The Body’s Internal Environment

A Dynamic Constancy

Integration & regulation: “the whole is greater than the sum of its parts”

Homeostasis: maintaining a constant, optimal internal environment

Conformers & Regulators

Conformers: allow internal environment to conform to external
Regulators: use control mechanisms to maintain constant internal environment despite external variations
Note: an organism may be different for different variables
The same fish may be a thermoconformer and an osmoregulator

Why is Homeostasis so important?

Among other things...
• Proteins
  – including the enzymes and other molecular machines that run everything,
  • are very sensitive to deviations in conditions
    – E.g., temp & pH
    –蛋白形状
• Note: an organism may be different for different variables
  The same fish may be a thermoconformer and an osmoregulator

Conformers vs. Homeostasis?

How can they be homeostatic and conforming?
• Live in a stable environment
  – At least with respect to the conformed variable
  and/or
• Be able to make new versions of proteins for each variation
  – Requires larger genome
  – Transition to new condition must be gradual enough to allow sufficient expression of new proteins
For Example:

**Thermoregulation**

- **Poikilotherm** (variable temp): body temp ($T_B$) varies with environment temp
- **Homeotherm** (same temp): maintains constant $T_B$
- **Ectothermic**: most of body’s thermal energy acquired from environment
- **Endothermic**: most of body’s thermal energy derived from metabolism

**Environmental Heat Transfer**

- **Radiation**: radiant energy absorbed/released as thermal
- **Conduction**: thermal energy absorbed by medium
- **Heat of evaporation**: evaporating water absorbs energy

**Metabolic Heat Production**

- Energy cannot be created nor destroyed
- Energy can be transformed
- All energy transformations lose some energy as heat

**Estimating metabolic rate**:
- Measure rate of:
  - Net food energy consumption
  - Oxygen consumption
  - Carbon dioxide production
  - Heat production
Once again, ...

**Size Matters!**
- Heat exchange with the environment is proportional to body surface area ($x^2$)
- Heat generation from metabolism is proportional with body mass (or volume = $x^3$)
  - Small organisms have a large $sa/v$ ratio
  - Large organisms have a small $sa/v$ ratio

**Environment also matters!**
- Conduction & Convection in Aquatic vs. Terrestrial —
  - Water absorbs heat energy 50–100x faster than does air!
  - It’s near impossible for a small aquatic organism to be endothermic
  - It’s near impossible for a large terrestrial organism to be ectothermic

**Size & Environment Matter!**
- Conduction & Convection in Aquatic vs. Terrestrial —
  - Water absorbs heat energy 50–100x faster than does air!
  - Poikilotherms — toleration ≠ thriving
  - Even if can survive $T$ temps, do best in a small range
    - $↑↑T_b$ $↑$ stress & mortality
    - $↑↑T_b$ $↑$ metabolic rate & activity
  - Lizards —
    - $↓$ discrimination in $T$-maze tests
    - $↓$ behavior: warm lizards flee; cool lizards threaten

**Poikilotherms — Tolerating extreme cold**
- How can your proteins work below freezing?
  - Make unsaturated fats in membranes to remain fluid
  - Concentrate antifreeze alcohols (esp. glycerol) in tissues to lower freezing point
  - Synthesize ice-binding proteins to prevent ice crystals from growing

**Poikilotherms — Tolerating extreme cold**
- How can your proteins work below freezing?
  - Give up! — Go dormant
  - Largest land animals in Antarctica are tiny mites & springtails — freeze quickly most of year; thaw quickly to scavenge seal castings in brief warm season
  - Frogs and others:
    - $↑↑T_b$ $↑$ stress & mortality
    - $↑↑T_b$ $↑$ metabolic rate & activity
    - $↓$ discrimination in $T$-maze tests
    - $↓$ behavior: warm lizards flee; cool lizards threaten
Homeotherms

- Behavioral homeothermy
- Physiological homeothermy
- Anatomical homeothermy
- Part-time homeothermy
- (combinations of any/all of the above)

Behavioral Homeothermy

- Live in a stable environment
  - or
- Move with the constant conditions

Behavioral Homeothermy

- Seek shade/wet to cool off
  - Kangaroos lick their legs.
  - Camels pee on them
- Orient body to minimize radiation

Behavioral Homeothermy

- Seek sun/dry to warm up (basking)
- Orient body to maximize radiation

Behavioral Homeothermy

- Seek sun/dry to warm up (basking)
- Or maybe some wet heat!

Behavioral Homeothermy

- Seek/conserve body heat

- Japanese macaque sitting in a hot spring
- Huddling
- Sleep curled up
Physiological Homeothermy — endothermy & feedback loops

- **Negative feedback**
  - Homeostasis

  - External change triggers
  - An internal change which triggers
  - A reaction which restores
  - The normal state

Homeostasis

- “same” “stay”

- **Dynamic Constancy** (= Dynamic Equilibrium):
  - Fluctuate around set point.
  - Set point may be reset for new situations.

Homeostatic Mechanisms

- Negative feedback loops
  - **Intrinsic** — within an organ
  - **Extrinsic** — integrating multiple organs

Negative Feedback Loop

- Sensor
- Integrating center
- Effector

- Sensor activated
- Effector activates
- Normal range
- Time

Negative Feedback: Room Thermostat

- Set point
- Stimulus
- Heat produced
- Response
- Control center
- Signal via wire

Antagonistic Effectors

- Pairs of effectors with opposing actions provide much tighter control.
**Endothermic Effector Sets**

1. **Heat producer**: metabolic heat, esp. from **muscle**
2. **Heat exchanger**: integument system
3. **Heat convection** between producer & exchanger: circulatory system

*In addition to these effectors, need nervous & endocrine systems to integrate & coordinate actions.*

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**Heat Production — muscle activity**

- Some insects may fly inefficiently, just to generate enough heat to keep warm.

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**Heat Exchange — integument**

- **Skin**:
  - **Epidermis**: Pigments reduce/enhance radiant absorption
  - **Dermis**: produce hair or feathers trap air space
    - convection, conduction, evaporation
  - Pigments further reduce/enhance radiant absorption
- **Hypodermis**:
  - Blood vessels regulate convective loss of metabolic heat
  - Adipose tissue insulates from conductive transfer

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**Non-shivering thermogenesis**: uncoupling ATP production so respiration yields more heat per unit fuel

Food energy + O₂ → Cell respiration → CO₂ + H₂O + energy

ADP → ATP → **HEAT**

Esp. in brown fat of newborn & hibernating mammals
Heat Exchange — integument

- Increase insulation by increasing fat layer — blubber
- Sea otters — problem: small; no blubber; live in cold water
- Increase insulation by increasing hair density
- Increase heat production by increased metabolic rate

Hair Density of 3 Mammals

Human Rat Sea Otter

Animal

Hairs per Square cm

Insulation

Like a 150 pound person having to eat 125 hamburgers per day!!!

Average Daily Insulation for Sea Otter

Metabolism: Must eat 25% of body weight in food per day!

Heat Exchange — integument

- Polar bears — large, thick fat layer & fur
- Black skin absorbs radiant energy — fur acts as light guide to direct sunlight to skin while appearing white
- High calorie diet to support increased metabolic rate

Heat Exchange — integument

- Evaporative cooling: evaporating water absorbs much heat energy
- Wet epidermis cools much faster
- IF you can afford the water loss!

540 calories/g water evaporated

Negative Feedback: Body Thermostat
Blood flow & heat transfer

Regulation of Heat Loss

- ↑blood flow and/or ↑surface area → ↑ heat exchange

- Radiators: Increase cooling by vasodilation to long, thin appendages

- Counter-current exchangers: Decrease heat loss — reclaim it in returning blood flow
- Marine mammals, arctic homeothers, sloths

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- Baleen whales lose heat through their tongues

- Counter-current exchangers: Decrease heat loss — reclaim it in returning blood flow
- Marine mammals, arctic homeothers, sloths

- Counter-current exchangers: Also in large-body, active, endothermic poikilotherms (lamnid sharks, tunas, billfish)
- $T_b$ not constant, but swimming muscles, brain & eyes may be 10–15° warmer than ambient ocean temp
**Dynamic Constancy**
- Fluctuate around set point.
- Set point may be reset for new situations.
  - $\downarrow T_B$ at times of low activity (sleep)
  - $\uparrow T_B$ to fight infection (fever)

**Part-time Homeothermy**
- Using physiological homeothermy only under certain conditions
- Arabian oryx — when water is available

**Part-time Homeothermy**
- Using physiological homeothermy only under certain conditions
- Mouse Opossum — when food intake is sufficient

**Part-time Homeothermy**
- Long-term torpor = hibernation
- Belding ground squirrels

**Part-time Homeothermy**
- Using physiological homeothermy only under certain conditions
- Hummingbird
  - Small body = high metabolism
  - Can’t store enough energy overnight
  - Torpor: lower metabolic rate and $T_B$

**All Living Things Require Energy...**
balance energy needs with energy production

...but there are major tradeoffs in strategies for making/spending that energy
Endothermic-Homeotherms vs. Ectothermic-Poikilotherms — relative advantages

**General Rules:**
- Endotherms use more O₂/metabolism as outside temp ↓
- Ectotherms use less O₂/metabolism as outside temp ↓

**Ambient Temperature**
- Breathing Rate/O₂ Use
  - Boiling
  - Freezing

**Hyperthermia, Death**

**Hypothermia, Death**

**Endothermic-Homeotherms vs. Ectothermic-Poikilotherms — relative advantages**

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**Adjusting to a new environment**

- **Acclimatization**: an organism gradually
  - Δ metabolic rate, thickness of fat/fur/feathers; enzyme expression; etc.
  - **Aclimation**: adjusting to an artificial change
- **Adaptation**: a population shifts its characters over many generations
  - **Bergmann’s Rule**: species farther from the equator have larger body mass (cooler climate → ↓ sa/v ratio)
  - **Allen’s Rule**: colder climates → shorter appendages; warmer climates → longer

**Energy Budgets**

- Sustained energy output (Joule) of a poikilotherm (lizard) and a homeotherm (mouse) as a function of core body temperature. The homotherm has a much higher output, but can only function over a very narrow range of body temperatures.

**Thermal Neutral Zone**: temperature range requiring the lowest metabolic rate in endotherms.

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