osmoregulation mechanisms in gills, salt glands, and kidneys

**Ionic & Osmotic Homeostasis**

**Group C**
Freshwater and terrestrial invertebrates

**Group D**
Freshwater and terrestrial vertebrates; marine vertebrates not in A or B

extracellular
~300 mOsm

Inorganic ions
Na^+Cl^-

Inorganic ions
Na^+Cl^-

intracellular
~300 mOsm

Inorganic ions
K^+

Inorganic ions
Na^+Cl^-

Osmotic concentration
Salt Secretion:

Seawater (or gland lumen)

K⁺ ➔ recycle

K⁺ ➔ active Na⁺/K⁺ ATPase

Na⁺ ➔ 2Cl⁻

Cl⁻ ➔ recycle

Na⁺ ➔ Down electrochemical gradient (Paracellular)

Apical membrane

(Basolateral membrane)

(Eckert 14-14)

Figure in Box 26.2
Hill et al. 2004

Chloride Cell
Salt Glands

Shark rectal glands to dispose of excess NaCl
- blood hyperosmotic to seawater, but less salt
- more urea and TMAO (trimethylamine oxide)
- NaCl actively secreted

Shark Rectal Salt Glands

Salt-secreting cells:
- Na/K-ATPase pump in basolateral membrane
- generates gradient for Na⁺ by which Na⁺/2Cl⁻/K⁺ cotransporter drives up [Cl⁻] in cell
- Cl⁻ across apical membrane
- Na⁺ follows paracellularly down electrochemical gradient (and H₂O)
- apical membrane impermeable to urea and TMAO
- therefore iso-osmotic secretion with lots of NaCl

... slightly different in birds and lizards →
Salt Glands

Nasal/orbital salt glands of birds and reptiles - especially species in desert or marine environments.

Hypertonic NaCl secretions (2-3x plasma osmolarity)

Allows some birds to drink salt water and end up with osmotically free water

Fish Gills

Chloride cells involved in osmoregulation -(recall lab paper on smolting)
- lots of mitochondria to power ATPases
- mechanism similar in nasal glands (birds and reptiles), and shark rectal gland
Freshwater fish: The mechanism basically reversed to allow uptake of salt from water against concentration gradient.

Hill et al. 2004, Fig 26.7

Eckert 14-31
Sea ↔ Freshwater

**Switch** between getting rid of excess salt in seawater and taking up salt in freshwater

**Growth hormone** and **cortisol** for → sea

(more active chloride cells with more Na/K-ATPase activity)

**Prolactin** for → freshwater

---

**Osmoregulatory Mechanisms**

**Apical** surface (faces lumen and outside world)

**Basal** surface (faces body and extracellular fluid)

- Active movement of ions/salts requires **ATP**
- Movement of **water follows** movement of ions/salts
Gradients established and used...to move ions, water

Kidney Functions:

- Osmoregulation
- Blood volume regulation
- Maintain proper ion concentrations
- Dispose of metabolic waste products
- pH regulation (at ~ 7.4)
- Dispose of toxins and foreign substances

How does the kidney accomplish this?
Mammalian Kidney
- Paired
- 1% body mass
- 20% blood flow

- Urine contains:
  - Water
  - Metabolic byproducts (e.g., urea)
  - Excess salts etc.

- From ureter to urinary bladder
  (smooth muscle, sphincter, inhibition)
- Out via urethra during micturition

Mammalian Kidney Anatomy
Nephron Anatomy

1 - Proximal tubule
2 - Loop of Henle
   - descending
   - ascending
3 - Distal tubule

- numerous nephrons empty into collecting duct
- collecting ducts empty into renal pelvis
Nephron Anatomy

Figure 9.8 Diagram of a mammalian kidney. The kidney contains a large number, up to several million, of anguli nephrons. Only one nephron is illustrated in this diagram and is shown enlarged to the right. The outer layer of the kidney, the cortex, contains the Malpighian bodies and the proximal and the distal convoluted tubules. The capillary network within the Malpighian body is known as the glomerulus. The inner portion, the medulla, contains Henle's loops and collecting ducts.

The urine is initially formed by filtration in the Malpighian bodies. The filtered fluid is modified and greatly reduced in volume as it passes down the renal tubules and into the collecting ducts. These empty the urine into the renal pelvis, from where it is conveyed via the ureter to the bladder.

Knut Schmidt-Nielsen 1997

Figure 9.11 Diagram showing the cortical nephron, or "long-looped" (locally and therefore called (or cortical) nephron, by a loop formed by the tubule capillary. The anastomosed nephron is surrounded by a capillary network. Most mammalian kidneys contain a mixture of these two types of nephron, but some species have only one or the other kind. [Smith 1981]

Countercurrent exchange

DOG KIDNEY Close-up view of glomeruli from a dog kidney after arterial injection of silicone rubber. The glomerulus in the center of the photo shows the slightly thicker vessel leading into the glomerulus and the somewhat thinner vessel leaving it. The diameter of these vessels is about 15 to 20 μm; the diameter of the glomerulus is about 150 μm. (Courtesy of A. Clifford Banger, Harvard University)

Knut Schmidt-Nielsen 1997
Kidney Processes - overview

1. FILTRATION
   blood --> filtrate

2. REABSORPTION
   filtrate --> blood

3. SECRETION
   blood --> filtrate

All 3 involved in final Urine Composition

Table 9.2 The maximum concentrations of various mammals is correlated with the animal, desert animals having the highest concentrations and fresh-water animals below.

<table>
<thead>
<tr>
<th>Animal</th>
<th>Urine maximum osmotic concentration (Osm liter$^{-1}$)</th>
<th>Urine/plasma concentration ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beaver$^a$</td>
<td>0.52</td>
<td>2</td>
</tr>
<tr>
<td>Pig$^a$</td>
<td>1.1</td>
<td>3</td>
</tr>
<tr>
<td>Human$^b$</td>
<td>1.4</td>
<td>4</td>
</tr>
<tr>
<td>White rat$^h$</td>
<td>2.9</td>
<td>9</td>
</tr>
<tr>
<td>Cat$^h$</td>
<td>3.1</td>
<td>10</td>
</tr>
<tr>
<td>Kangaroo rat$^d$</td>
<td>5.5 $^{Dipodomys}$</td>
<td>14</td>
</tr>
<tr>
<td>Sand rat$^d$</td>
<td>6.3</td>
<td>17</td>
</tr>
<tr>
<td>Hopping mouse$^e$</td>
<td>9.4</td>
<td>25</td>
</tr>
</tbody>
</table>

$^a$ B. Schmidt-Nielsen and O’Dell (1961).
$^h$ MaxMillen and Lee (1967).

Filtration plus secretion

Figure 9.10 Excretion of phenol red by the bullfrog. The amount filtered increases in proportion to the plasma concentration. In addition, phenol red is added to the urine by active tubular transport, increasing the amount in the urine. The amount added by tubular secretion remains constant at plasma concentrations above 0.05 mg per milliliter; this indicates that the tubular maximum for phenol red has been reached. [Forster 1948]

Knut Schmidt_Nielsen 1997
Sympathetic innervation tends to constrict

Hill et al. 2004, Fig 25.7

<table>
<thead>
<tr>
<th>U/P ratio</th>
<th>Effects on water excretion</th>
<th>Effects on solute excretion</th>
<th>Effects on composition of blood plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>U/P = 1 (isometric urine)</td>
<td>Water is excreted in the same relative to solutes as prevails in the blood plasma.</td>
<td>Solute are excreted in the same relative to water as prevails in the blood plasma.</td>
<td>The formation of urine leaves the ratio of solutes to water in the blood plasma unchanged, thus does not alter the plasma oncotic pressure.</td>
</tr>
<tr>
<td>U/P &lt; 1 (hypotonic urine)</td>
<td>Water is preferentially excreted. Urine contains more water relative to solutes than plasma.</td>
<td>Solute are preferentially held back from excretion. Urine contains less solutes relative to water than plasma.</td>
<td>The ratio of solute to water in the plasma is shifted upward. The oncotic pressure of the plasma is raised.</td>
</tr>
<tr>
<td>U/P &gt; 1 (hypertonic urine)</td>
<td>Water is preferentially held back from excretion. Urine contains less water relative to solutes than plasma.</td>
<td>Solute are preferentially excreted. Urine contains more solutes relative to water than plasma.</td>
<td>The ratio of solutes to water in the plasma is shifted downward. The oncotic pressure of the plasma is lowered.</td>
</tr>
</tbody>
</table>

Humans: 125 ml/min or 180 L/day

(14-20)
Filtration:

**Bowman’s capsule**
3 layers
1. Glomerular endothelial cells
   - 100x leakier than other capillary walls
2. Basement membrane
   - negatively charged glycoproteins
   - repel plasma proteins by charge
3. Epithelial cells
   - podocytes create slits

Filtrate = protein-free and cell-free plasma

**Glomerular Filtration Rate (GFR)**
Humans: 125 ml/min or 180 L/day (60x plasma vol.)
About 20% of the plasma and solutes that enter glomerulus end up in BC

Bowman’s capsule

1. Starvation Implications?

2. Kidney Stone Implications?
Filtration Regulation:

1. **Myogenic props. of afferent arteriole resist stretch**

2. Secretions from cells of **juxtaglomerular apparatus** (where distal tubule passes near bowman’s capsule)
   - **Macula densa** cells (distal tubule)
     - monitor osmolarity and flow in distal tubule
     - paracrine hormonal activity on afferent arteriole
   - **Granular or juxtaglomerular** cells (afferent arteriole)
     - release **renin** which alters blood pressure...
Filtration Regulation:

Renin (from granular cells) released in response to
- low renal BP,
- low solute [ ] in distal tubule,
- or sympathetic activation

Renin leads to activation of Angiotensin II which
causes systemic vasoconstriction to inc. BP
stimulates aldosterone from adrenal cortex
vasopressin (ADH) from post. pit.
(these promote salt, water reabsorption)

3. Sympathetic innervation (reduce GFR)
   - afferent vasoconstriction
   - decreased space between podocytes

Renal Clearance:

Volume of plasma cleared of a substance by the kidney.

(Filtration, Reabsorption, Secretion)

Inulin (=GFR) b/c neither reabsorbed nor secreted

If clearance > GFR = secretion
If clearance < GFR = reabsorption
1. FILTRATION  
blood --> filtrate

2. REABSORPTION  
filtrate --> blood

3. SECRETION  
blood --> filtrate

Reabsorption:

of 180 L/day filtered, ~178.5 L reabsorbed in humans

Lots of active transport of salts and other substances

Tight junctions not so tight in proximal tubule, so water can move from filtrate to plasma

Because of reabsorption (and secretion), Renal clearance does NOT often equal GFR

(Eckert 14-19)
Reabsorption limit – Glucose example

Tm at 300 mg/min/100ml plasma

Reabsorption:
Proximal Tubule
70% filtered Na\(^+\) actively reabsorbed (by Na\(^+\)/K\(^+\)ATPase pump in basolateral membrane) Cl\(^-\) and water follow
75% of filtrate is reabsorbed including glucose and amino acids (Na\(^+\) dependent) also, phosphates, Ca\(^+\), electrolytes as needed

Parathyroid hormone controls phosphate and Ca\(^+\) reabsorp.
triggers calcitriol production (Vit. D) for Ca\(^+\)

At end of proximal tubule filtrate is isoosmotic with plasma (~300mOsm)
however, remaining substances are 4x concentrated
Gradients established and used:

(a)

Mammalian Kidney

(b)

Mammalian Kidney
Reabsorption:

**Loop of Henle**
- Descending limb
  - no active NaCl transport
  - low urea and NaCl permeability
  - permeable to water
- Ascending thin limb
  - no active NaCl transport
  - but permeable to NaCl
  - low urea permeability
  - low water permeability
- Ascending thick limb
  - NaCl transported out of tubule
  - low water permeability

Countsccurrent multiplier

One driver of concentrating mechanism of nephron

Reabsorption (and Secretion): (Eckert 14-18)

**Distal Tubule**
- K⁺, H⁺, NH₃ into tubule
- under endocrine control
- Na⁺, Cl⁻, HCO₃⁻ back into body
- water follows
  (Na⁺ reabsorption facilitated by aldosterone)

Angiotensinogen → Renin → Ang. I → ACE in lung → Ang. II → aldosterone from adrenal cortex

ADH from post. pit.

**Collecting Duct**
- permeable to water
- hormone control (ADH/vasopressin)
- water (via aquaporins) follows osmotic gradient
- permeable to Urea in inner medulla
- ADH role in water reabsorption/urine concentration

- Renin -> Ang. II
  -> ADH

- Baroreceptor input (atrial and arterial)

- EtoH inhibits ADH release

Atrial Natriuretic Peptide (ANP)
- released by atrium cells in response to stretch (elevated BP)

- opposite effect of renin-angiotensin system
- decreases sodium reabsorption
- therefore increased urine production
- ANP inhibits release of ADH, renin, aldosterone
ADH acts in stippled region of collecting duct

Urine can be 100-1200 mOsm in humans (plasma about 300)

Secretion:

From plasma into tubule of nephron

K+, H+, NH3, organic acids, organic bases

Organic anions (OA-):

Liver conjugates toxins and waste to glucuronic acid

Secreted into tubule lumen and excreted

Na/K-ATPase
Table 14-9: Some organic ions secreted by the proximal tubule

<table>
<thead>
<tr>
<th>Anions</th>
<th>Cations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Endogenous</strong></td>
<td><strong>Endogenous</strong></td>
</tr>
<tr>
<td>Urates</td>
<td>Dopamine</td>
</tr>
<tr>
<td>Hippurates</td>
<td>Epinephrine</td>
</tr>
<tr>
<td>Oxalate</td>
<td>Norepinephrine</td>
</tr>
<tr>
<td>Prostaglandins</td>
<td>Creatinine</td>
</tr>
<tr>
<td>cAMP</td>
<td></td>
</tr>
<tr>
<td><strong>Exogenous</strong></td>
<td><strong>Exogenous</strong></td>
</tr>
<tr>
<td>Furosemide</td>
<td>Morphine</td>
</tr>
<tr>
<td>Bumetanide</td>
<td>Amiloride</td>
</tr>
<tr>
<td>Penicillin</td>
<td>Quinine</td>
</tr>
<tr>
<td>Aspirin</td>
<td>Atropine</td>
</tr>
<tr>
<td>Chlorothiazides</td>
<td>Isoproterenol</td>
</tr>
</tbody>
</table>

Countercurrent Exchangers (passive)

Countercurrent Multipliers (active)

See p.736 in your text
Endotherms in the COLD...

Countercurrent Heat Exchange

Figure 8.9 Countercurrent heat exchange. (A) A diagram representing the circulatory pattern in a limb of a mammal, showing the temperature changes of the blood in the absence (a) and presence (a') of countercurrent heat exchange. Arrows indicate direction of blood flow. In (a), the warm blood leaves the heart and passes through the arteries and veins, while the cold blood returns to the heart. In (a'), the warm blood flows through the veins, while the cold blood flows through the arteries. This process helps to keep the temperature of the body constant by transferring heat from the warm blood to the cold blood.

Urine concentrating ability

ADH acts in stippled region of collecting duct

Urine can be 100-1200 mOsm in humans (plasma about 300)

1. Single Effect
2. End-to-end Gradient

Figure 27.12
Hill et al. 2004
Countercurrent Multiplication

Countercurrent Multiplication
Non-mammalian kidneys:

- Only birds also have loops of Henle

- Freshwater fish with more and larger glomeruli to make lots of dilute urine

- Some marine fish without glomeruli or bowman's capsule - urine formed by secretion, ammonia secreted by gills

- Osmoregulation also via extrarenal organs
Urine concentrating ability

1200 mOsm in humans
9000 mOsm on kangaroo rats
9600 mOsm in *Perognathus* (mouse)

- Length of loops of henle
- Corticomedullary concentration gradient

(Eckert 14-34)

-Urine concentrating ability

Some urea "recycled"

(Eckert 14-34)
Hill et al. 2004, Fig. 27.14

(a) Antidiuresis: kidney producing concentrated urine
(b) Diuresis: kidney producing dilute urine

Urine concentrating ability

- Vasa Recta
- Loops of Henle only in Mammals and Birds -> Hyperosmotic Urine

(a) Juxtedudillary nephron (b) Cortical nephron

(Aminal Physiology Figure 27.14 (Part 1))

(Eckert 14-18)