**Temperature regulation**

What distinguishes these two species in regard to their thermal biology?

- Squirrel
- Iguana

What distinguishes these two fish species in regard to their thermal biology?

- Trout
- Tuna

What do these two endotherms have in common?

- Belding's Ground Squirrel
- Hummingbird

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**Q₁₀ and reaction rates**

- \( Q_{10} \) is a measure of the temperature sensitivity of an enzymatic reaction rate or a physiological process due to an increase by 10°C. Discontinuities are indicating physiological perturbations. Most \( Q_{10} \) values are around 2 and reflect a doubling of molecules with an energy higher than the activation energy that is required for an enzymatic reaction to occur.
Seasonal adjustments of temperature sensitivity: Acclimatization/acclimation

- If we apply a Q10 of 2 for a summer fish (24°C) we expect that a winter fish at 4°C has only 1/2 the metabolic rate. Instead it shows the same MR.

Over a range of temperatures fish can compensate (or acclimatize) for the decrease in temperature.

How is this possible? Synthesis of more efficient enzymes that catalyze more reactions at a lower temperature.

**Homeostasis:** Maintenance of "functional" metabolic rate to sustain activity levels to avoid predation as well as to feed.

Ecto- versus endothermic organisms

- Body temp of ectotherm (lizard) decreases with decreasing environmental temp, while the temp of the endotherm remains constant. The latter has to increase its metabolic rate (MR) in response to cold and hot. MR of ectotherm follows the change in environmental temp. Notice the much higher MR of endotherm.
How do endotherms produce so much heat?

- Energy is being lost as heat during every energy transfer that occurs (in both ecto- and endotherms).

So why do endotherms produce more heat?

- Concentrations gradients of ions across cell membranes (K⁺ inside, Na⁺ outside) have to be maintained.
- Proton gradients across the mitochondrial membranes have to be maintained.

Membranes of endotherms are more leaky to ions than those of ectotherms. They need to expand more energy and thus release more heat to maintain ion gradients.

Types of thermoregulation

- **Endotherms** (produce their own heat)
  - Most birds and mammals
  - Some small birds and mammals
  - Bees and some other insects
  - A few fish

- **Heterotherms** (allow body temperature to fluctuate)
  - Mole-rats
  - Many insects
  - Some terrestrial invertebrates
  - Freshwater invertebrates
  - Most freshwater fish

- **Ectotherms** (rely on heat from environment)
  - Amphibians, lizards, snakes, turtles, crocodiles
  - Marine invertebrates
  - Marine fish

- **Ectotherms** (keep body temperature constant)
  - Polar marine fish and invertebrates

- **Torpor/hibernation**
  - Hummingbirds/squirrels and bears

- **Tuna and mackerel**
## Ecto- versus endothermy

<table>
<thead>
<tr>
<th></th>
<th>Ectotherms</th>
<th>Endotherms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature produced</td>
<td>depends on environment</td>
<td>independent of environment</td>
</tr>
<tr>
<td>Metabolic rate</td>
<td>10 times lower</td>
<td>10 times higher</td>
</tr>
<tr>
<td>Energy intake</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Temperature range of enzyme function</td>
<td>narrow to wide</td>
<td>(mostly) narrow</td>
</tr>
<tr>
<td>Behavioral strategies</td>
<td>sun basking</td>
<td>torpor and hibernation</td>
</tr>
<tr>
<td></td>
<td>(increase in $T_b$ above ambient temp)</td>
<td>(lower energy intake required)</td>
</tr>
</tbody>
</table>

**Thermoregulation in ectotherms: Behavior**

- A lizard's body temp is often quite different from ambient temp: **Behavioral strategies**: spending time in a burrow, basking in the sun, seeking shade, climbing vegetation, and changing its orientation with respect to the sun.
Types of heat exchange

Heat flows "downhill," from regions of higher to regions of lower temperature: through convection, evaporation, radiation and conduction.

liquid becomes gas (heat loss) - release of energy in form of heat
transfer of heat between two physical bodies that are not in direct contact

direct transfer between two physical bodies (surface area, gradient, heat conduction)
flow of air or water over a physical body (maintains large gradient)

Heat budget

- Body heat usually comes from metabolism and solar radiation ($R_{abs}$ for radiation absorbed). Heat leaves the body by: radiation emitted ($R_{out}$), convection, conduction and evaporation. Heat can also enter the body via convection and conduction - the sign of those factors will change to negative.

$$\text{heat}_{in} = \text{metabolism} + R_{abs} = R_{out} + \text{convection + conduction + evaporation}$$

- The dividing of the heat budget into various components allows us to quantify and compare the various adaptations of organisms to cope with their thermal environment.

Most of the heat that an organism loses depends on the surface temperature of the animal. This temperature can be controlled by altering the blood flow under the skin.
**Intertidal zonation**

How does temperature contribute to setting vertical distribution patterns in the rocky intertidal?

Vertical distribution of *Tegula* congeners

- **T. funebralis** (T. rugosa)  
  +1.5 to -0.5 m  
  Mean low low water

- **T. brunnea**  
  -0.5 to -7 m  
  Lowest low tide

- **T. montereyi**  
  -3 to -12 m

Riedman et al. 1981, Watanabe, 1984
The different thermal niches of *Tegula funebralis* and *T. brunnea*?

**T. funebralis**

**T. brunnea**

- **Temperature (°C)**: 10, 15, 20, 25, 30, 35, 40
- **Tidal Height (m)**: -1, 0, 1, 2

**Thermotolerance in *Tegula* congeners**

1°C per 12 min (field-acclimatized) (n = 20 each)

**Heat-shock proteins (Hsps)**

Hsps have two general functions:

1. Hsps facilitate folding under *non-stressful conditions*:
   - during translation (molecular chaperones)
   - during transport of proteins across membranes.

2. Under *stressful conditions*:
   - Hsps stabilize proteins (marginal stability)
   - catalyze the refolding of partially denatured proteins.

**Heat-shock response**

- Strong induction of preferential heat-shock protein (Hsp) expression, e.g., Hsp70, Hsp90.

- Induced by environmental stress: hypoxia or hyperoxia, osmotic shock, pH change, heat; alcohols, toxins, and free radicals.

- Environmental stressors denature proteins (marginal stability of proteins).

- Hsps enhance thermotolerance.
The onset temperature ($T_{on}$), the temperature of maximum synthesis ($T_{peak}$) and the upper temperature ($T_{off}$) of heat-shock protein 70 (Hsp70) synthesis are lower in the subtidal more heat-sensitive species.

Vertical distribution range, body temperatures, thermal tolerance and heat-shock protein synthesis are positively correlated in Tegula congeners.

Heat production and conservation in ectotherms

- Heat produced through muscle activity gets lost through the gill. Tuna, great white sharks and mackerels all have the ability to trap most of the heat through a countercurrent heat exchanger which maintains a constant gradient over a longer distance (incoming arteries are getting warmed up by outgoing veins) to transfer the heat. Why is this beneficial? Greater power output.

(a) "cold" fish

Gills: blood is oxygenated and cooled to SW temp.

Heart pumps blood to the gills.

Veins return blood to heart.

Cold blood flows through the center of the fish in the large dorsal aorta.

Arteries carry blood to the tissues.

(b) "hot" fish

Gills: blood is oxygenated and cooled to SW temp.

Heart pumps blood to the gills.

Veins return blood to heart.

Cold blood flows from the gills to the body in arteries just under the skin.

Countercurrent heat exchanger: arterial blood flowing into the muscle is warmed by venous blood flowing out of muscles.
How do mammals regulate their body temperature?

**Heat generation in mammals**

How do endotherms maintain a constantly high temperature? Through a higher density of "burners" or mitochondria in their cells.

**Brown adipose tissue**: Abundant with fat and mitochondria, rich blood supply. A protein called thermogenin uncouples the movement of protons across membranes from ATP production, burning fuel without producing ATP but heat is still released.

Found in newborn humans and many small mammals and hibernators.

**Shivering**: The organism uses the contractile machinery of skeletal muscles to consume ATP without movement. The conversion of ATP to ADP releases heat.

(a) Cells in normal adipose tissue
(b) Cells in brown adipose tissue
Heat conservation: Countercurrent heat exchange

Air conducts heat poorly and is therefore a good insulator. Structures that trap air can insulate: the underfur in mammals and down feathers in birds.

Decreased surface area: smaller appendages and larger body size.

Decreased blood flow reduces heat loss.

Water is an effective conductor of heat, quickly draining heat away from an organism. Marine mammals either have fur or blubber.

How to deal with overheating

• Increase blood flow (dilation of arteries) to the surface of the body.

• Evaporative water loss (sweating): 1 g of water absorbs about 580 calories of heat when it evaporates. The heat comes from the skin or from an internal epithelium.

  Panting increases the flow of air across moist surfaces (convection).

• Increase in body temperature: temporary "storage" of heat and release during night time when temperatures are cooler. A camel’s body temperature can increase by 7°C during the day (when it is deprived of drinking water). ☀
The vertebrate thermostat

Thermal sensors in the hypothalamus detect changes in blood temperature. Additional info come from temperature sensors in the skin. Set points depend on day time and activity. Response: Shivering, increased activity of brown adipose tissue and blood flow through surface arteries.

Experiment

Question: Does the hypothalamus act as a thermostat?

Implant probes into brain that can heat or cool the hypothalamus. Measure metabolic rate and hypothalamic temperature.

Squirrel was maintained at low environmental temp. When the hypothalamus was cooled...

Thermal sensors in the hypothalamus detect changes in blood temperature. Additional info come from temperature sensors in the skin. Set points depend on day time and activity. Response: Shivering, increased activity of brown adipose tissue and blood flow through surface arteries.

Ground squirrel brain

Ground squirrel

Hypothalamus

Squirrel was maintained at low environmental temp. When the hypothalamus was cooled...

Heating the hypothalamus...

.. its metabolic heat production increased...

.. and the animal’s body temp rose.

.. decreased its metabolic heat...

.. and the animal’s body temp fell.

Conclusion: The hypothalamus acts as a thermostat.

Principles of homeostasis

Negative regulatory feedback loop. Control unit to achieve homeostasis.

Metabolic rate through shivering and activity of BAT, regulation of blood flow, sweating etc.

Blood and skin temperature

Temperature sensors in hypothalamus and skin

Hypothalamus (in all vertebrates)

Figure 41-14a. Biological Science, 3rd
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Energy conservation: Torpor and hibernation

Some birds and mammals use regulated hypothermia (versus hyperthermia) to survive periods of cold and food scarcity. Torpor is a daily, hibernation a seasonal phenomenon.

During winter bouts of hibernation are interrupted by brief returns to normal temps at 37°C (arousal).

Entrance into hibernation: drop in metabolic rate (MR) is followed by a drop in temp.

Bout lasts days to weeks.

Arousal: large rise in MR followed by warming.