Homeostasis & Thermoregulation

The Body’s Internal Environment
A Dynamic Constancy

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
    - Esp., temp & pH
    - $\bigotimes$ protein shape $\bigcirc$ $\bigodot$ $\bigotimes$

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

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

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: direct transfer of thermal energy
- 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 (x²).
- Heat generation from metabolism is proportional with body mass (or volume = x³).
  - Small organisms have a large SA/V ratio.
  - Large organisms have a small SA/V ratio.

<table>
<thead>
<tr>
<th>Total surface area (length x width x number of sides)</th>
<th>6</th>
<th>150</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total volume (length x width x height)</td>
<td>1</td>
<td>150</td>
<td>1500</td>
</tr>
<tr>
<td>Surface-to-volume ratio (surface area/ volume)</td>
<td>6</td>
<td>12</td>
<td>5.6</td>
</tr>
</tbody>
</table>

**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 freezing, do best in a small range
  - ↑↑Tb — stress & mortality
  - ↑↑Tb — 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

- Western fence lizard

- 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:
      - Ice on skin
      - Adrenalin rush
      - Liver glycogen released as glucose
      - Cells concentrate glucose to lower freezing point
      - 67% of body freezes solid, but cells remain fluid down to ~5°C.
      - Regains activity within hours of thawing

- A frozen arctic wood toad

Marine iguanas of the Galapagos
- Juveniles & adult females feed on exposed intertidal alga
- Only large males have sufficient body mass to generate enough heat to forage underwater

- Western fence lizard

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### 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!
  - Japanese macaque sitting in a hot spring

#### Behavioral Homeothermy
- Seek/conserve body heat
  - Huddling
  - Sleep curled up
Physiological Homeothermy — endothermy & feedback loops

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

Homeostasis

**Homeostasis**

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

Negative Feedback Loop

**Negative Feedback Loop**

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.

Redundant effectors allow stronger responses to stronger deviations.

**Negative Feedback: Body Thermostat**

- Heat production: muscle activity
- Some insects may fly inefficiently, just to generate enough heat to keep warm.

**Shivering**: "ineffective" muscle contractions
Heat Production — another effector?

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

Food energy + $O_2$ \[\rightarrow\] $CO_2 + H_2O + energy$

Cell work \[\rightarrow\] ATP \[\rightarrow\] HEAT

Esp. in brown fat of newborn & hibernating mammals

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

Heat Exchange — integument

- Increase insulation by increasing fat layer — blubber

Hair Density of 3 Mammals

Humane Rat Sea Otter

Animals

Hair Density of 3 Mammals

Insulation

Like a 150 pound person having to eat 125 hamburgers 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!

Like a 150 pound person having to eat 125 hamburgers per day!!!
Blood flow & heat transfer

Regulation of Heat Loss

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

Radiator

- Increase cooling by vasodilation to long, thin appendages

Counter-current exchangers

- Decrease heat loss — reclaim it in returning blood flow
- Marine mammals, arctic homeotherms, sloths

Marine mammals, arctic homeotherms, sloths

Rete mirabile

Baleen whales lose heat through their tongues

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

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.
  - $T_B$ at times of low activity (sleep)
  - $T_B$ 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

**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 O$_2$/metabolism as outside temp $\downarrow$.
- Ectotherms use less O$_2$/metabolism as outside temp $\downarrow$.

<table>
<thead>
<tr>
<th>Ambient Temperature</th>
<th>Breathing Rate/O2 Use</th>
<th>Boiling</th>
<th>Freezing</th>
<th>Hyperthermia, Death</th>
<th>Hypothermia, Death</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecto</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endo</td>
<td></td>
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**Thermal Neutral Zone:** temperature range requiring the lowest metabolic rate in endotherms.

**Adjusting to a new environment**

- **Acclimatization:** an organism gradually
  - $\Delta$ 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 father from the equator have larger body mass (cooler climate $\rightarrow$ $\downarrow$ sa/v ratio)
  - **Allen’s Rule:** colder climates $\rightarrow$ shorter appendages; warmer climates $\rightarrow$ 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.

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

<table>
<thead>
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<th><strong>Advantages</strong></th>
<th><strong>Disadvantages</strong></th>
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<tr>
<td>Endothermic-Homeotherms</td>
<td>Activity level independent of environmental temp</td>
<td>High food energy demands</td>
</tr>
<tr>
<td>Ectothermic-Poikilotherms</td>
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