Water and Salt Physiology
ADAPTATIONS: Active ion transport uptake across gill epithelium of a freshwater fish

Ions are **loss** in the urine and by diffusion in the gills

Na and CL are **gain** by two independent active transport in the gills
Chloride cell and pavement cells in gill epithelium of a freshwater teleost fish

Gill epithelium consists of two types of cells:

**Chloride cells** : (ion transport)

**Pavement cells** : (O₂ uptake)

Low in Calcium
Water–salt relations in freshwater fish

(a) Freshwater teleost

Salt loss by diffusion

Water uptake by osmosis

Gills

Salts and water in food

Hyperosmotic to ambient water

Salts and water in feces

Large amounts of urine, very hyposmotic to plasma

Active uptake of $\text{Na}^+$ and $\text{Cl}^-$

UP ratio $< 1$
Marine environment
Most marine invertebrates are ISOSMOTIC to sea water.

Solutes in the blood are mostly inorganic ions.

Ion composition regulation by kidneys and gills.
Water–salt relations in marine teleost fish

The marine teleost fish are **Hyposmotic regulators**

(b) Marine teleost

- Salt gain by diffusion
- Water loss by osmosis

The sea is a **desiccating environment**

- 1000 mOsm
- 300 mOsm

Hyposmotic to ambient water

Gills
Water-Salt regulation in a Marine teleost fish

**Loss** of water by osmosis and urine production. Water acquired by **drinking** and eating

Eliminate divalent ions by urine.
Eliminate monovalent ions actively by the **gills** (extrarenal excretion) (**principal osmotic regulator**)

(b) Marine teleost

Water loss by osmosis

Salt gain by diffusion

Salts and water in food

Salts and water in seawater ingested

Small amounts of urine, nearly isosmotic to plasma, rich in Mg$^{2+}$ and SO$_4^{2-}$

Active extrusion of Cl$^-$, active or passive outflux of Na$^+$

**UP ratio = 1**
Birds in ocean environments: salt glands of a herring gull

**Hyposmotic regulators**

- **Lobe**
- **Central canal**
- **Salt gland**

**Drink sea water**

**Eliminate ions using kidneys and salt glands**
Water-salt relations in a marine shark

Hyperosmotic regulators

Salt gain by diffusion across gills

Water gain by osmosis across gills

Rectal gland secretions rich in NaCl, plus salts and water in feces

Modest amounts of urine, modestly hyposmotic to plasma, rich in Mg$^{2+}$ and SO$_4^{2-}$

The roles of the gills in salt excretion are uncertain

Urea and trimethylamine oxide (TMAO) are counteracting organic solutes
Water–salt relations in a marine shark

**Group A**
Marine invertebrates and hagfish

- **Blood plasma**
  - Inorganic ions
  - $\text{Na}^+\text{Cl}^-$

- **Intracellular fluid**
  - Organic solutes
  - Inorganic ions
  - $\text{Na}^+\text{Cl}^-$

**Group B**
Marine sharks, skates, rays, and coelacanth

- **Blood plasma**
  - Organic solutes

- **Intracellular fluid**
  - Organic solutes
  - Inorganic ions
  - $\text{Na}^+\text{Cl}^-$

Osmotic concentration

~1000 mOsm
UREA and Trimethylamine oxide (TMAO)

Tri methylamine oxide
\CH3\N–O/CH3

H₂N—C—NH₂
Urea
Animals from brackish water

**Brackish water**  
*Salinity*: from 0.5 - 30

*Osmotic pressure*: 15 - 850

A typical shoreline of the Chesapeake Bay
Animals from brackish water

Stenohaline: narrow range of salinity

Euryhaline: broad range of salinity

Most invertebrates in the ocean are **stenohaline osmoconformers**
Acclimation of mussels to changed salinity

(a) Each group studied while living in its natural salinity

(b) 2 days after salinity switch

(c) 6 days after switch

(d) 10 days after switch

(e) 30 days after switch

Baltic Sea mussels living at Baltic Sea salinity: 15 g/kg
North Sea mussels living at North Sea salinity: 30 g/kg

KEY
- - - - - - - - - -
Mussels from North Sea
- - - - - - - - - -
Mussels from Baltic Sea

Ciliary activity on a scale of 0–3
Salinity of the test water (g/kg)
Terrestrial environments: air is a fluid that **dehydrates** organisms.

**Evaporation**: is a gas diffusion mechanism. Water (as vapor) moves from an area of higher partial pressure to one of lower partial pressure.

**Humidity**: is the water content of air.

**Saturation water vapor pressure**: maximum water pressure before condensation in the form of liquid.
Evaporation

Terrestrial organisms lose water by evaporation

1. **Air humidity**: lower water vapor pressure of air --- higher evaporation
2. **Temperature of body fluid**: warmer more evaporation.
3. **Rate of air movement**: windy more evaporation.
4. **Permeability of integument to water**: High ---- higher evaporation.
**Humidic**: restricted to humid microenvironments

Earthworms, slugs, centipedes, amphibians

**Xeric**: capable of living in dry environments

Mammals, birds, reptiles, insects, arachnids

How rapidly they desiccate!
Low integumentary permeability to water reduces evaporative water loss

The evolution of a low permeability of integument to water is one of the most important adaptations to a xeric life.

Very thin layer of lipids are responsible of low integumentary permeability.

**Mammals**: glycolipids in the skin

**Insects**: long-chain carbohydrates and waxes in the epicuticle.
Differentiation in protection against evaporative water loss in grasshoppers populations

Differences in the lipid composition in the epicuticle

The Insect Integument

Bristle

Duct of Dermal Gland

Exocuticle

Endocuticle

Trichogen Cell

Epidermal Cells

Dermal Gland

Differences in the lipid composition in the epicuticle

Rate of evaporative water loss (mg H$_2$O/h) on log scale

Body weight (g) on log scale

Northern population

Southern population

25 C
The rate of evaporative water loss of insects increases at a transition temperature.

The increase in permeability at a transition temperature is a consequence of lipid melting.
Respiratory evaporative loss depends on the function of the breathing organs.

**Humidic** animals have respiratory surfaces directly exposed to the air.

**Xeric** animals have invaginated respiratory structures.
The temperature of air exhaled from the nostrils

The rate of metabolism is important

80% of water recovered
Within a group, total rate of evaporative water loss is an allometric function of size.

Smaller animals ---- higher metabolism

Higher metabolism------- higher respiratory water loss

Adaptations: better extraction of oxygen, cooling of exhaled air.
Total rate of evaporative water loss depends on body size and phylogenetic group

Small bodies------- higher weight-specific rates of evaporative water loss (EWL)

Small bodies------- higher surface/volume ratio

------- Higher metabolism

<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>Weight-specific rate of evaporative water loss (percent of body weight per hour)</th>
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<tbody>
<tr>
<td>44</td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>0.9</td>
<td>1.5</td>
</tr>
<tr>
<td>0.2</td>
<td>2.5</td>
</tr>
<tr>
<td>1.9</td>
<td>0.5</td>
</tr>
<tr>
<td>0.03</td>
<td></td>
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<tr>
<td>16–39</td>
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<tr>
<td>44</td>
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Permeability integuments, metabolic rate
Excretory water loss depends on the concentrating ability of excretory organs.

Terrestrial animals modulate concentration, composition and volume of urine.

Two ways to minimize loses:

1. **Concentrate** the urine

2. **Reduce the amount of solute** excreted in the urine

Low U/P ratios

High U/P ratios

Salt glands help to decrease water required for excretion (birds, lizards)
Excretory water loss depends on the **concentrating ability** of excretory organs.

The **Maximum concentration of urine** mammals can produce is in part a function of size and part related with the habitat.
**Water-turnover rates of free-living terrestrial vertebrates as a function of body size**

**Water turn over**: is the water lost and gain per day

Animals with **high water turnover** are more expose to dehydration

The water-turnover rates of a particular group is a function of body size

![Graph showing water-turnover rates for different groups of animals](image)

- Eutherian mammals
- Marsupials
- Birds
- Reptiles

Mammals and birds turn over more than reptiles
Amphibians occupy xeric habitats despite their humidic nature

- Amphibians are able to invade dry habitats thanks to:
  
  **Protective behavior**
  Advantageous patterns of seasonality
  Particular physiological adaptations

- Problems:
  
  High integumental water permeability
  Low ability to concentrate urine
  Carnivores: high urea

- Solutions:
  
  Absorb water across their skins (also drink)
  Behavioral and seasonal dormancy
  Decrease integumental water permeability.
  Reduce urinary water losses (uric acid)

Arboreal frogs (*Phyllomedusa*) spread protective lipids over their skin surface
Insects are excellent water managers

- Low integumentary permeability
- Low respiratory water losses
- Ability to concentrate the urine

Water losses are low and organisms survive on metabolic water for long periods
Xeric vertebrates are well adapted to prevent water losses.

**Problems:**
- High metabolic rates
- Carnivores: high urea
- Limited access to water

**Solutions:**
- Low integumental water permeability.
- Reduce urinary water losses (uric acid)
- Behavior to avoid water stress

A kangaroo rat water budget

- Very low cutaneous water permeability.
- Very concentrated urine
- Very low fecal water losses
Metabolic water

Approximate catabolic gains and losses of water in caged kangaroo rats (*Dipodomys*) and laboratory rats (*Rattus*) when eating air-dried barley and denied drinking water at 25°C and 33% relative humidity. The values given are grams of H₂O per gram (dry weight) of barley ingested. Those for the kangaroo rats are from Box 25.1.

<table>
<thead>
<tr>
<th>Category of water gain or loss</th>
<th>Kangaroo rats</th>
<th>Laboratory rats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross metabolic water produced</td>
<td>0.54 g/g</td>
<td>0.54 g/g</td>
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<tr>
<td>Obligatory water losses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Urinary</td>
<td>0.14</td>
<td>0.24</td>
</tr>
<tr>
<td>Fecal</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>Total obligatory water losses</td>
<td>0.47</td>
<td>0.60</td>
</tr>
<tr>
<td>Net gain of metabolic water</td>
<td>+ 0.07</td>
<td>– 0.06</td>
</tr>
</tbody>
</table>

Important to CONSERVE water
Summary

Terrestrial organisms lose water by evaporation.

**Evaporation:**
1. Air humidity: lower water vapor pressure of air—higher evaporation.
2. Temperature of body fluid: warmer more evaporation.
3. Rate of air movement: windy more evaporation.
4. Permeability of integument to water: High—higher evaporation.

Terrestrial organisms **gain water** by

1. Drinking preformed water.
2. Eating preformed water.

**Obligatory water losses:** respiratory, urinary and fecal obligatory water losses.

**Humidic:** restricted to humid microenvironments

**Xeric:** capable of living in dry environments

The evolution of a **low permeability of integument to water** is one of the most important adaptation to a xeric life.