Osmoregulation

Water & Electrolyte Balance
Major Fluxes Within The Body

GOAL: maintain homeostasis

Protein Nitrogen  Urea

Salts Na, Cl, K

Salts Na, Cl, K

Fuel + O₂

Energy & Work

CO₂ + H₂O

Water

Water
Osmoregulation

• Water & Electrolytes
• Do Marine Mammals Drink Seawater?
• Reducing Water Loss
• Water Balance During Reproduction
Life In the Sea

• No freshwater

• Different electrolyte concentrations
  • Seawater (1000 mOsm L\(^{-1}\))
  • Body water (300 mOsm L\(^{-1}\))

• Prey:
  – hypotonic (fish) with seawater
  – isotonic/ hypertonic (invertebrates)
<table>
<thead>
<tr>
<th></th>
<th>Habitat</th>
<th>Solute (mmol per liter)</th>
<th>Osmotic concentration (mOsm liter⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Na</td>
<td>K</td>
</tr>
<tr>
<td><strong>Sea water</strong></td>
<td></td>
<td>~450</td>
<td>10</td>
</tr>
<tr>
<td><strong>Cyclostomes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hagfish (Myxine)ᵇ</td>
<td>Marine</td>
<td>549</td>
<td>11</td>
</tr>
<tr>
<td>Lamprey (Petromyzon)ᶜ</td>
<td>Marine</td>
<td>317</td>
<td></td>
</tr>
<tr>
<td>Lamprey (Lampetra)ᵇ</td>
<td>Fresh water</td>
<td>120</td>
<td>3</td>
</tr>
<tr>
<td><strong>Elasmobranchs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ray (Raja)ᵇ</td>
<td>Marine</td>
<td>289</td>
<td>4</td>
</tr>
<tr>
<td>Dogfish (Squalus)ᵇ</td>
<td>Marine</td>
<td>287</td>
<td>5</td>
</tr>
<tr>
<td>Fresh-water ray (Potamotrygon)ᵈ</td>
<td>Fresh water</td>
<td>150</td>
<td>6</td>
</tr>
<tr>
<td><strong>Coelacanth (Latimeria)ᵉ</strong></td>
<td>Marine</td>
<td>197</td>
<td>7</td>
</tr>
<tr>
<td><strong>Teleosts</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goldfish (Carassius)ᵇ</td>
<td>Fresh water</td>
<td>115</td>
<td>4</td>
</tr>
<tr>
<td>Toadfish (Opsanus)ᵇ</td>
<td>Marine</td>
<td>160</td>
<td>5</td>
</tr>
<tr>
<td>Eel (Anguilla)ᵇ</td>
<td>Fresh water</td>
<td>155</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Marine</td>
<td>177</td>
<td>3</td>
</tr>
<tr>
<td>Salmon (Salmo)ᵇ</td>
<td>Fresh water</td>
<td>181</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Marine</td>
<td>212</td>
<td>3</td>
</tr>
<tr>
<td><strong>Amphibians</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frog (Rana)ᶠ</td>
<td>Fresh water</td>
<td>92</td>
<td>3</td>
</tr>
<tr>
<td>Crab-eating frog (R. cancrivora)ᵍ</td>
<td>Marine</td>
<td>252</td>
<td>14</td>
</tr>
</tbody>
</table>

ᵃWhen no value is listed for urea, the concentration is of the order of 1 mmol per liter and osmotically insignificant. Values for ray, dogfish, and coelacanth include trimethylamine oxide.
ʰValues for frogs kept in a medium of about 800 mOsm per liter, or four-fifths of normal sea water.
Water & Electrolyte Balance

Preformed water:
1) Food is 60-80%
2) Seawater

Water

- Respiration
- Metabolism
- Drinking Food (preformed)

Cutaneous

- Milk
- Feces
- Urine
Water & Electrolyte Balance

Preformed water:
1) Food is 60-80%
2) Seawater

Metabolism

Water

Respiration

Cutaneous

Drinking Food (preformed)

Milk Feces Urine
Metabolic Water Production (MWP)

\[ 6O_2 + C_6H_{12}O_6 = 6H_2O + 6CO_2 \]

Energy

1g Fat = 1.07 g \(H_2O\)
1g Protein = 0.56 g \(H_2O\)
1g Carbohydrate = 0.39 g \(H_2O\)
Do Marine Mammals Drink Seawater?
Can Marine Mammals Drink Seawater?
Other Marine Vertebrates

- Seabirds & Reptiles
- Extra-renal salt glands
- Excrete excess electrolytes
- Not found in MM
## Drinking Seawater

Dolphin: gains water from drinking seawater  
Human: loss in water

<table>
<thead>
<tr>
<th></th>
<th>Seawater consumed volume mL</th>
<th>Cl⁻ conc. mmol liter⁻¹</th>
<th>Max Urine conc. mmol liter⁻¹</th>
<th>Urine volume produced mL</th>
<th>Water balance gain or loss mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolphin</td>
<td>1000</td>
<td>535</td>
<td>820</td>
<td>650</td>
<td>+350</td>
</tr>
<tr>
<td>Human</td>
<td>1000</td>
<td>535</td>
<td>400</td>
<td>1350</td>
<td>-350</td>
</tr>
</tbody>
</table>
Kidney Structure

- Blood flow through the kidney
  - Malpighian body
  - Proximal convoluted tubule
  - Distal convoluted tubule
  - Henle's loop
  - Collecting duct

- Kidney regions
  - Cortex
  - Medulla
  - Renal papilla
  - Pelvis
  - Ureter
Basic Kidney Function

Longer the loop = higher urine concentration
Marine Mammal Kidneys

• Larger, high concentrating ability
• Terrestrial animals- produce small volumes, high conc.
• Large amts., moderately high urea conc.
Reniculate or Lobulate Kidney

• “bag of grapes”
• group of smaller interconnected kidneys

• Greater surface area of medulla (↑ conc.)
• Not in Sirenians
Reniculate or Lobulate Kidney

- Humans - 1 lobe
- Otters, bears - 6 to 8
- Delphinids - hundreds
- Mysticetes - 3 to 5 thousand
Kidney: Dog vs. Sea lion
Kidney: Dog vs. Sea lion

Cortex

Medulla
Do Marine Mammals Drink Seawater? (mariposia)

Tests in lab
- Bottlenose dolphin
  - Fed
- Common dolphin
  - Fasted
- CA sea lion
  - Fed
- N. elephant seal
  - Fed
- Manatee
  - Fed
• Ingest 6 liters/day
• 30% of total water

• Drink while fasting
• Skin permeable to water
California sea lion

• No access to water (fed) maintained balance (45 days)
• Salt added to diet, maintained balanced
• Gained enough water from prey & metabolic water
Northern elephant seal

- Based on stomach temperature measurements
- Occurred 20% of the days in captivity
- Regularly before first feed (70%)
Manatees

• Associated with fresh water in the wild

• Without access to fresh water (9 days)
  – increased plasma osmolality
  – plasma conc. Na & Cl

• Refused to eat sea grass
Do Marine Mammals Drink Seawater?

- **Field measurements & observations**
  - Weanling elephant seals
  - Sea otter
  - Fur seals & sea lions: Antarctic vs. Galapagos
Isotopic labels to measure turnover rates

Animals Total Body Water Pool
Isotopic labels to measure turnover rates

Animals Total Body Water Pool

Labeled Injectate
Isotopic labels to measure turnover rates

Isotope mixed with body water

Animals Total Body Water Pool
Isotope Turnover

![Diagram of isotope turnover](image)

- **Time**
- **Isotope Concentration**
- **H_2O**
- **Sample 1**
- **Sample 2**

The graph shows the decrease in isotope concentration over time post-injection of H_2O.
Fasting northern elephant seals

- Slopes were not different
- Amount of water = to metabolic water production
- No water ingested during fasting
Sea Otter

Total Water Influx

Consume invertebrate prey

25 kg otter: 6.7 L/day

Water in food (67.7 %)

Metabolic water Production (9.3 %)

Sea water (23 %)
Otariid Water Consumption

Depends on environment & behavior
Reducing water loss

- Cutaneous Water Loss
- Respiratory Evaporative Water Loss
- Fecal & Urinary Loss
Cutaneous Evaporative Water Loss

- Sweat glands
  - prominent in fur seals
  - reduced in phocids
  - absent in cetaceans

- Challenge in warm climates
Respiratory Evaporative Water Loss (EWL)

• Apneustic breathing
• Fewer breaths reduces EWL from the lungs
• Allows greater $O_2$ acquisition
  – Humans: 4% $O_2$ per liter of air
  – Marine mammals: 8% $O_2$/L
Apnesutic Breathing

Lester & Costa 2006

Net water loss

Net water gain

Apnea duration (min)
Nasal turbinates

- Countercurrent exchanger
- Large surface area
- Allows water to be trapped/retained
Nasal turbinates
Inhalation: 15°C ~10mg H₂O/L air
Air warmed when passed by warm tissue
Warm air picks up moisture from turbinates
Tissue is cooled as heat is transferred
Lungs ~40mg H₂O/L air

Exhalation:
Air is cooled as it passed cool tissue
Water is lost to turbinates
Temperature Differential in Nasal Turbinates

Elephant seals: 80-90% water recovery
Urinary & Fecal Water Loss

• Fuel source plays a big part
  – Protein
    • CO₂
    • Water
    • Nitrogen
  – Carbohydrates & Fats
    • CO₂
    • Water
Nitrogenous Waste Products

Ammonia

\[ \text{NH}_3 \]

Urea

\[ \text{CH}_4\text{ON}_2 \]

Uric Acid (not shown)

Vary in amt. of water excretion & toxicity
Changes in Body Composition During Fasting

Female northern elephant seal

Relying heavily on fat stores

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>2 - 4 Days Post-Partum</th>
<th>Weaning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adipose 34.4%</td>
<td>Lean 23.1%</td>
</tr>
<tr>
<td></td>
<td>Lean 65.6%</td>
<td>Lean 76.9%</td>
</tr>
</tbody>
</table>

Female northern elephant seal
Reduction in nitrogenous wastes
Urinary Output Declines

Graph showing the decline of urine production (ml/24 hr) over days of fasting.

- Point 'a' (8) indicates a urine production of 500 ml/24 hr at 0 days of fasting.
- Point 'b' (7) shows a decrease in urine production to 300 ml/24 hr by 20 days of fasting.
- Point 'c' (6) shows a further decrease to 100 ml/24 hr by 30 days of fasting.
- Point 'd' (3) indicates a continued decrease in urine production to 0 ml/24 hr by 70 days of fasting.

Days Fasting: 0, 10, 20, 30, 40, 50, 60, 70.
Water balance during reproduction
How do animals maintain water balance when demands are high?

Got Milk?
Otariid Strategy

1) Females go to sea to feed between suckling bouts
2) Water acquisition is not a problem
Phocid Strategy

1) Fasting = no food or water ingested
2) Real challenge during reproduction
   Solution – Lower water content & alter milk composition
Phocids Change Milk Composition Through Time

1) Water content declines
2) Lipid content increases
3) Protein content is constant

Fig. 8.1. Percentage changes in fat, water, and protein of northern elephant seal milk throughout lactation (from Riedman and Onnis, 1979).