Regulating the Internal Environment

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An Overview of Homeostasis

Regulating and conforming are the two extremes in how animals cope with environmental fluctuations

- **Regulator**: animals use mechanisms of homeostasis to moderate internal change in the face of external fluctuation.
- **Conformer**: animals allow some conditions within their bodies to vary with certain external changes.
- No organisms are perfect regulators or conformers: Even for a particular environmental variable, a species may conform in one situation and regulate in another.

Homeostasis balance an animal's gains versus losses for energy and materials

- Animals are open systems that must exchange energy and materials with their environments.
  - Normally, an animal's inputs of energy and materials only exceed its outputs when there is a net increase in organic matter due to growth and reproduction.
  - Most energy and materials budgets are interconnected, with changes in the flux of one component affecting the exchanges of other component.

Regulation of Body Temperature

- Within the optimal temperature range, many animals can maintain a constant internal temperature as the external temperature fluctuates.

Four physical processes account for heat gain or loss

- **Conduction**: direct transfer of heat between molecules - 1% heat loss.
- **Convection**: mass flow of air or liquid past the surface - 40% heat loss.
- **Radiation**: emission of electromagnetic waves - 50% heat loss.
  - The fur of both polar bears is actually clear, not white. Each hair functions like an optical fiber that transmits UV radiation to the skin.
- **Evaporation**: the loss of heat from the liquid surface - 9% heat loss.

Ectotherms have body temperatures close to environmental temperature; endotherms can use metabolic heat to keep body temperature warmer than their surroundings

- **Endotherm**s usually maintain a consistent internal temperature even as the environmental temperature fluctuates.
  - Endotherms generally consume much more food than **ectotherm**s of equivalent size.
  - These connections between body temperature, aerobic metabolism, and mobility were important in the evolution of endothermy.
- Cold-blooded and warm-blooded: misleading

Thermoregulation involves physiological and behavioral adjustments that balance heat gain and loss

1. Adjusting the rate of heat exchange between an animal and its environment.
   - **Vasodilation** and **vasoconstriction**:
   - **Countercurrent heat exchange** in the legs of a bird or the flippers of a dolphin: heat transfer from arteries to parallel veins.
2. Cooling by evaporative heat loss
   - Panting can increase evaporation from the respiratory tract.
   - Sweating can increase evaporation across the skin.
3. Behavioral responses: re-location
4. Changing the rate of metabolic heat production.
   - Many species of mammals and birds can double or triple their metabolic heat production when exposed to cold.

Most animals are ectothermic, but endothermy is widespread

<u>Mammals and Birds</u> have two ways to increase the rate of heat production:

1. Increasing contraction of muscles: moving around or shivering
2. Action of **epinephrine** and **thyroxine**: **non-shivering thermogenesis** (NST) takes place in **brown fat** located in the neck and between the shoulders -specialized for rapid heat production.

- Birds:
  - Cooling mechanism: no sweat glands, but instead using panting to promote evaporative heat loss, such as vascularized pouch in the floor of the mouth.
  - Reducing heat loss: Feathers provide excellent insulation, and **countercurrent heat exchanger**.

- Marine Mammals: Seals, whales, etc.
  - Reducing heat loss: a thick layer of insulating fat, blubber, just under the skin. Countercurrent heat exchange in the tail and flippers (no blubber).
  - Cooling mechanism: Blood vessels allowing greater amounts of blood to be cooled by the surrounding water.
- Terrestrial mammals:
  - Reducing heat loss: raising their fur to increases insulation - goose bumps.
  - Cooling mechanism: Sweating or spreading saliva on body surfaces.

<u>Amphibians and Reptiles</u> are generally ectotherms.

- Increasing heat uptake by **behavioral adaptation**s: seeking warm places, orienting themselves toward heat sources such as solar heat to in crease heat uptake and expanding the body surface exposed to a heat source.
- Cooling: sitting in the shade, dipping into water or turning in another direction to lower the surface area exposed to the sun.

<u>Fishes</u>

-The body temperature is usually within 1- 2℃ of the surrounding water temperature.

- Some large, active fishes maintain an elevated temperature at their body core: The heat generated by their swimming muscles is retained by specialization of the circulatory system.

Invertebrates

- Absorption of sunlight: desert locust (ectotherm)
- Large flying insects generate internal heat by contracting all the flight muscles like shivering in synchrony (endotherm): Insects can sustain the intense activity.
- Honeybees use social organization to increase body temperature.
  - Increasing temperature: individuals move from the cooler outer edges of the cluster to the warmer center and back again--distributing the heat.
  - Cooling: transporting water to hive and fanning with their wings to promotes evaporation and convection.

Feedback Mechanism in Thermoregulation

- **Thermostat**: control center (warm and cold receptor) in the **hypothalamus**

Adjustment to Changing Temperatures

- **Acclimation**: Many animals can adjust to a new range of environmental temperature over a period of many days or weeks.
  - Producing variants of enzymes that have the same function but different temperature optima.
  - Membranes change in the proportions of saturated and unsaturated lipids.

- **Stress-induced protein**s like **heat-shock protein** in bacteria, fungi, plant cells and animal cells: synthesized in minutes to maintain the integrity of other protein that would be denatured by severe heat.

Torpor conserving energy during environmental extremes

- **Torpor**: An alternative physiological state in which metabolism decreases and the heart and respiratory system slow down.
- **Hibernation**:
- **Estivation (**or **aestivation)**: allowing an animal to survive long periods of elevated temperatures and diminished water supplies.
  - Hibernation and estivation are often triggered by seasonal changes in the length of daylight. As the days shorten, some animals will eat huge quantities of food before hibernating.
- **Diurnation**: lasting for much shorter time periods than hibernation.
  - All endotherms show a daily torpor that is not triggered by the availability of food, and is a built-in rhythm controlled by the **biological clock**. The need for sleep in humans may be a remnant of daily torpor.

Water Balance and Waste Disposal

Water balance and waste disposal depend on transport epithelia

- **Transport epithelium**: A layer or layers of specialized epithelial cells that regulate solute movement. Joined by **tight junction**s, the epithelial cells form a selectively permeable barrier at the tissue-environmental boundary.

An animal's nitrogenous wastes are correlated with its phylogeny and habitat

- Nitrogenous wastes are metabolites from proteins and nucleic acids.

<u>Ammonia</u>: very soluble in water and toxic.

  - Most aquatic animals excrete ammonia

Urea: 100,000 times less toxic than ammonia

- Mammals, adult amphibians, many marine fish and turtles excrete urea: an important adaptation for living on land.
- Liver production: a metabolic cycle combines ammonia with CO_2

Uric acid: much less soluble in water than either ammonia or urea.

- The major nitrogenous waste of land snails, insects, birds, and some reptiles.

Cells require a balance between osmotic gain and loss of water

- **Osmosis**, a special case of diffusion, is the movement of water across a selectively permeable membrane.
- **Osmolarity** (mOsm/L):
  - Water flows by osmosis from hypo-osmotic solution to hyperosmotic one.

Osmoregulators expend energy to control their internal osmolarity; osmoconformers are isoosmotic with their surroundings

- **Osmoconformer**: Animals do not actively adjust their internal osmolarity.
- **Osmoregulator**: Animals that are not isoosmotic with their surroundings.

Maintaining Water Balance in the Sea

- Marine animals (not osmoconformers):
  - Shark and ray:
    1. Pumping salt out through the anus by rectal glands.
    2. Urea retention: producing **trimethylamine oxide** (**TMTO**) to protect themselves from the damaging effect of urea.
  - Bone fish: using the epithelium of their gills to pump out the excess salt.

Maintaining Osmotic Balance in the Fresh Water

- Freshwater animals:
  - Freshwater protozoa: contractile vacuoles in *Amoebae* and *Paramecium*.
  - Fishes:
    1. Excreting large amount of very dilute urine
    2. Gill **chloride cell**s pumping sodium and chloride ions into the blood

Special Problem of Living in Temporary Waters

- **Euryhaline** animals: living in fluctuations of osmolarity, e.g., *Artemia*.
- **Anhydrobiosis** (**cryptobiosis**): loss almost all body water and survive in a dormant state when their habitats dry up, e.g., tardigrades (water bears) use **trehalose** (one kind of disaccharides) to replace water associated with membrane and protein.

Maintaining Osmotic Balance on Land

- Prevent dehydration: waxy layers or keratinized skin cells.
- Behavioral adaptation: 1) thirst controlling by nerve and hormones; 2) **nocturnal**; 3) reducing water loss from excretory organs.

Excretory Systems

Most excretory systems produce urine by refining a filtrate derived from body fluids: an overview

- **Filtration**, **reabsorption** and **secretion**

Diverse excretory systems are variations on a tubular system

Protonephridia: Flame-Bulb Systems

- Flame-cell system (flame cell, tubule, and nephridiopore): dead-end type and function mainly in osmoregulation.

Metanephridia

- Each segment of the earthworms has its own pairs of metanephridia: internal openings (**nephrostome**) to collect body fluids, a network of capillaries, collecting tubule, bladder, and nephridiopore.

Malpighian Tubules

- Dead-end tubules: pump salts and nitrogenous wastes from the blood to perform osmoregulation
- The rectum pumps most of the solutes and water back into the hemolymph.

Vertebrate Kidneys

- Function in both excretion and osmoregulation:

Nephron and associated blood vessels are the functional units of the mammalian kidney

Structure and Function of the Nephron and Associated Structure

- Outer **renal cortex** and inner **renal medulla**:
  - kidney (cortex, medulla, renal pelvis) → ureter → bladder → urethra

- 1100 ~ 2000L blood → 180L filtrate → 1.5L urine

- **Nephron**: the functional unit of the kidney
  1. **Cortical nephron**s have reduced loops of Henle: about 80%.
  2. **Juxtamedullary nephron**s have well-developed loops of Henle that extend to the medulla of the kidney: about 20%.
  - **Bowman's capsule**: a cup-shaped receptacle embraces a ball of capillaries (**glomerulus**):

- **Filtration**: The fluid containing water, urea, salts, and other small molecules present in blood flow from capillaries into the renal tubule:
  - Nonselective in Bowman's capsule with regard to small molecules: **Podocyte**s along the porous capillaries function as a filter.

  - Pathway of the filtrate: Bowman's capsule → proximal tubule → **loop of Henle** → distal tubule → collecting duct (the filtrate is called urine)
  - Blood vessel associated with the nephron: renal artery → afferent arteriole → glomerulus → efferent arteriole → peritubular capillaries → vasa recta → renal vein

- **Secretion**: in proximal and distal convoluted tubules - selective addition (both passive and active transport) of plasma solutes to the filtrate.
  - H^+ secretion: maintaining a constant pH for the body fluids.
- **Reabsorption**: nearly all the sugars, vitamins, and other organic nutrients in the filtrate are reabsorbed; most of the water of the filtrates is reabsorbed in mammals and birds

From blood filtrate to urine: a closer look

1. **Proximal (convoluted) tubule**:
   - Reabsorption: glucose, a.a., NaCl (75%), water (70%), K^+, HCO_3^- and other nutrients
   - Secretion: NH_3, H^+, drugs and other poisons (processed in the liver)
2. **Descending limb of the loop of Henle**: permeable to water only.
   - NaCl concentration increases as water moves out by osmosis.
3. **Ascending limb of the loop of Henle**: permeable to salt, but not to water.
   - In thin segment of ascending limb, NaCl diffuses out of tubule. However, Thick segment of ascending limb actively pumps NaCl out of the tubule.
4. **Distal tubule**: secreting K^+ and H^+; reabsorbing NaCl, HCO_3^- and water.
5. **Collecting duct**: permeable to water but not to salt.
   - Determining how much salt is actually excreted in the urine by active reabsorbing NaCl.
   - Some of urea diffuses out of the duct and into the interstitial fluid.

The mammalian kidney's ability to conserve water is a key terrestrial adaptation

Conservation of water by two solute gradients

- NaCl and urea.
- Counter-current cooperation:
  - Two limbs of the loop of Henle:
  - The vasa recta - loop of Henle:

How the Nervous System and Hormones Regulate Kidney Functions

- **Antidiuretic hormone** (**ADH**): one important hormone in osmoregulation
  - Osmoreceptor cells located in the hypothalamus stimulate the release of ADH when blood osmolarity rises above 300 mOsm/L: sweating or diarrhea cause excess water loss and increasing blood osmolarity.
  - The main targets of ADH are the distal convoluted tubules and the collecting ducts of the kidney: increasing water reabsorption.
  - Alcohol can inhibit the release of ADH and cause excessive loss of water in the urine and dehydrating the body.

- **Renin**/**Angiotensin**:
  - When the blood pressure in the afferent arteriole drops, or when the Na^+ concentration of the blood is too low, the **juxtaglomerular apparatus** (**JGA**; in the vicinity of the afferent arteriole) releases renin to the bloodstream.
  - Within the blood, renin activates a plasma protein, angiotensin. The active form of angiotensin, **angiotensin II**, functions as a hormone:
    1) Causing constriction of arterioles to raise blood pressure.
    2) Stimulating adrenal glands to release aldosterone, which acts on the distal convoluted tubules of the nephrons to stimulate the reabsorption of Na^+.

- **Atrial natriuretic protein** (**ANP**): hormone with opposite effect of the renin-angiotensin-aldosterone system.
  - The wall of the atrium of heart releases ANP in response to an increase in blood volume and pressure: inhibiting the release of renin and aldosterone.

Diverse adaptation of the vertebrate kidney have evolved in different

habitats

- Desert mammals have long loops of Henle. However, aquatic mammals have short loops of Henle.

- The epithelium of reptile cloaca helps conserve fluid by reabsorbing some of the water present in urine and feces.

Interacting regulatory systems maintain homeostasis

- Numerous regulatory systems are involved in maintaining homeostasis in an animal's internal environment.

- The regulation of body temperature involves mechanisms that also have an impact on such parameters of the internal environment as osmolarity, metabolic rate, blood pressure, tissue oxygenation, and body weight.

- Under some conditions, usually at the physical extremes compatible with the organism's life, the demands of one system might come into conflict with those of other systems. For instance, in very warm and dry environments, the conservation of water takes precedence over evaporative heat loss.

- Roles of the liver in homeostasis:
  - Take glucose from blood and storage excess glucose as glycogen:
  - Synthesize plasma protein to maintain the osmotic balance of blood:
  - Detoxify chemical poisons and prepare metabolic wastes for disposal: