The Urinary System
Chapter 23

• Anatomy of the urinary system
• Functions of the urinary system
• Anatomy of the kidney
• Urine formation
  – glomerular filtration
  – tubular reabsorption
  – tubular secretion
• Urine storage and elimination
Position of the Kidneys

• The kidneys are **retroperitoneal**, located behind the peritoneal membrane of the abdomen.

• Adipose Capsule
  – Adipose cushions and positions kidney.
  – This fat is not normally used to store energy, rather it is protection from mechanical injury and for maintaining position of kidney and vessels.
  – Loss of this fat can lead to **renal ptosis** (drooping of kidney).
  – Renal ptosis can lead to renal failure if vessels get pinched.
Gross Anatomy of the Kidney
Kidney Anomalies

Occasionally people will have only one kidney on one side or one horseshoe-shaped kidney as in these images.
Kidney Functions

- Filters blood plasma and eliminates nitrogenous wastes and returns useful substances to blood.
- Regulates water balance and osmolarity of body fluids which also affects blood volume and blood pressure.
- Secretes renin which is part of the angiotensin system that regulates blood pressure.
- Secretes erythropoietin (RBC production).
- Regulates acid-base balance of the blood.
- Contributes to calcium homeostasis through Vitamin D activation (the liver also activates Vitamin D).
Excretion

- **Excretion** is the separation and elimination of wastes from body fluids.
- Excretion is accomplished by several organ systems:
  - **respiratory system**: CO$_2$ exhaled into the air
  - ** integumentary system**: water, salts, urea in sweat
  - **digestive system**: water, salts, excess lipids, undigested fibers in feces
  - **urinary system**: water, salts, toxins, drugs, hormones, excess H$^+$, nitrogenous wastes and many other metabolic wastes into urine
Nitrogenous Wastes

- **Urea**
  - amino acid catabolism produces highly toxic ammonia (NH$_3$) that the liver converts into less toxic urea

- **Uric Acid**
  - uric acid is produced from nucleic acid catabolism

- **Creatinine**
  - Creatinine is a breakdown product of creatine, which is a byproduct of the phosphagen enzyme system for ATP production in skeletal muscle. The normal daily production of creatine and subsequently creatinine, is usually very stable. Creatinine is excreted from the body entirely by the kidneys. With normal renal excretory function, the serum creatinine level should remain at a constant low level.
## Properties and Composition of Urine

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>1.001–1.028</td>
</tr>
<tr>
<td>Osmolarity</td>
<td>50–1,200 mOsm/L</td>
</tr>
<tr>
<td>pH</td>
<td>6.0 (range 4.5–8.2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solute</th>
<th>Concentration*</th>
<th>Output (g/day)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inorganic ions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>533 mg/dL</td>
<td>6.4 g/day</td>
</tr>
<tr>
<td>Sodium</td>
<td>333 mg/dL</td>
<td>4.0 g/day</td>
</tr>
<tr>
<td>Potassium</td>
<td>166 mg/dL</td>
<td>2.0 g/day</td>
</tr>
<tr>
<td>Phosphate</td>
<td>83 mg/dL</td>
<td>1 g/day</td>
</tr>
<tr>
<td>Ammonia</td>
<td>60 mg/dL</td>
<td>0.68 g/day</td>
</tr>
<tr>
<td>Calcium</td>
<td>17 mg/dL</td>
<td>0.2 g/day</td>
</tr>
<tr>
<td>Magnesium</td>
<td>13 mg/dL</td>
<td>0.16 g/day</td>
</tr>
<tr>
<td>Nitrogenous wastes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urea</td>
<td>1.8 g/dL</td>
<td>21 g/day</td>
</tr>
<tr>
<td>Creatinine</td>
<td>150 mg/dL</td>
<td>1.8 g/day</td>
</tr>
<tr>
<td>Uric acid</td>
<td>40 mg/dL</td>
<td>0.5 g/day</td>
</tr>
<tr>
<td>Urobilin</td>
<td>125 μg/dL</td>
<td>1.52 mg/day</td>
</tr>
<tr>
<td>Bilirubin</td>
<td>20 μg/dL</td>
<td>0.24 mg/day</td>
</tr>
<tr>
<td>Other organics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amino acids</td>
<td>288 μg/dL</td>
<td>3.5 mg/day</td>
</tr>
<tr>
<td>Ketones</td>
<td>17 μg/dL</td>
<td>0.21 mg/day</td>
</tr>
<tr>
<td>Carbohydrates</td>
<td>9 μg/dL</td>
<td>0.11 mg/day</td>
</tr>
<tr>
<td>Lipids</td>
<td>1.6 μg/dL</td>
<td>0.02 mg/day</td>
</tr>
</tbody>
</table>
Composition and Properties of Urine

• Appearance
  – ranges from almost colorless to deep amber; yellow color is partly due to urochrome, from breakdown of hemoglobin
  – other colors from digestion of food (carotenoids) or drugs
  – cloudiness can be due to bacteria

• Odor - bacteria degrade urea into ammonia

• Osmolarity - ranges from dilute in a well-hydrated person (50 mOsm/L) to highly concentrated (1,200 mOsm/L) in a dehydrated person. Normal blood = 300 mOsm/L.

• pH – is usually around 6, but can vary 4.5 - 8.2

• Chemical composition: 95% water, 5% solutes
  – solutes are mostly urea, ammonia, Na⁺, K⁺, Cl⁺, creatinine
Urine Output

- Normal volume: 1-2 liters/day
- **Polyuria** > 2 liters/day
- **Oliguria** < 500 ml/day
- **Anuria**: 0 to 100 ml/day
Anatomy of the Kidney

- Renal Cortex: outer 1 cm
- Renal Medulla: composed of renal pyramids
- Renal Pelvis: connective tissue cavity that collects urine
- Hilum is the indented area of the kidney where the blood vessels and ureter attach
Kidney Stones

x-ray of “Staghorn” Kidney Stone and the kidney stone after surgery
Blood Flow Through the Kidney

Renal Artery → Glomerulus → Renal Vein
Nephrons: the functional units of the kidney have **vascular** parts and **tubular** parts
vascular parts of the nephron:

afferent arteriole
glomerulus
efferent arteriole
peritubular capillaries
vasa recta
tubular part of the Nephron

Bowman’s Capsule

Proximal Convoluted Tubule

Loop of Henle (nephron loop)
  - descending thin limb
  - ascending thick limb

Distal Convoluted Tubule

Collecting duct
Renal Filtrate Formation and Excretion

- plasma in glomerular capillary
- Bowman’s capsule
- proximal convoluted tubule (PCT)
- loop of Henle (nephron loop)
- distal convoluted tubule (DCT)
- collecting duct
- minor calyx
- major calyx
- renal pelvis
- ureter
- urinary bladder
- urethra
Summary of Filtration by the Nephron

I. Glomerular filtration
   Creates a plasmalike filtrate of the blood

II. Tubular reabsorption
    Removes useful solutes from the filtrate, returns them to the blood and
    Tubular secretion
    Removes additional wastes from the blood, adds them to the filtrate

III. Water conservation
    Removes water from the urine and returns it to blood, concentrates wastes

Blood flow
Renal corpuscle
Flow of filtrate
Peritubular capillaries
Renal tubule
H₂O
H₂O
H₂O
Urine
Filtration, Reabsorption, Secretion and Excretion by the Nephron
Renal Corpuscle = glomerulus and Bowman’s capsule
Glomerular Filtration Membrane

- Filtration slits
- Capillary endothelium
- Pedicels
- Basement membrane
- Fenestrations
- Podocyte cell body
Glomerular Filtration Membrane

- **Fenestrated Endothelium**
  - 0.08 micron pores exclude cells and large proteins like albumin

- **Basement Membrane**
  - double layer of collagen from podocytes and endothelial cells is a selectively permeable membrane that only passes water, ions and small molecules, but not proteins
  - blood plasma has 7% protein but glomerular filtrate should only have about 0.03% protein

- **Filtration Slits**
  - podocyte arms have interdigitating pedicels that form filtration slits that support the membrane and allow liquid to pass through.
Filtration Pressure

Blood hydrostatic pressure (BHP): 60 mmHg out
Colloid osmotic pressure (COP): -32 mmHg in
Capsular pressure (CP): -18 mmHg in
Net filtration pressure (NFP): 10 mmHg out
Glomerular Filtration Rate (GFR)

- GFR = volume of filtrate formed per minute
- GFR = \( \approx 150-180 \text{ L/day} \) (50 x total blood volume)
- 99% of filtrate is reabsorbed, only 1-2 L urine excreted per day
- GFR is controlled by adjusting glomerular blood pressure through:
  - autoregulation: smooth muscle of afferent arteriole stabilizes glomerular BP over a range of 80 to 170 mmHg (systolic)
    - \( \uparrow \) BP stretches smooth muscle of afferent arteriole which responds by constricting and reducing blood flow.
    - \( \downarrow \) BP relaxes smooth muscle around afferent arteriole
  - sympathetic control:
    - acute stress triggers sympathetic neurons to constrict juxtaglomerular smooth muscle of afferent arterioles resulting in \( \downarrow \) GFR and urine production and redirect more blood flow to the heart, brain and skeletal muscles.
Overview of Urine Formation

http://www.biologymad.com/resources/kidney.swf
<table>
<thead>
<tr>
<th>Region of the Tubular Nephron</th>
<th>Function Summary</th>
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<tbody>
<tr>
<td>Proximal Convoluted Tubule</td>
<td>Continuous, selective reabsorption of useful glomerular filtrates and returns them to the blood.</td>
</tr>
<tr>
<td>Descending Thin Limb of Loop of Henle</td>
<td>Freely permeable to water which is removed from the urine and returned to the blood.</td>
</tr>
<tr>
<td>Ascending Thick Limb of Loop of Henle</td>
<td>Actively and constantly pumps Na⁺, K⁺, and Cl⁻ out of urine and returns it to the blood resulting in a dilute, hypotonic urine.</td>
</tr>
<tr>
<td>Distal Convoluted Tubule</td>
<td>Responsive to aldosterone which activates pumps that move Na⁺ from the urine and returns it to the blood and water follows. NaCl and water retention reduces urine output and helps maintain blood volume and pressure.</td>
</tr>
<tr>
<td>Collecting Duct</td>
<td>Impermeable to water resulting in a large amount of dilute urine. Vasopressin (ADH) released due to dehydration increases collecting duct permeability resulting in water reabsorption and reduced urine output.</td>
</tr>
</tbody>
</table>
A Summary of Renal Function
Proximal Convoluted Tubule Reabsorption

• Reabsorbs 65% of glomerular filtrate into peritubular capillaries including:
  – glucose (over 90%), amino acids, small proteins, vitamins, salts (Na\(^+\), K\(^+\), Ca\(^{+2}\), Mg\(^{+2}\), Cl\(^-\)), bicarbonate, water

• PCT is a long tubule of cells with microvilli and abundant mitochondria for active transport.
  – PCT metabolism alone accounts for 6% of total calorie consumption at rest.

• Transport Maximum: transport proteins of cell membrane can become saturated.
  – if blood glucose is extremely high, the PCT can not transport it all and some remains in urine (glycosuria).
Proximal Convoluted Tubule Secretion

- **Waste secretion** from blood and interstitial fluid into urine
  - urea, uric acid, ammonia, some hormones, many drugs and toxins
- ** Acid-base balance** - regulates pH of body fluids.
  - excretion of excess hydrogen ions (H\(^+\)) into urine
  - reabsorption of bicarbonate (HCO\(_3^−\)) ions back into blood
The Role of the Loop of Henle

- **Descending Limb of Loop of Henle**
  - always freely permeable to water and urea
  - water follows gradient **out** of tubule

- **Ascending Limb of Loop of Henle**
  - pumps Na\(^+\), K\(^+\), and Cl\(^-\) out of urine into interstitial tissue constantly
  - maintains high osmolarity of renal medulla
  - always impermeable to water
  - tubular fluid becomes hypotonic
Countercurrent Multiplier of the Loop of Henle

- More salt is continually added by the PCT.
- The higher the osmolarity of the ECF, the more water leaves the descending limb by osmosis.
- The more water that leaves the descending limb, the saltier the fluid is that remains in the tubule.
- The more salt that is pumped out of the ascending limb, the saltier the ECF is in the renal medulla.
- The saltier the fluid in the ascending limb, the more salt the tubule pumps into the ECF.
The Effects of Aldosterone on the DCT

Aldosterone (salt-retaining hormone)
  – Steroid hormone secreted by adrenal cortex in response to:
    • decreased amount of Na\(^+\) in the blood
    • drop in blood pressure
  – Causes cells of DCT to reabsorb Na\(^+\) from urine
  – Water is reabsorbed following the salt gradient.
  – Overall effect is ↓ urine volume and ↑ blood volume and ↑ blood pressure.
The Effects of Vasopressin (ADH) on the DCT and Collecting Ducts

- Vasopressin is an antidiuretic hormone (ADH)
  - dehydration stimulates neurons in the hypothalamus that send axons into the posterior pituitary which releases vasopressin
  - vasopressin increases the permeability of DCT and CD to water by causing collecting duct cells to transfer **aquaporin** from storage vesicles in the cytoplasm to the cell membrane. Aquaporin is an integral membrane protein that lets water flow through cells from the urine back into blood.
  - overall effect is retention of water and decreased urine volume
The Effects of Vasopressin (ADH) on the DCT and Collecting Ducts

(a) Absence of ADH
- Large volume of dilute urine

(b) Presence of ADH
- Small volume of concentrated urine
The Role of Capillaries

• Peritubular Capillaries and Vasa Recta
  – peritubular capillaries surround the PCT and DCT
  – vasa recta follow the loop of Henle
  – provide blood supply to cortex and medulla
  – absorb water and solutes secreted from the urine into the interstitial tissue
  – return water and useful solutes to systemic circulation
Atrial Natriuretic Peptide (ANP)

Atrial Natriuretic Peptide (ANP) is an antagonist to vasopressin:

- **High Blood Pressure** stimulates cells in the right atrium to secrete ANP into the blood
- ANP makes the collecting duct less permeable to water which results in:
  - ↑ urine volume
  - ↓ blood volume
  - inhibits renin/angiotensin/aldosterone pathway
- Overall effect is lower Blood Pressure
Renal Failure

• Renal Failure may result from:
  – loss of blood flow to the kidney
  – blockage of urine flow
  – infection or other disease of the kidney

• Renal Failure may lead to:
  – **azotemia**: ↑ blood urea nitrogen (BUN)
  – **uremia**: toxic effects as nitrogenous wastes accumulate in the blood
The Juxtaglomerular Apparatus

Juxtaglomerular (JG) Cells
- enlarged smooth muscle cells around the afferent arteriole regulate blood flow and GFR
- contract or relax around the afferent arteriole in response to the macula densa cells and sympathetic neurons
- also secrete renin in response to ↓ BP (renin activates an endocrine response that raises BP)

Mesangial Cells
- connected by gap junctions to JG and MD cells
- probably mediate communication between JG and MD cells

Macula Densa Cells
- epithelial cells at the beginning of the DCT
- monitor flow and salinity of urine
Renin-Angiotensin Control of Blood Pressure

- Drop in blood pressure
  - Liver
    - Angiotensinogen (453 amino acids long)
    - Angiotensin I (10 amino acids long)
    - Angiotensin-converting enzyme
      - Angiotensin II (8 amino acids long)

- Hypothalamus
- Cardiovascular system
- Vasoconstriction
- Thirst and drinking
- Elevated blood pressure
- Salt and water retention
- Adrenal cortex
- Kidney
- Lungs

Renin

Kidney
END