Outline

Last time:
- Ionic and osmotic regulation in and out of the cell
- Ion uptake mechanisms

This Time:
- (1) Ionic Regulation and Excretion
- (3) Ionic and Osmotic Regulation in Different Organisms in Different Environments

Ion Uptake

- The Ion Uptake enzymes are often conserved in amino acid sequence (often no structural differences)

The following are often NOT conserved:
- Distribution and concentration of Ion Uptake enzymes in a cell
- The organization of the cells in an organ

Urine

What is it?
Osmoregulated urine is a convenient way to regulate ionic concentration (through excretion) and remove nitrogenous wastes.

Costs and Benefits of different nitrogenous waste products (Table 5.7)

- **Ammonia**: Marine Animals, Inexpensive, water soluble, 1N/molec. (lose less C), permeable thru lipid bilayer, highly toxic
- **Urea**: Expensive (2 ATP), water soluble, 2N/molec., moderately permeable thru lipid bilayer, moderately toxic
- **Uric Acid**: Very Expensive, water insoluble, minimize water loss, not permeable thru lipid bilayer, 4N/molec., Low toxicity

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**Urine concentrations relative to blood**

<table>
<thead>
<tr>
<th>Marine invertebrates</th>
<th>isosmotic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater inverts + verts</td>
<td>hyposmotic (dilute)</td>
</tr>
<tr>
<td>Terrestrial Animals</td>
<td>hyperosmotic</td>
</tr>
<tr>
<td>Marine Vertebrates</td>
<td>isosmotic</td>
</tr>
<tr>
<td>teleosts</td>
<td>(use gills to remove salt)</td>
</tr>
<tr>
<td>elasmobranchs</td>
<td>close to isosmotic</td>
</tr>
<tr>
<td>mammals</td>
<td>hyperosmotic</td>
</tr>
</tbody>
</table>

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**Water and Solute Balance 2**

Osmo/Ion-regulatory Organs
Question:
- What do osmoregulatory organs of different animals have in common?
- In what ways do they differ and why?
- What are some key differences between osmoregulation in aquatic and terrestrial environments?

Most animals have tubular osmoregulatory structures involving the same types of ion uptake and excretion mechanisms (see book).

In aquatic habitats nitrogenous excretion can occur across gills or integument (skin)…will be removed through simple diffusion.

In terrestrial habitat osmoregulation and (nitrogenous) excretion is done together…use excess water to remove wastes.

Osmoregulatory Organs

<table>
<thead>
<tr>
<th>Osmoregulatory Organs</th>
<th>Common Themes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contractile vacuoles</td>
<td><strong>Tubular structures</strong></td>
</tr>
<tr>
<td>None demonstrated</td>
<td><strong>Remove or absorb ions</strong></td>
</tr>
<tr>
<td>Nephridial organs</td>
<td><strong>Remove or take up water</strong></td>
</tr>
<tr>
<td>Protonephridia (closed ends)</td>
<td></td>
</tr>
<tr>
<td>Metanephridia (open ends)</td>
<td></td>
</tr>
<tr>
<td>Nephridia</td>
<td></td>
</tr>
<tr>
<td>Gut</td>
<td></td>
</tr>
<tr>
<td>Antennal glands</td>
<td></td>
</tr>
<tr>
<td>Malpighian tubules</td>
<td></td>
</tr>
<tr>
<td>Kidneys</td>
<td></td>
</tr>
<tr>
<td>Gill</td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td></td>
</tr>
<tr>
<td>Salt glands</td>
<td></td>
</tr>
</tbody>
</table>

Osmoregulatory Organs

- **Contractile vacuoles**
  - Protozoans, Sponges
- None demonstrated
- Coelenterates (strictly marine)
- Echinoderms (strictly marine)
- Nephridial organs
  - Protonephridia (closed ends)
  - Metanephridia (open ends)
  - Nephridia
- Gut
  - Many animals
  - Crustaceans
  - Insects
  - Vertebrates
- Antennal glands
  - Crustaceans
  - Molluscs
  - Fishes
- Malpighian tubules
  - Crustaceans
  - Molluscs
  - Fishes
- Kidneys
  - Amphibians
- Gill
  - Birds
  - Reptiles

Common Themes

- Tubular structures
- Remove or absorb ions
- Remove or take up water

FIGURE 12.4
The Malpighian tubules of insects. a. The Malpighian tubules arise as outpouchings of the midgut over the fat body. A segmental nerve conducts afferent and efferent nerve fibers to the Malpighian tubules. The Malpighian tubules are secreted across the hindgut of the insect.
Fish Gills

Vertebrate Kidney

- Contains simple tubular structures
- But which are compacted
- Around 1 million of these tubules (nephrons) in humans
- Filtration-Reabsorption System

Evolutionary History of the kidney

First evolved in freshwater teleosts
Freshwater fish are hyperosmotic relative to environment

Face two problems: (1) Water rushing in thru osmosis (2) loss of solutes

Solution: (1) Active uptake in gills (2) Kidney to excrete dilute urine (hypotonic) (3) Reabsorb ions across nephron tubules

Vertebrate Kidney

- Enormous osmo-iono-regulatory capacity
- Receives 20-25% of total cardiac output
- Osmoregulation
- Excretion
- Regulate Blood Pressure
- pH Balance: produces about 1 liter of slightly acidic urine daily (pH 6.0) (blood maintained at pH 7.4)

Salt glands of birds

Human Kidney
The Nephron

The Functional Unit

Countercurrent Multiplier system

A mechanism through which water is moved out of the tubule (to conserve water in the organism)
Countercurrent Multiplier system

- A general method for exchange (heat, gas, liquid)
- (in this case water and ions)
- Creates a concentration gradient along the loop
- Requires a loop structure
- Common in animals, engineering, gills, lungs
- Relies on asymmetry and flow through the tube

Countercurrent Multiplier system

- Na⁺ Cl⁻ are pumped out
- And diffuses to the Other side

Countercurrent Multiplier system

- Impermeable to water
- Impermeable to solutes
- The interstitium become concentrated

Countercurrent Multiplier system

- Water diffuses out of The descending loop

Countercurrent Multiplier system

- Impermeable to solutes
- H₂O

Countercurrent Multiplier system

- The fluid at the hairpin Becomes more concentrated

Countercurrent Multiplier system

- The fluid at the hairpin Becomes more concentrated
- Which gives the ascending loop more ions to pump out
Countercurrent Multiplier system

Impermeable to solutes

Which gives the ascending loop more ions to pump out

Countercurrent Multiplier system

Which causes more water to diffuse out

The fluid at the hairpin becomes more concentrated

Countercurrent Multiplier system

So with little energy, the fluid becomes increasingly concentrated

(3) Ionic and Osmotic Regulation in Different Organisms in Different Environments

- Last Time: Inside Cell vs Outside Cell
- This Time: Inside the Organism (both intracellular & extracellular fluids) vs The Environment

Water and Solute Balance 2

Ionic and Osmotic Regulation in Different Organisms in Different Environments

Extracellular Fluids (blood)

The Cell

Na+
K+
Mg++
Ca++

HCO3-
Cl-

Organic Anions

Ca++

Na+

Last time we discussed strategies for regulation concentrations in and out of the cell
Now, we want to discuss the interaction between the organism and the environment. Organic anions include Cl\(^-\), HCO\(_3\)-, Na\(^+\), K\(^+\), Mg\(^{++}\), Ca\(^{++}\), Cl\(^-\), and other similar ions. The cell maintains homeostasis by regulating its internal osmotic concentration. Extracellular fluids and osmotic regulation vary much more. Osmo/ionic regulators maintain relatively stable blood osmotic pressure over a range of pressures in the environment.

Differences in body fluid regulation in different environments show evolutionary patterns: intracellular ionic concentrations are conserved (constraints of basic cell biochemistry) and extracellular fluids and intra and extra cellular osmotic regulation varies much more.
Intracellular differences among species

- Ionic composition is more conserved across species (differences related to evolutionary adaptations)
- Osmotic concentration differs among species:
  - Using osmolytes or urea to fill Solute Gap with Environment
  - Depends on environment
  - And on Evolutionary History

Osmolytes

- Organic osmolytes: small solutes used by cells to maintain cell volume
- Compatible solutes: does not perturb macromolecules in the cell and are interchangeable (one functions as well as another)
- However, not all osmolytes are compatible solutes and some have specific functions (read about in Yancey 2005)

Osmotic Regulation

Examples of Osmolytes:
- Carbohydrates, such as trehalose, sucrose, and polyhydric alcohols, such as glycerol and mannitol
- Free amino acids and their derivatives, including glycine, proline, taurine, and beta-alanine
- Urea and methyl amines such as trimethyl amine oxide (TMAO) and betaine
Metabolic Cost of Osmoregulation

- The cost of iono- and osmoregulation varies greatly among animals
- Depends on gradient between environment and Extracellular fluid
- Permeability of the integument (skin)
- And particular evolutionary strategy

Examples:
Low in Marine Invertebrates
Marine Teleosts: 8-17% of resting metabolic rate
Freshwater teleosts: 3-7% of resting metabolic rate

TABLE 26.3 The composition of the blood plasma or other extracellular body fluids in some marine invertebrates and hagfish

<table>
<thead>
<tr>
<th>Animal and Body Fluid</th>
<th>Ion Concentration (mmol/L)</th>
<th>Osmotic Concentration (mOsm/kg H2O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle (Mytilus) Blood Plasma</td>
<td>Na⁺ 163, K⁺ 10, Ca²⁺ 0.2</td>
<td>340</td>
</tr>
<tr>
<td>Squid (Loligo) Blood Plasma</td>
<td>Na⁺ 160, K⁺ 10, Ca²⁺ 0.2</td>
<td>350</td>
</tr>
<tr>
<td>Crab (Callinectes) Blood Plasma</td>
<td>Na⁺ 150, K⁺ 10, Ca²⁺ 0.2</td>
<td>360</td>
</tr>
<tr>
<td>Sea Anemone (Eudendrium)</td>
<td>Na⁺ 140, K⁺ 10, Ca²⁺ 0.2</td>
<td>370</td>
</tr>
<tr>
<td>Hagfish (Myxine) Blood Plasma</td>
<td>Na⁺ 130, K⁺ 10, Ca²⁺ 0.2</td>
<td>380</td>
</tr>
<tr>
<td>Seawater</td>
<td>Na⁺ 140, K⁺ 10, Ca²⁺ 0.2</td>
<td>390</td>
</tr>
</tbody>
</table>

Source: After Potts and Pary 1964.

Extracellular ionic composition is close to seawater (intracellular is not)

Adaptations to Fresh Water

Freshwater species are hypotonic relative to the environment
Energetic cost of osmotic-ionic regulation is 3-7% of resting metabolic rate

1. Reduce ionic and osmotic gradient with the environment to reduce energetic cost
2. Reduce body permeability to ions
3. Excrete high volumes of dilute urine
4. Active ion uptake
5. Obtain ions from food

Freshwater animals have reduced ionic and osmotic body fluid concentrations

Composition of blood plasma and other fluids

<table>
<thead>
<tr>
<th>Animal</th>
<th>Na⁺ (mmol/L)</th>
<th>K⁺ (mmol/L)</th>
<th>Ca²⁺ (mmol/L)</th>
<th>Mg²⁺ (mmol/L)</th>
<th>Cl⁻ (mmol/L)</th>
<th>H₂PO₄⁻ (mmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
<td>163</td>
<td>10</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Squid</td>
<td>160</td>
<td>10</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crab</td>
<td>150</td>
<td>10</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea Anemone</td>
<td>140</td>
<td>10</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hagfish</td>
<td>130</td>
<td>10</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seawater</td>
<td>140</td>
<td>10</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: After Potts and Pary 1964.
Freshwater animals excrete high volumes of dilute urine

**TABLE 26.2 Rates of urine production, and osmotic and Na⁺ U/P ratios, in some freshwater animals**

| Animal               | Rate of urine production (mL/100 g body wt-day) | Osmotic U/P ratio | Na⁺ U/P ratio
|----------------------|-----------------------------------------------|-------------------|----------------
| Small (Hippopotamus amphibius) | 36 - 131                                      | 0.20              | 0.28
| Grayfish (Arctos vivanus)    | 8                                             | 0.10              | 0.006 - 0.06
| Mosquito louse (Aedes aegypti) | ≤ 20                                          | 0.12              | 0.05
| Frog (Rana catesbeiana)      | 32                                            | —                 | —
| Clownfish (Amphiprion bicinctus) | 56                                          | 0.16              | 0.10
| Goldfish (Carassius auratus) | 33                                            | 0.14              | 0.10


* The Na⁺ U/P ratio is the urine Na⁺ concentration divided by the plasma Na⁺ concentration.

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**Elasmobranchs, cartilaginous fishes**

- Low Extracellular ionic AND osmotic concentration
  (1/3 of seawater, evolution in fresh water?)
- Solute gap for BOTH extra and intracellular fluids filled by urea!!
- Some species slightly hyperosmotic (limited osmoregulator, not osmoconformer)

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**Elasmobranchs, cartilaginous fishes**

- Urea is a waste product
- It destabilized proteins (but Trimethylamine N-oxide TMAO stabilizes)
- Close to isosmotic
- Don’t need to drink
- Some are slightly hyperosmotic
- Water flows into gills (gains the water it needs this way)


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**TABLE 26.5 Composition of the blood plasma and excretory fluids of the dogfish shark and coelacanth**

<table>
<thead>
<tr>
<th></th>
<th>Osmotic pressure (mOsm)</th>
<th>Na⁺</th>
<th>Cl⁻</th>
<th>Urea</th>
<th>TIMAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dogfish shark (Squalus acanthias) Blood plasma</td>
<td>1018</td>
<td>286</td>
<td>246</td>
<td>351</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>Urine</td>
<td>780</td>
<td>337</td>
<td>203</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Rectal-gland secretion</td>
<td>1018</td>
<td>540</td>
<td>533</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Seawater</td>
<td>930</td>
<td>440</td>
<td>406</td>
<td>0</td>
</tr>
<tr>
<td>Coelacanth (Latimeria chalumnae) Blood plasma</td>
<td>931</td>
<td>197</td>
<td>137</td>
<td>377</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>Urine</td>
<td>961</td>
<td>184</td>
<td>15</td>
<td>388</td>
</tr>
<tr>
<td></td>
<td>Seawater</td>
<td>1035</td>
<td>470</td>
<td>548</td>
<td>0</td>
</tr>
</tbody>
</table>

Terrestrial Adaptations

- Active behavioral uptake of water
- Ion uptake from food
- Skin and cuticle evolved to prevent water loss
- Concentrated Urine (kidneys)
- Some terrestrial animals can survive water loss (camel-survive 30% loss)

Essentially a terrestrial vertebrate (cow) living in the sea
Excrete Concentrated Urine (powerful kidneys)