16.1 The Urinary System

• Functions of the Urinary System

1. Excretion of Metabolic Wastes
   • Most are nitrogenous
     – Urea (primary nitrogenous waste)
       – by-product of amino acid metabolism - made from ammonia released from amino acids
     – Ammonium
     – Creatinine
       – the breakdown product of creatine phosphate
     – Uric acid
       – made from nucleotide breakdown

Functions of the Urinary System

2. Osmoregulation
   • Maintenance of the proper balance of water and salt in the blood
   • Blood volume and pressure related to salt balance
     – Salts such as NaCl have the ability to cause osmosis.
     – The more salts in blood, the greater the blood volume.
   • Kidneys also regulate other ions, K⁺, HCO₃⁻, Ca²⁺
Functions of the Urinary System

3. **Maintenance of Acid-Base Balance**
   • Along with the respiratory system, the kidneys regulate the acid-base balance of the blood.
   • pH is kept at around 7.4.
     – Accomplished by excretion of \( H^+ \) and reabsorption of bicarbonate (\( HCO_3^- \)).

Four Functions of the Urinary System

4. **Secretion of Hormones**
   • Renin – leads to secretion of aldosterone (involved in reabsorption of \( Na^+ \))
   • Erythropoietin – stimulates red blood cell production
   • Vitamin D activation – to promote calcium absorption

Organs of the Urinary System

• **Kidneys**
  – Paired, bean-shaped, reddish-brown organs located in lumbar region
  – Behind peritoneum
  – Covered by renal capsule
    • Tough fibrous connective tissue
  – Has a depression (hilum) on the concave side
    • Renal artery enters
    • Renal vein and ureter exits
Organs of the Urinary System

• Ureters
  – Small muscular tubes about 25 cm long and 5 mm in diameter
  – Conduct urine from kidney to bladder
    • Convey urine by peristalsis
  – Three-layered wall
    • Inner mucosa, smooth muscle, outer connective tissue

Organs of the Urinary System

• Urinary Bladder
  – Stores urine until expelled from body
  – Has three openings
    • Two for the ureters, one for the urethra
  – Has expandable wall due to circular fiber and two layer of longitudinal muscle
    • Transitional epithelium of mucosa become thinner
  – Has two sphincter muscles to control the release of urine into the urethra

Organs of the Urinary System

• Urethra
  – Small tube that leads from the urinary bladder to an external opening
  – Serves to remove urine from the body
  – Longer in males than females
    • Also transports semen in males
Urination

• Urination is triggered when the urinary bladder fills to 250 ml:
  – Stretch receptors send signal to spinal cord
  – Motor nerve impulses cause sphincters to relax and bladder to contract, so that urination is possible
• In older children and adults, the brain controls this reflex.

• Urination/Micturition
  – Bladder fills to 250ml
  – Stretch receptors send signal to spinal cord
  – Motor nerve impulses cause sphincters to relax and bladder to contract
16.2 Anatomy of the Kidney and Excretion

- Lengthwise section of the kidney reveals three regions.
  - **Renal cortex** – outer granulated layer that dips down in between a radially striated inner-layer
  - **Renal medulla** – contains cone-shaped tissue masses called renal pyramids
  - **Renal pelvis** – central cavity continuous with ureter
Anatomy of a Nephron

- A microscopic view reveals that a kidney is composed of over a million nephrons.
  - Each nephron has its own blood supply, including two capillary regions.
    - From renal artery, an afferent arteriole leads into the glomerulus.
    - Blood leaves the glomerulus via an efferent arteriole.
    - The efferent arteriole takes blood to the peritubular capillary network.
      - These surround rest of the nephron
    - Blood then enters renal vein.
Parts of a Nephron

- **Glomerular capsule** (Bowman capsule)
  - Cuplike structure
  - Inner layer composed of podocytes
    - Form pores for passage of small molecules
- **Proximal convoluted tubule (PCT)**
  - Cuboidal epithelial cells with microvilli
    - Increased surface area for absorption

Parts of a Nephron

- **Loop of Henle**
  - U-shaped tube
  - Lining of simple squamous epithelium
- **Distal convoluted tubule** (DCT)
  - Cuboidal cells with numerous mitochondria but lacking microvilli
  - Designed for tubular excretion rather than reabsorption
- **Collecting Ducts**
  - Several nephrons connect to one colleting duct

Figure 16.4a

A nephron and its blood supply
Urine Formation

• Urine formation is divided into three steps.
  – Glomerular filtration
  – Tubular reabsorption
  – Tubular secretion

Glomerular Filtration

• **Glomerular filtration** occurs when blood enters the afferent arteriole and glomerulus.
  – Blood pressure forces water and small molecules into the glomerular capsule (filtration).
    • Large molecules and formed elements cannot leave the capillaries.
  – **Glomerular filtrate** contains small dissolved molecules in similar concentration as plasma.
    • Unfiltered molecules and components leave the glomerulus via the efferent arteriole.
• **Glomerular Filtration**
  - Nephrons filter about 180 liters of water per day, along with considerable amounts of small molecules and ions.
  - Remaining processes alter composition of the filtrate.
Tubular Reabsorption

• Molecules and ions are reabsorbed both actively and passively.
• Reabsorbed materials travel from the nephron into the blood of the peritubular capillaries.
• Sodium is reabsorbed by active transport (about 65%).
• Chloride follows and is passively reabsorbed.
• This causes in increased osmolarity of the blood, which allows water to be absorbed by osmosis from the tubule into the blood.

Tubular Reabsorption

• Nutrients, such as glucose and amino acids, also return to the blood
• This is a selective process because only molecules recognized by carrier proteins are actively reabsorbed.
  – Glucose is almost completely reabsorbed due to plentiful supply of carrier proteins.
  – Excess glucose ends up being excreted because every substance has a maximum rate of transport.

Tubular Reabsorption

• In diabetes, excess glucose is present in the blood because the liver and muscles failed to store glucose as glycogen.
• The kidneys cannot reabsorb all the glucose in the filtrate.
• This also causes increased osmolarity in the filtrate, causing water to be reabsorbed into the peritubular capillary network.
• This leads to frequent urination and thirst.
Tubular Reabsorption

• The filtrate that enters the PCT is divided into two portions:

<table>
<thead>
<tr>
<th>Reabsorbed Filtrate Components</th>
<th>Nonreabsorbed Filtrate Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most water</td>
<td>Some water</td>
</tr>
<tr>
<td>Nutrients</td>
<td>Most nitrogenous waste</td>
</tr>
<tr>
<td>Required salts (ions)</td>
<td>Excess salts (ions)</td>
</tr>
</tbody>
</table>

Tubular Secretion

• **Tubular secretion** is a second way to remove substances from blood and add to tubular fluid.
  – Hydrogen ions, potassium ions, creatinine, many drugs actively transported from the blood
• Urine ends up containing two things.
  – Filtered substances that have not been reabsorbed
  – Substances that have been actively secreted

16.3 Regulatory Functions of the Kidneys

• Kidneys maintain the water-salt balance of the blood within normal limits.
  – Automatically affects blood volume and blood pressure
• Most of the water and salt (NaCl) present in the filtrate is reabsorbed across the wall of the proximal convoluted tubule.
Osmoregulation

- Excretion of hypertonic urine depends on reabsorption of water from the loop of the nephron and collecting duct.
  - Reabsorption of water requires
    1. Reabsorption of salt
    2. Establishment of solute gradient dependent on salt
    3. Reabsorption of water through channels called aquaporins

Reabsorption of Salt

- The kidneys regulate the salt balance in blood by controlling excretion and reabsorption of various ions.
- Sodium (Na⁺) is a key ion in plasma that must be regulated as well as other ions (K⁺, HCO₃⁻, Mg²⁺).
- More than 99% of Na⁺ filtered at the glomerulus is returned to the blood.
  - 67% by PCT
  - 25% by ascending limb of nephron
  - About 7% by DCT and collecting duct

Reabsorption of Salt

- Hormones control sodium reabsorption at the distal convoluted tubule.
  - Aldosterone promotes the excretion of potassium ions (K⁺) and the reabsorption of sodium ions (Na⁺).
    - The kidneys themselves promote aldosterone release when blood volume/pressure is too low for glomerular filtration.
  - Renin is released by the juxtaglomerular apparatus when blood pressure is low, which leads to aldosterone release.
• When blood pressure at the glomerulus is low
  – Juxtaglomerular Apparatus secretes renin
  – Renin changes angiotensinogen into Angiotensin I
  – Angiotensin I converted into Angiotensin II

Figure 16.6

• Angiotensin II stimulates the adrenal cortex to release aldosterone
  – Aldosterone promotes the excretion of K⁺ and the reabsorption of Na⁺
  – The reabsorption of Na⁺ is followed by the reabsorption of H₂O
  – Blood volume and blood pressure increase

Figure 16.6

Reabsorption of Salt

• Atrial natriuretic hormone (ANH) is a hormone secreted by the atria when the cardiac cells are stretched due to increased blood volume.
  – Another hormone regulating sodium
  – Secreted by right atrium of heart in response to stretching - indicates increased blood volume
  – Inhibits renin secretion by juxtaglomerular apparatus
  – Inhibits aldosterone release
  – Promotes sodium excretion - natriuresis
Establishment of Solute Gradient

- Long loop of nephron
  - Has two parts - descending limb and ascending limb
  - Salt diffuses out of lower part of ascending limb
  - Salt actively transported out of the upper part of ascending limb
  - Ascending limb impermeable to water

Establishment of Solute Gradient

- Less and less salt available for transport as fluid moves up the thick part of the ascending limb
- Osmotic gradient within the renal medulla is therefore created.
- Urea contributes to high solute concentration in medulla.
  - Leaks from lower collecting duct
- This results in a concentration gradient favoring reabsorption of water.
Reabsorption of Water

- Water leaves the descending limb of loop because of the osmotic gradient.
  - Countercurrent mechanism
- Salt is actively pumped out of the ascending limb.
  - Osmolarity is lowered
  - Fluid is hypotonic
  - Urine is hypotonic e.g., when excess water needs to be excreted

Reabsorption of Water

- When urine needs to be hypertonic, Antidiuretic hormone (ADH) is produced by the posterior pituitary gland.
  - In the absence of ADH, collecting duct is impermeable to water.
    - Dilute urine is produced.
  - In the presence of ADH, collecting duct becomes more permeable to water.
    - Concentrated urine is produced.

Diuretics

- **Diuretics** increase the flow of urine.
  - Alcohol
    - Inhibits ADH secretion
    - Dehydration causes hangover
  - Caffeine
    - Increases glomerular filtration rate
    - Decreases tubular reabsorption of sodium
  - Diuretic drugs
    - Many inhibit active transport of sodium at loop of the nephron or the distal convoluted tubule
Acid-Base Balance

- Normal pH for most body fluids is 7.4, which is optimal for most cellular proteins.
  - **Alkalosis**: pH is greater than 7.4
  - **Acidosis**: pH is less than 7.4

- Several mechanisms maintain a pH of ~ 7.4.
  - Acid-base buffer system
  - Respiratory center
  - The kidneys

Acid-Base Buffer Systems

- The pH of blood stays near 7.4 because the blood is buffered.
  - **Buffer**: chemical or combination of chemicals
    - Can take up excess $\text{H}^+$ or $\text{OH}^-$
    - Prevents large changes in pH
  - When $\text{H}^+$ added to blood the following occurs:
    $$\text{H}^+ + \text{HCO}_3^- \rightarrow \text{H}_2\text{CO}_3$$
  - When $\text{OH}^-$ added to blood the following occurs:
    $$\text{OH}^- + \text{H}_2\text{CO}_3 \rightarrow \text{HCO}_3^- + \text{H}_2\text{O}$$

Respiratory Center

- Increasing the breathing rate removes $\text{CO}_2$.
  - Removes hydrogen ions
  - Forces reaction to the right
    $$\text{H}^+ + \text{HCO}_3^- \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{H}_2\text{O} + \text{CO}_2$$

- Respiratory system adjusts proportion of bicarbonate and carbonic acid.
The Kidneys

- Only kidneys can remove many acids and bases.
- Kidneys are slower-acting than the other two mechanisms but more powerful.
- Kidneys reabsorb bicarbonate ions as needed.
- Kidneys excrete hydrogen ions as needed.
- In urine, ammonia can absorb hydrogen ions.
- Phosphate provides another means of buffering hydrogen ions in urine.

Acid-Base Balance: The Kidneys

Disorders of the Kidneys

- Many major illnesses can cause kidney disease.
  - Diabetes
  - Hypertension
  - Certain autoimmune diseases
- These conditions tend to damage the glomeruli, resulting in a decreased glomerular filtration rate, and eventually kidney failure.
Disorders of the Kidneys

• **Pyelonephritis**: infection of the kidneys
  – Usually result from urinary bladder infections
    • Infection is spread via ureter(s)
  – Most cured with antibiotics if diagnosed in time
  – Can cause severe damage

Disorders of the Kidneys

• **Kidney Stones**
  – Hard granules that form in the renal pelvis
  – Composed of substances such as calcium, phosphate, uric acid, and protein
  – Excess animal protein in diet, imbalanced urinary pH, and urinary tract infections may be contributing factors
  – May pass unnoticed in the urine; large stones can be very painful

Disorders of the Kidneys

• One of the first signs of kidney damage is presence of albumin, white blood cells, and/or red blood cells in the urine.
• Once more than two-thirds of the nephrons have been destroyed by a disease process, urea and other waste products accumulate in the blood.
  – Condition known as uremia
• Retention of water and salt lead to edema.
  – Can lead to heart failure
Treatment Options for Kidney Failure

- Patients whose kidneys are failing may undergo **hemodialysis**.
  - Diffusion of dissolved molecules through membrane
    - Selective permeability
    - Blood cleansed
    - pH adjusted
    - Water and salt balance maintained

An Artificial Kidney Machine

![Diagram of an artificial kidney machine](image)

**Figure 16.9**

- Continuous ambulatory peritoneal dialysis (CAPD)
  - Used when hemodialysis centers are not available
  - Peritoneum is the dialysis membrane
    - Fresh amount of dialysate is introduced directly into abdominal cavity through a permanently implanted tube
    - Waste and salts pass from blood vessels in abdominal wall into the dialysate
    - Fluid is collected several hours later
Treatment Options for Kidney Failure

- **Kidney transplant**
  - Surgical replacement of defective kidney with a healthy donor kidney
  - Organ rejection is possible.
  - The best match possibilities are from family members.
  - Current one-year survival rate is 95-98%.
  - Donor organs are in short supply.

Disorders of the Bladder and Urethra

- **Bladder and urethra infections**
  - Infections are likely the most common cause of problems.
  - Urine leaving the bladder is usually bacteria-free.
  - The distal urethra is normally colonized with bacteria.
  - Sometimes harmful bacteria from urethra gain access to the bladder.
  - Infections are more common in females, whose urethra is shorter and broader.
Disorders of the Bladder and Urethra

• **Bladder Stones**
  – Can form in people of any age
  – Occur as a result of bladder infections with associated inflammation or prostate enlargement in men
  – May actually be kidney stones that were carried to the bladder
  – Can be removed surgically or broken apart by lithotripsy

• **Bladder Cancer**
  – Most common type of cancer affecting the urinary system
  – In US, fourth most common type of cancer in men and the tenth most common in women
  – Greatly increased risk with smoking
  – Can be very malignant, necessitating removal of the bladder
Recently researchers have had success growing entire human bladders in the lab and implanting them into a limited number of patients.
Clinical trials of such replacement bladders are ongoing.

Figure 16.12