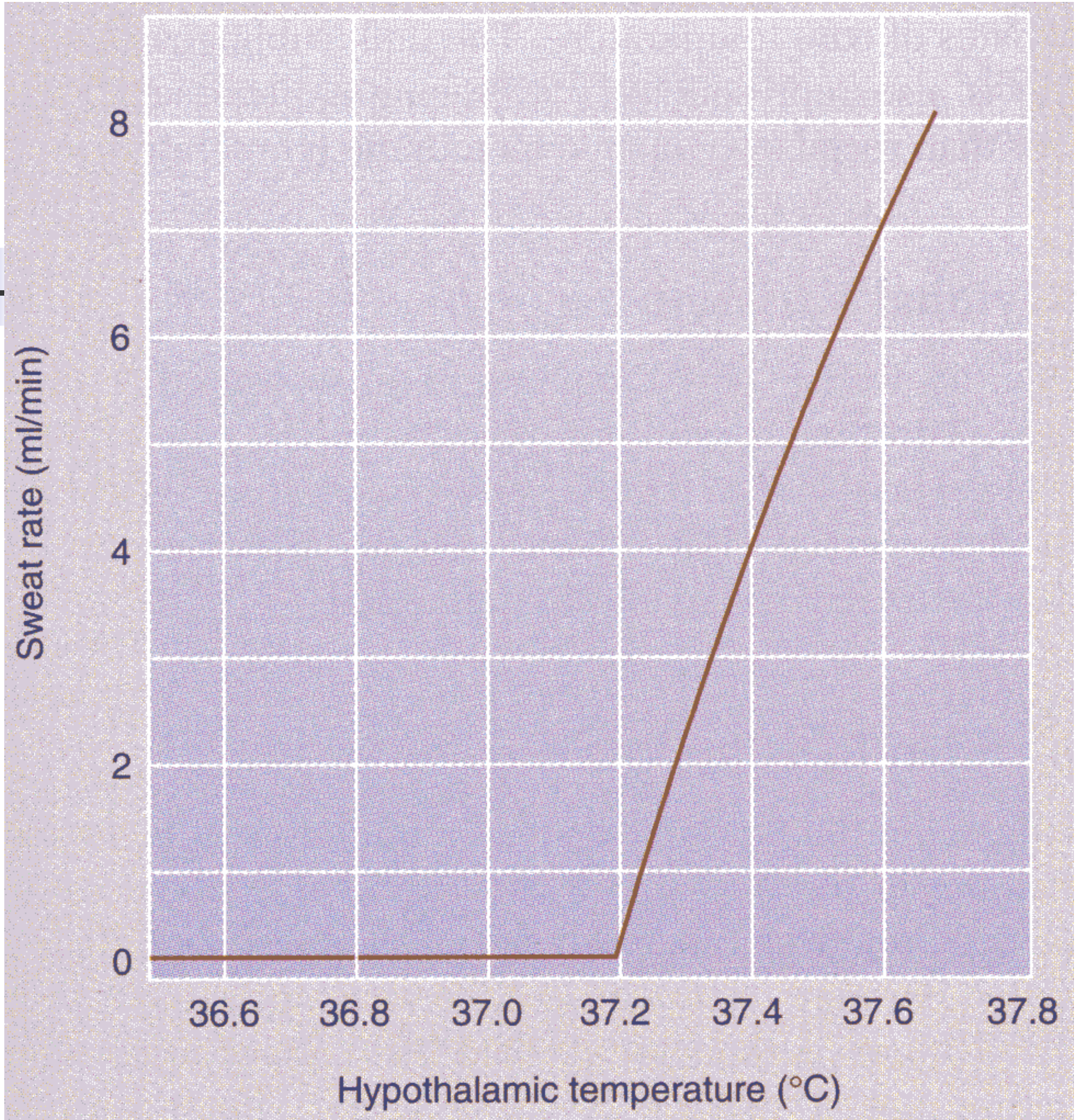


- 99 % -water
- 1 % -solid component (NaCl)
- Hyposmolarity

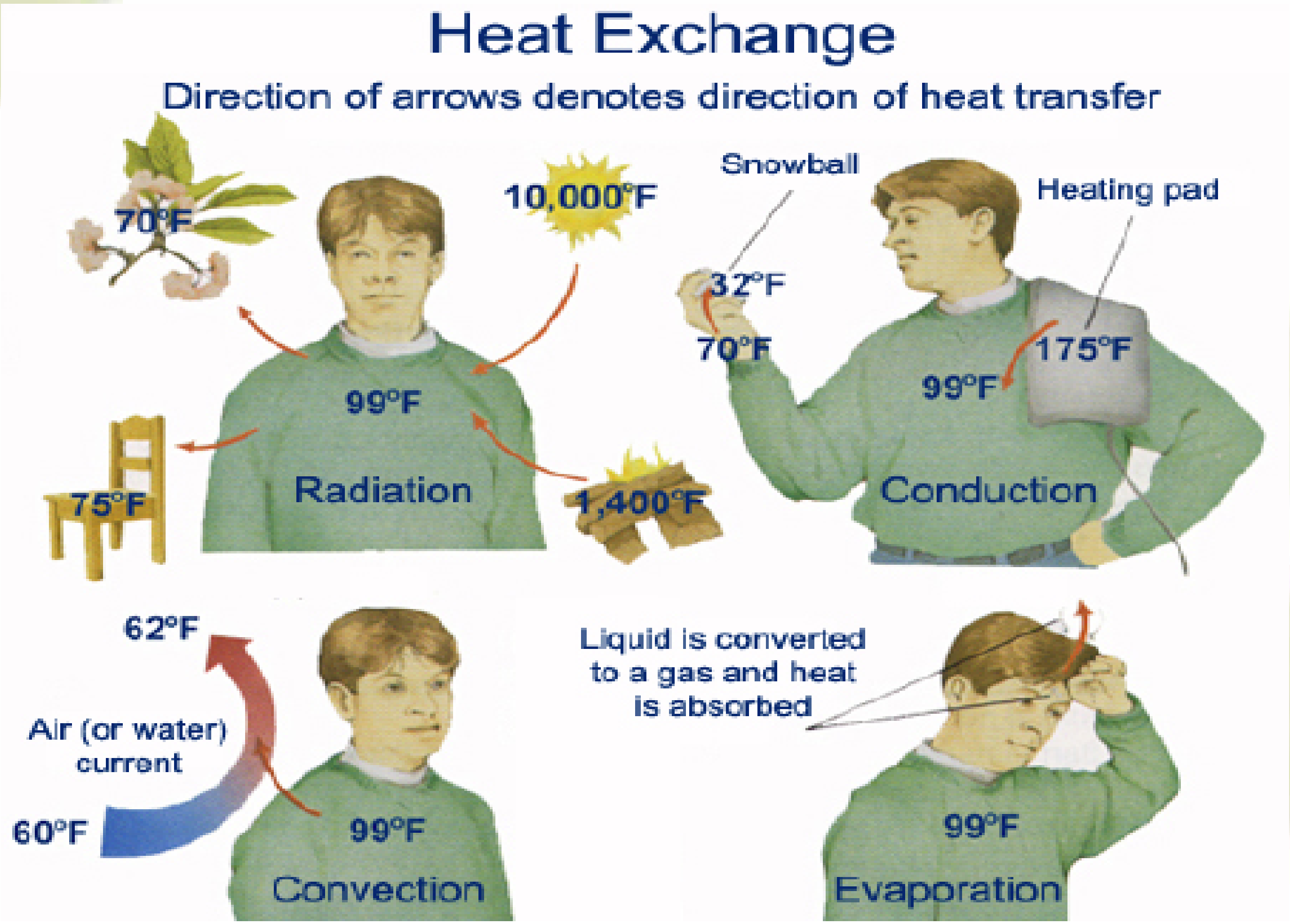
The degree of reabsorption depends on the rate of sweating.

Sweating

- **Sweating is a reflexible activity.**
- **The preoptic anterior hypothalamus (PO/AH) is the sweating center.**
- **The sweat glands are innervated by sympathetic cholinergic fibers.**
- **Epinephrine and norepinephrine**


8
6
4
2
0
Sweat rate (ml/min)
36.6
36.8
37.0
37.2
37.4
37.6
37.8
Hypothalamic temperature (°C)

Heat is lost from the skin



Regulation of thermolysis

- Regulation by circulatory system

Hot→sympathetic nerve↘

→cutaneous vasodilation

arteriovenous anastomosis open

→cutaneous blood flow↗

→skin temperature ↗

→heat loss ↗

Regulation of thermolysis

- Regulation by **sweating**

Hot → { **skin warm receptor(+)→afferent nerves**
brain T↗ →warm sensitive neurons (+)

→sweating center (PO/AH)

→sympathetic cholinergic fibers

→sweating (thermal sweating)

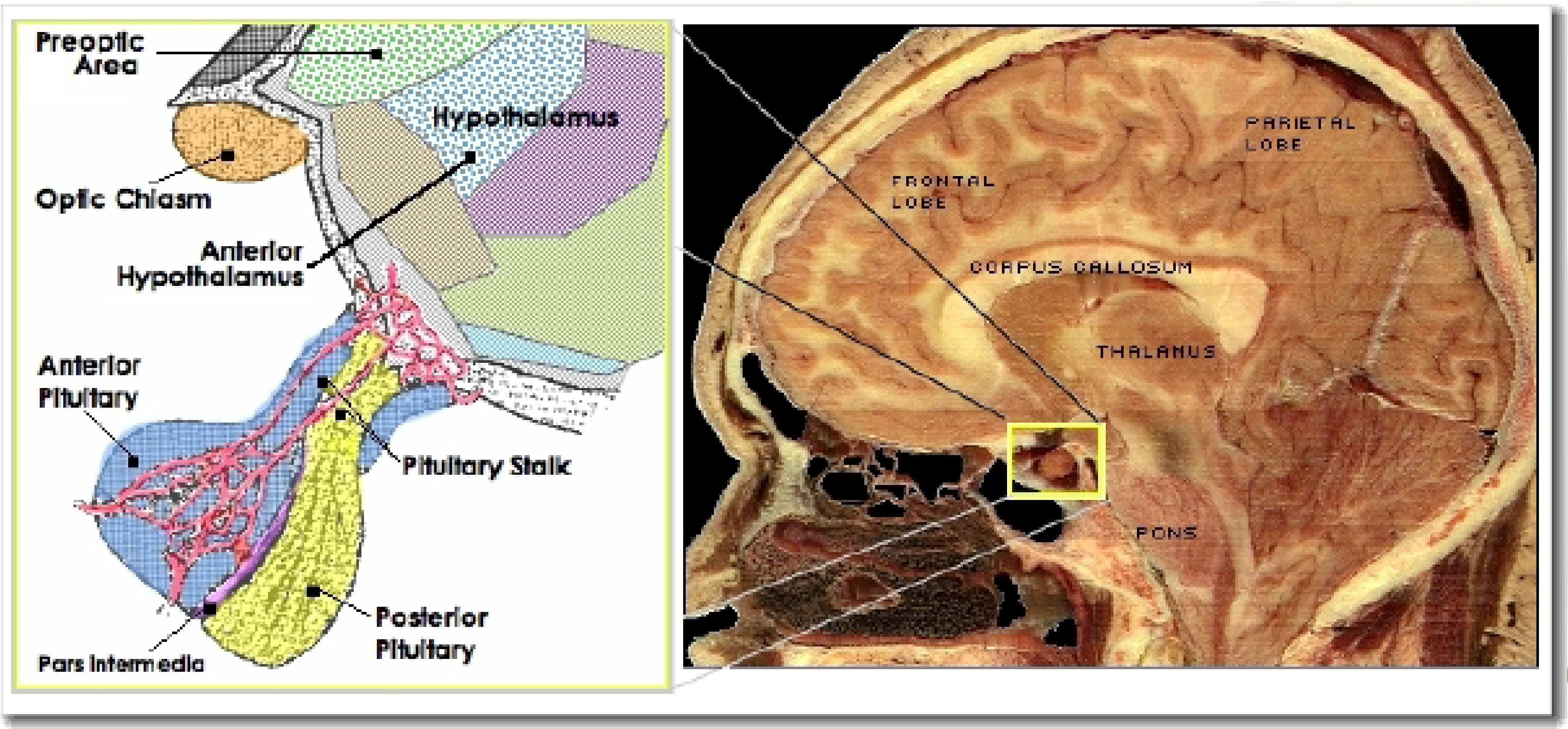
Mental sweating:

3. Thermoregulation

- Autonomic thermoregulation
- Behavioral thermoregulation

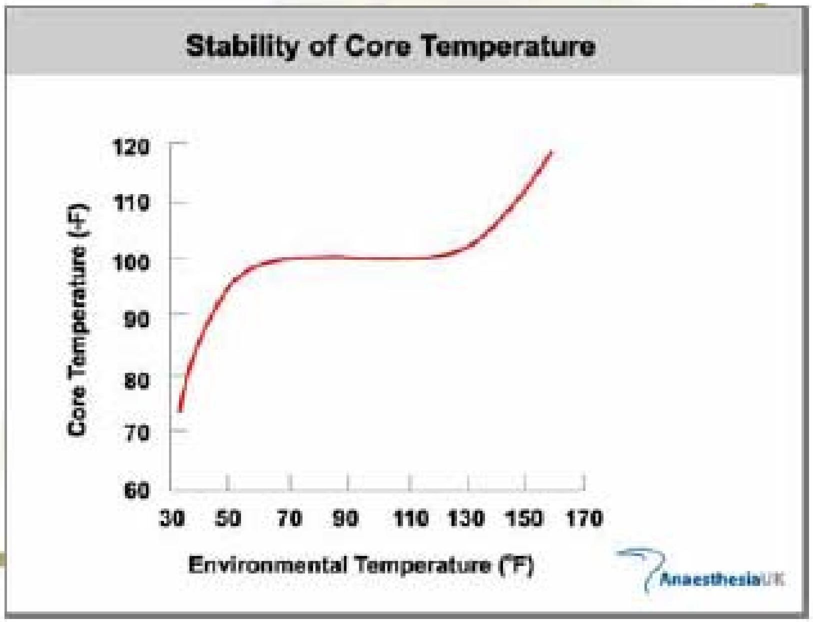
Thermoregulatory center

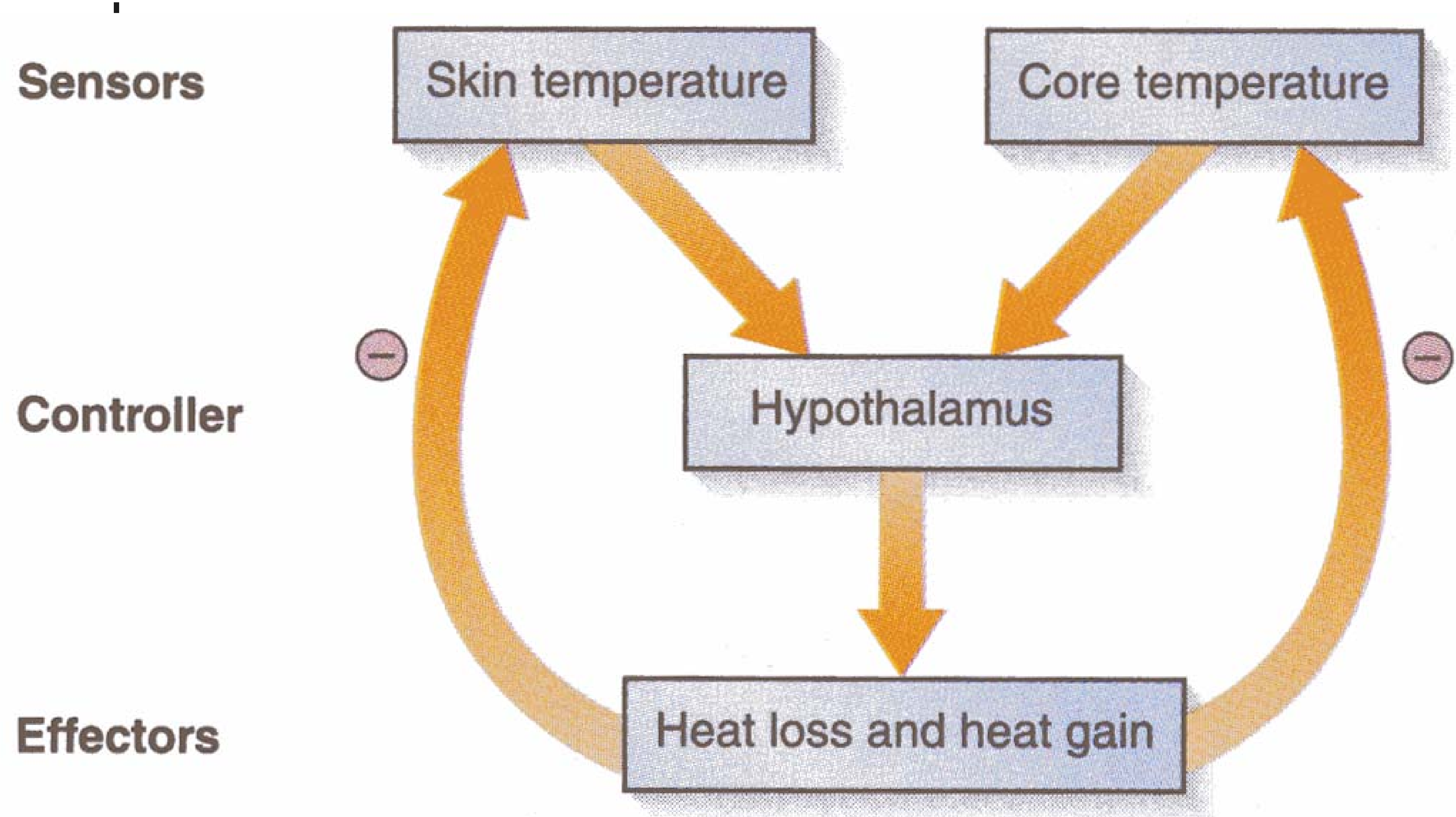
Preoptic/anterior hypothalamus (PO/AH)



Autonomic thermoregulation

- Body temperature is controlled by balancing heat production against heat loss




Sensors
Skin temperature
Core temperature
Controller
Hypothalamus
Effectors
Heat loss and heat gain

3.1 Thermoreceptor

- **Peripheral thermoreceptor**

  Cold receptor

  Warm receptor

- **Central thermoreceptor**

  Warm sensitive neuron

  Cold sensitive neuron

Peripheral thermoreceptor:

- Located in the skin and a few deep tissues of the body, such as mucosa, spinal cord and abdominal viscera. They are actually unspecified free nerve endings.
- There are far more cold receptors than warm receptors. Therefore, peripheral detection of temperature mainly concerns detecting cool and cold instead of warm temperature.
- Both the skin and deep body receptors are concerned with preventing hypothermia, that is, preventing low body temperatures.

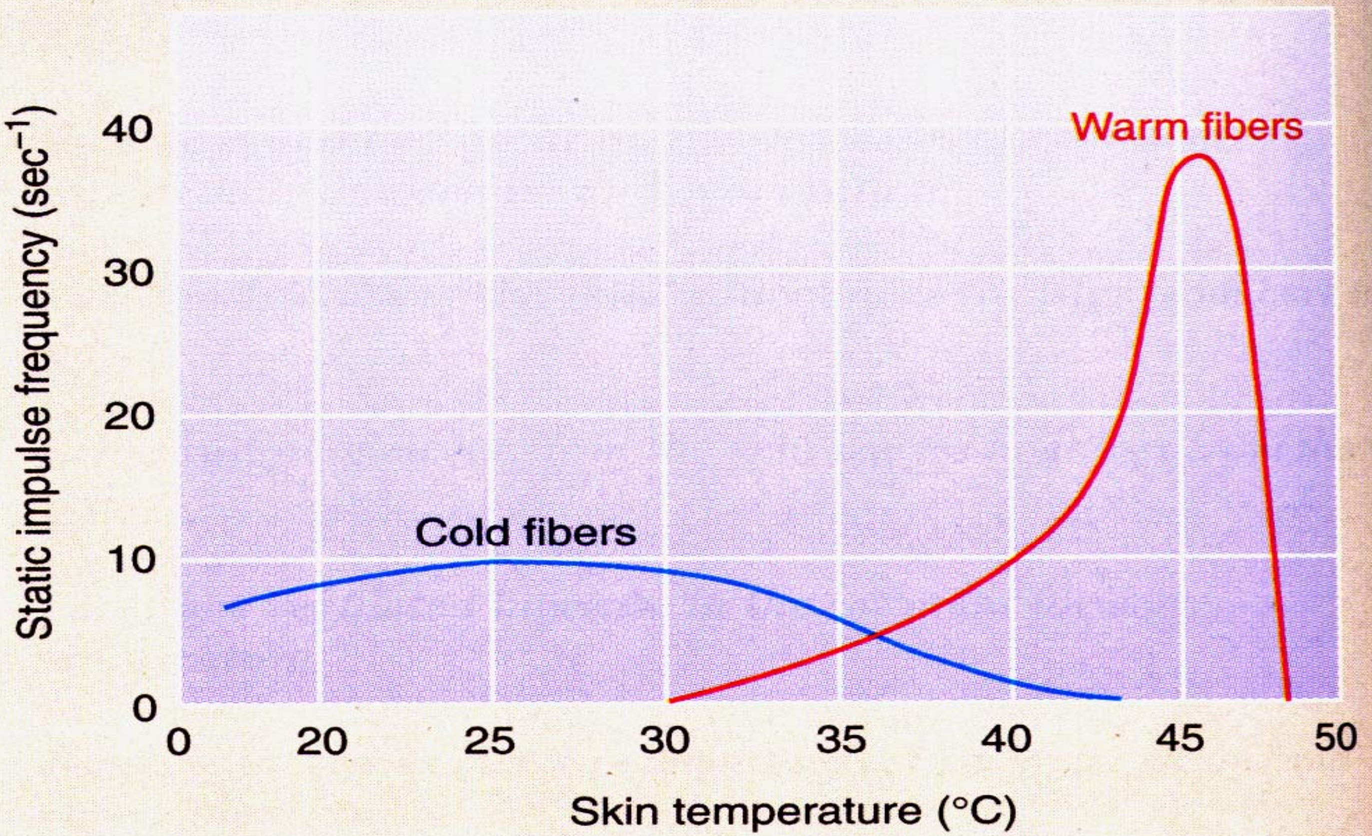
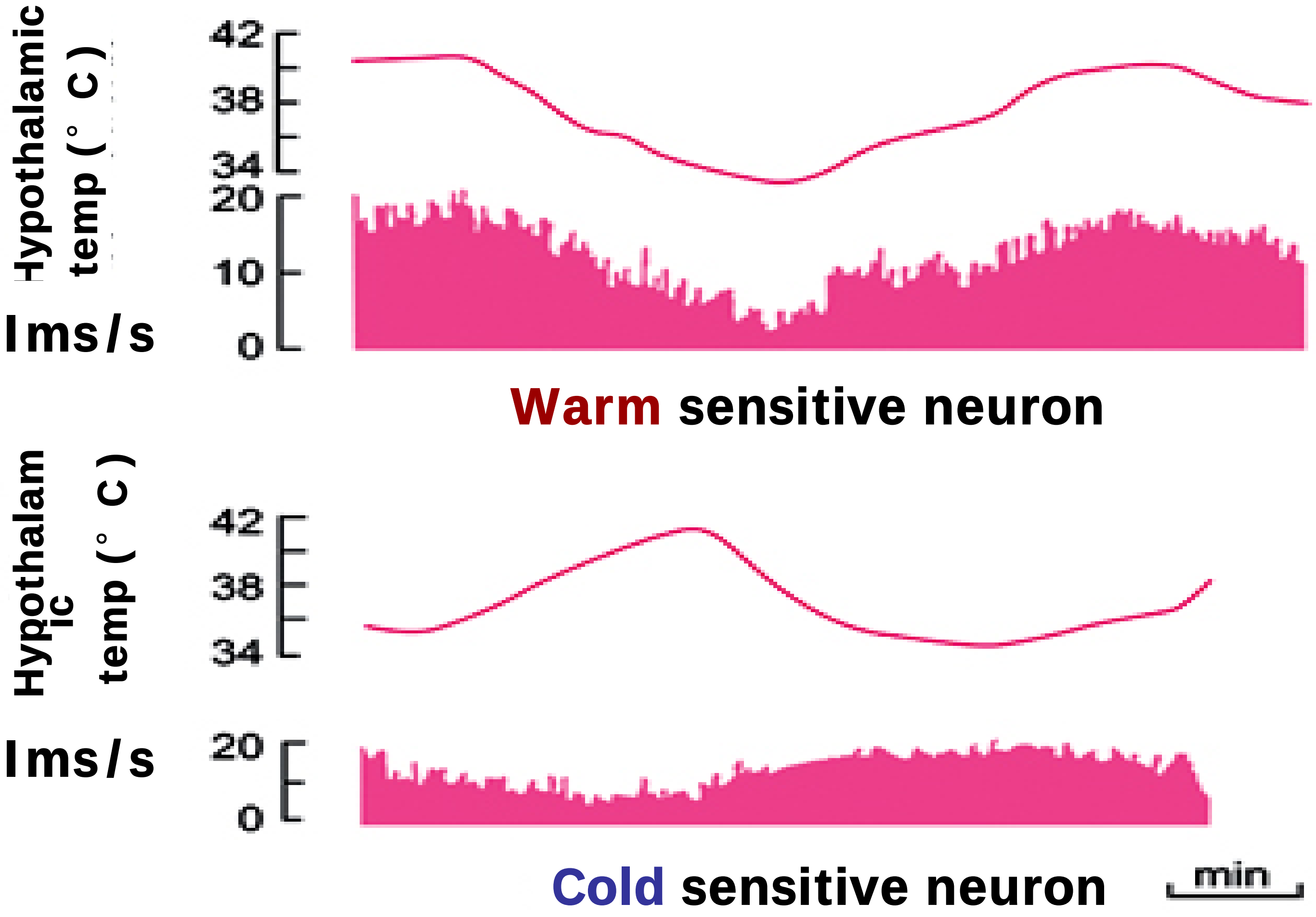


Figure 27–2

Static discharge frequency of cold and warm nerve fibers as a function of skin temperature.



The warm sensitive neurons increase their firing rate as the temperature rise. The cold sensitive neurons by contrast, increase their firing rate when the body temperature falls.

General question

How dose the body actively maintain a constant body temperature despite changes in ambient temperature?

Cold exposure

- **Immediate reflex effects**
  - **Shivering**
  - **Nonshivering thermogenesis (Sympathetic excitation)**
  - **Skin vasoconstriction**
- **Chronic effect**
  - **Thyroxine**

When the body is too hot

- Vasodilatation
- Sweating
- Decrease in heat production

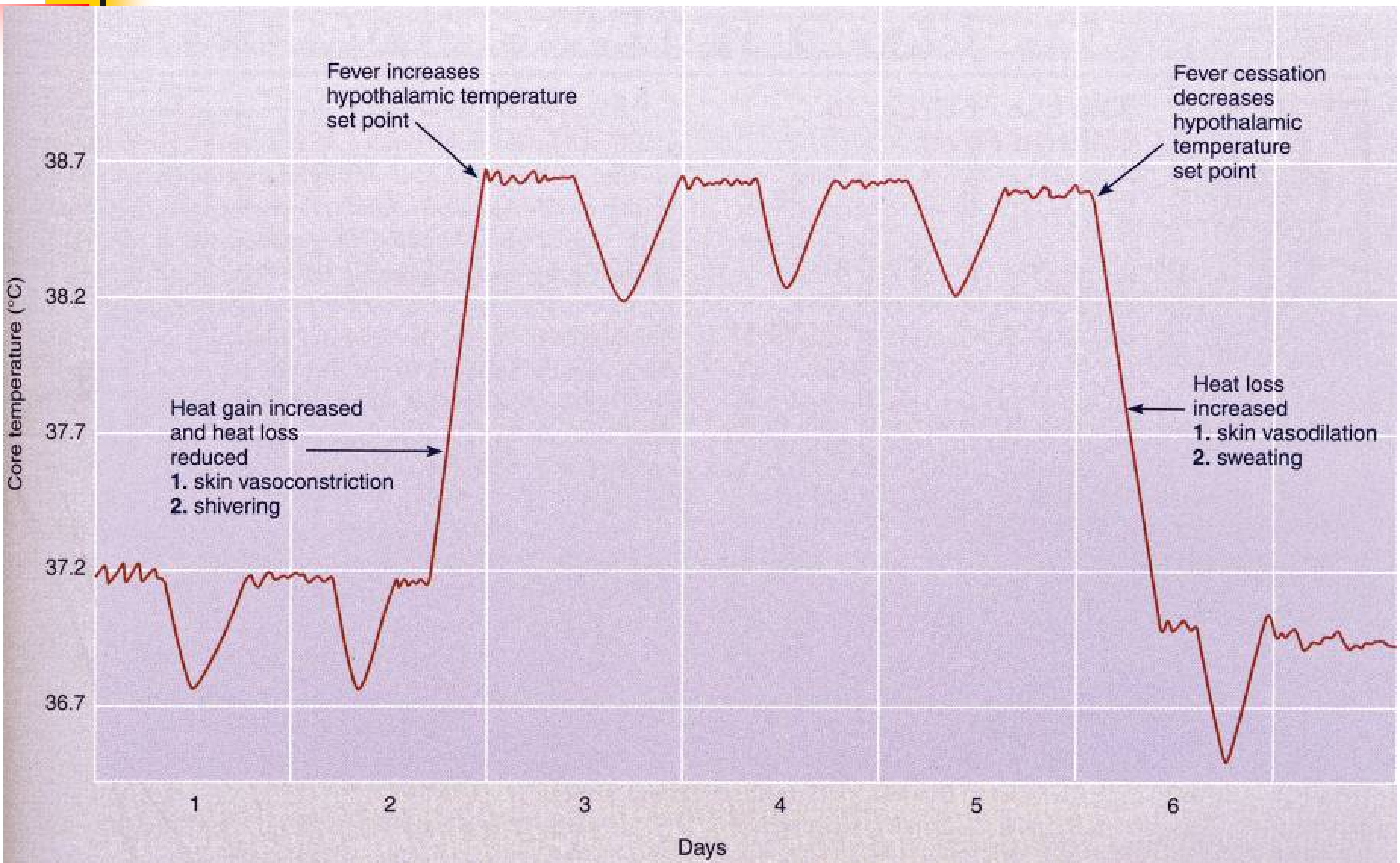
3.2 Set point theory

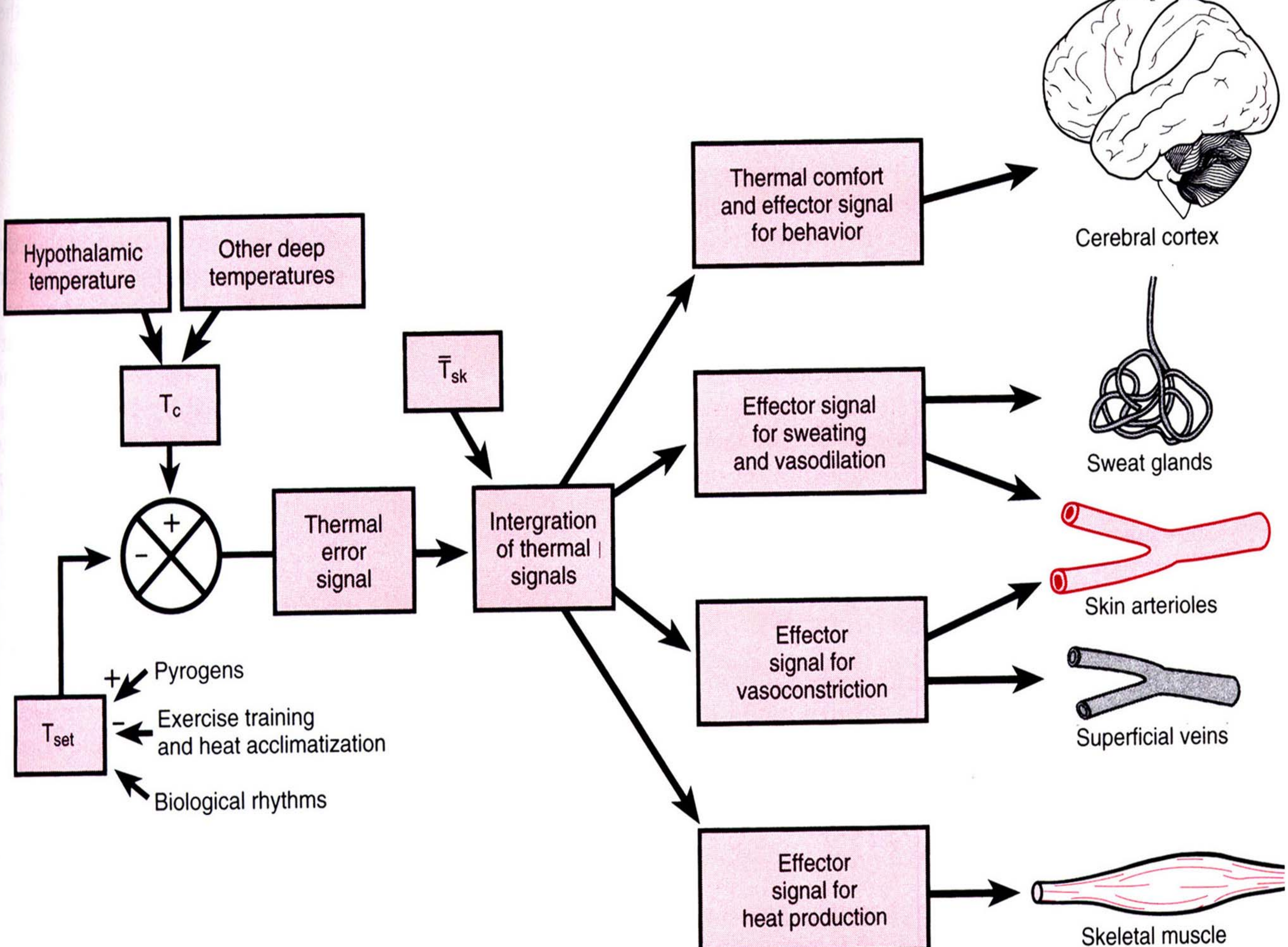
Set point is the level at which the body attemps to maintain its temperature.

When set point is raised, the result is a fever.

Most fevers are caused by infectious disease.

Time course of a typical fever





Control of human thermoregulatory re-

the set point (T_{set}) to generate an error signal, which is integrated

Summary

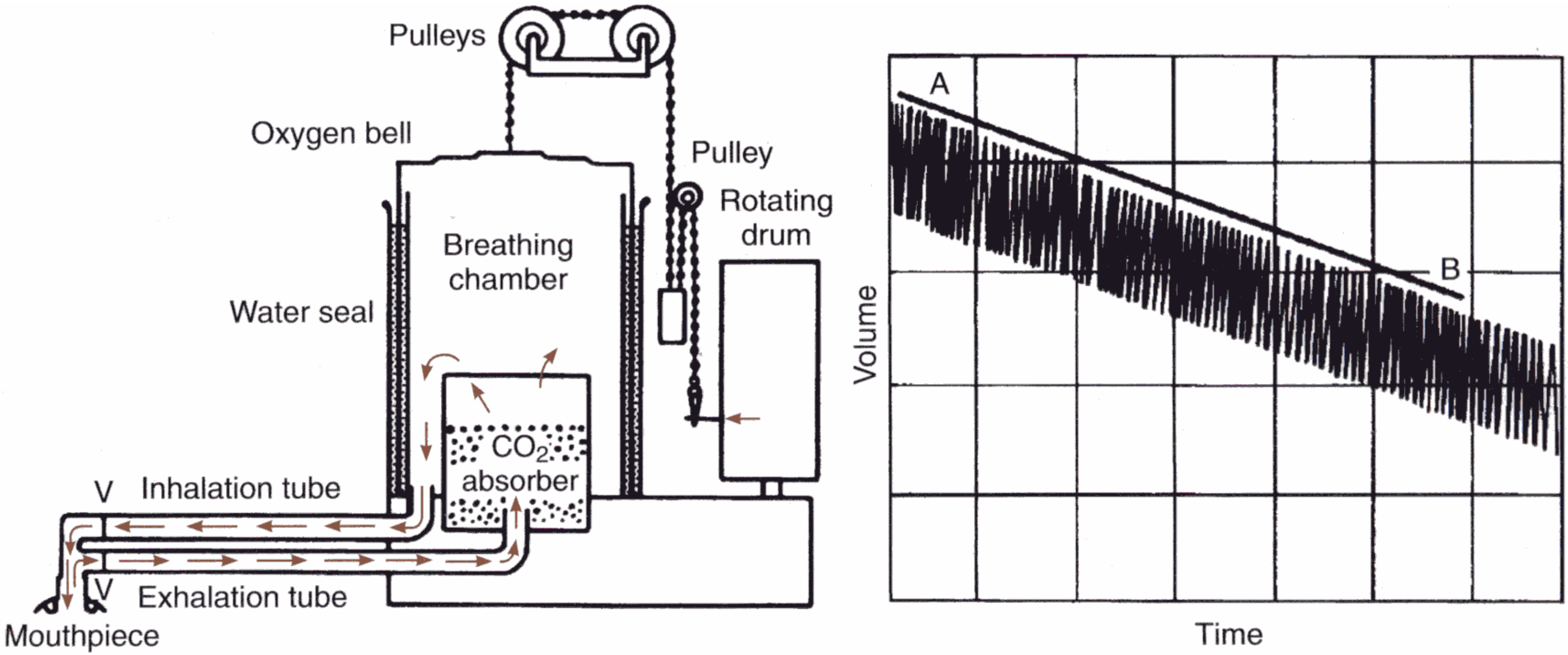
- Energy metabolism
- Measurement of energy metabolism
- Factors affecting the metabolic rate
- Basal metabolism
- Body temperature
- Forms of thermolysis
- Thermoregulation

The end

Measurement of O_2 consumption and CO_2 production

- **Measurement in a closed way**
- **Measurement in a open way**

Measurement of O_2 consumption and CO_2 production



Measurement of urea nitrogen

Urea nitrogen(g)×6.25 → protein oxidation(g)

The Caloric Values of Foods and The Relative Data

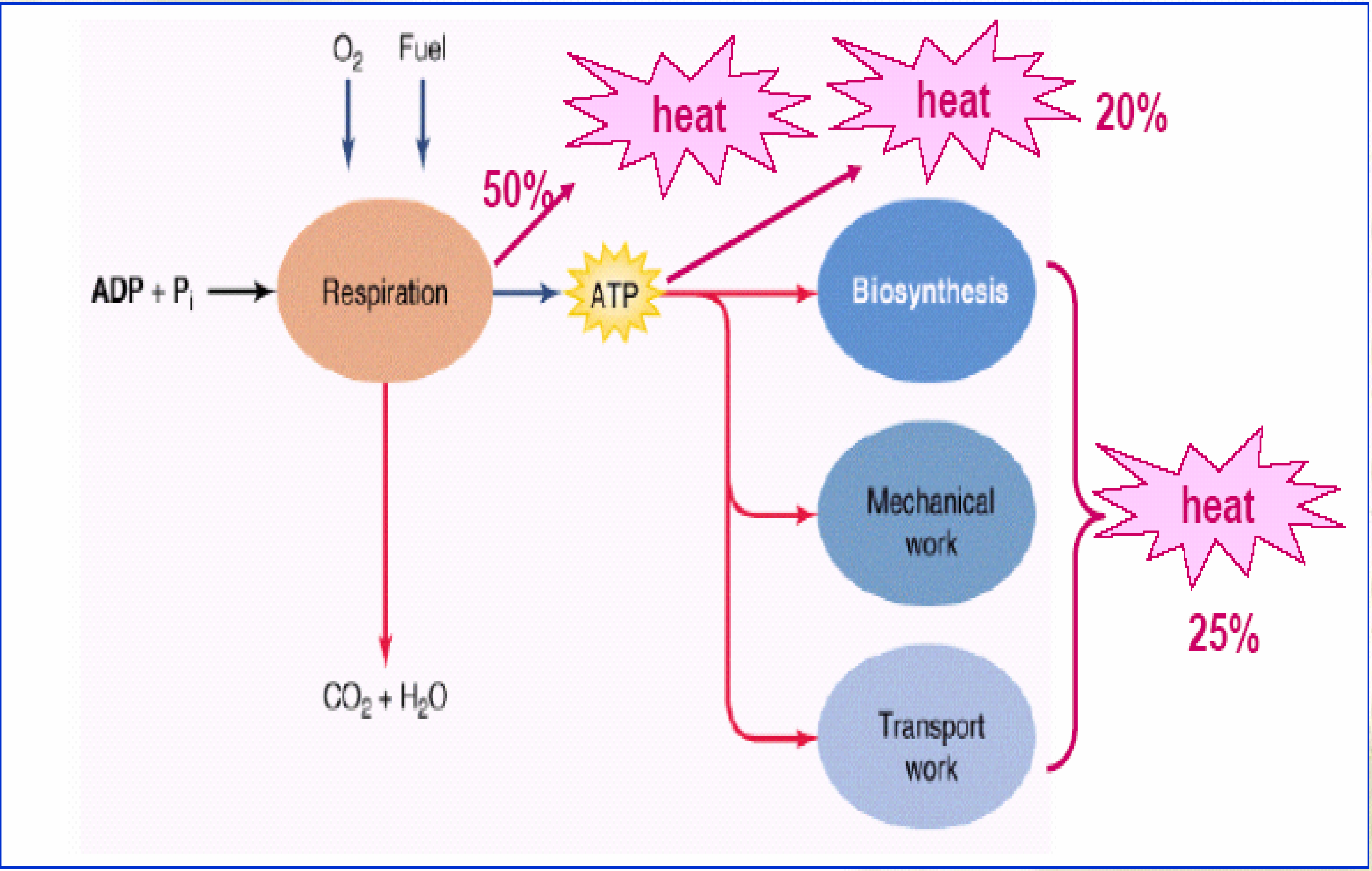
Food	Heat production (KJ/g) Physical calorie	Heat production (KJ/g) Biological calorie	Consumption of O2 (L/g)	Production of CO2 (L/g)	Thermal equivalent (kJ/g)	Respiratory quotient (RQ)
Glucose	17.16	17.16	0.83	0.83	20.94	1.00
Protein	23.44	18.00	0.95	0.76	18.83	0.80
Fat	39.77	39.77	2.03	1.43	19.67	0.71

For example: 24h O_2 consumption 400L, CO_2 production 340L, urea nitrogen 12g.

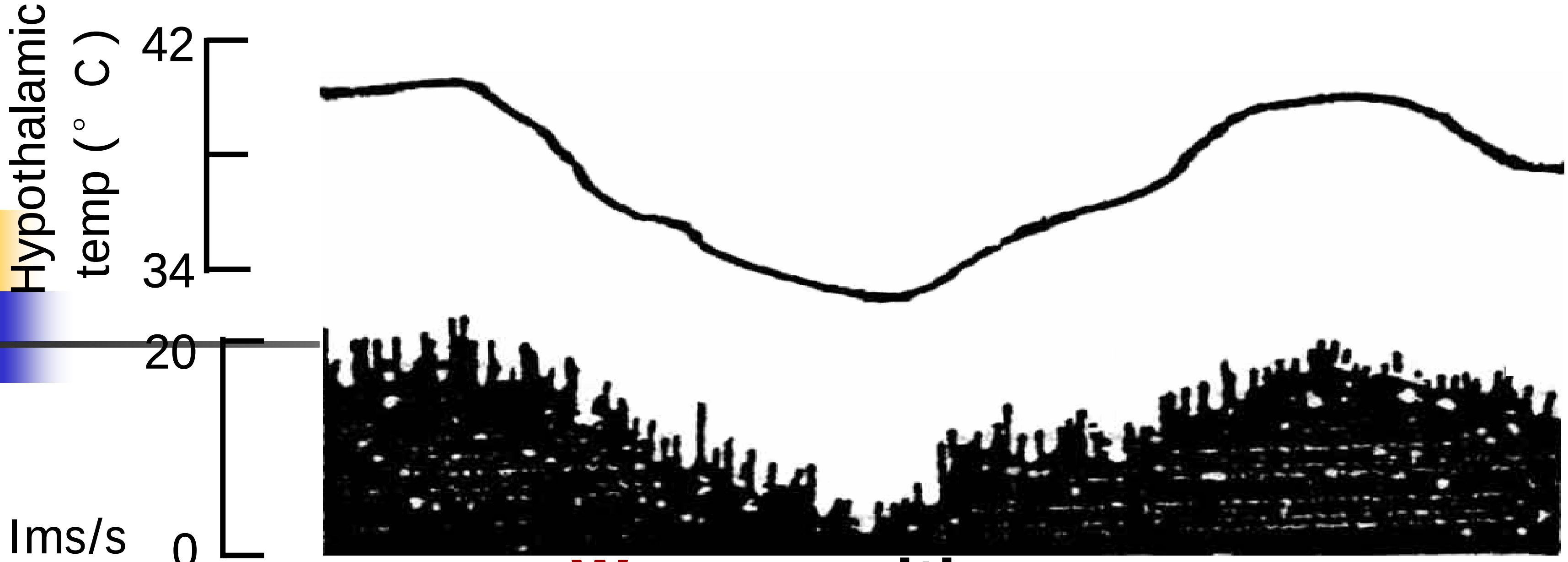
- Protein oxidation = 12 × 6.25 = 75g
- Protein heat production = 18 × 75 = 1350kJ
- Protein O_2 consumption = 0.95 × 75 = 71.25L
- Protein CO_2 production = 0.76 × 75 = 57L
- NPRQ = (340-57) / (400-71.25) = 283 / 328.75 = 0.86
- Non-protein heat production = 20.4 × 328.75 = 6706.5kJ
- Total heat production = 1350 + 6706.5 = 8056.5kJ

NPRQ	carbohydrate （%）	fat （%）	thermal equivalent of oxygen
0.707	0.00	100.0	19.61
0.71	1.10	98.9	19.62
0.72	4.76	95.2	19.67
0.73	8.40	91.6	19.72

0.80	33.4	66.6	20.09
0.81	36.9	63.1	20.14
0.82	40.3	59.7	20.19
0.83	43.8	56.2	20.24
0.84	47.2	52.8	20.29
0.85	50.7	49.3	20.34
0.86	54.1	45.9	20.40



Heat is the end product of almost all the energy released in the body



■ **Warm sensitive neuron**

■ **Cold sensitive neuron**