Urinary System Functions

- Major *excretory* pathway for wastes transported by blood
  - Filtration, secretion, and reabsorption by the kidney's microscopic tubules
  - Includes wastes from metabolism, excess water and excess solutes
- Collection, transport, exit of urine – product of kidney’s function
  - Responsive to condition
- Urine release controlled by reflex actions

Organs and Vessels of the Urinary System
Kidney Function

Maintain the body’s internal environment by:
- Regulating total water volume and total solute concentration in water
- Regulating ion concentrations in ECF
- Ensuring long-term acid-base balance
- Excreting metabolic wastes, toxins, drugs
- Producing *erythropoietin* (EPO) and renin
- Activating vitamin D
- Carrying out gluconeogenesis, if needed
Physiology of Kidney

- **Typical human:**
  - 180 L of fluid processed daily, but only 1.5 L of urine is formed
- Kidneys filter body’s entire plasma volume 60 times each day
- Consume 20–25% of oxygen used by body at rest
- “Filtrate” is basically blood plasma minus proteins
- Urine is produced from filtrate
  - Urine
    - <1% of original filtrate
    - Contains metabolic wastes and unneeded substances

Nephrons and Nephron Structure

- **Nephrons** are the structural and functional units that form urine
- > 1 million per kidney
- Two main parts
  - **Renal corpuscle**
    - Glomerulus – “tuft” of capillaries
    - Glomerular (or Bowman’s) capsule
  - **Renal tubule**
    - Including tubules, loop, and duct
- Collecting ducts in the thousands to drain nephrons
Figure 25.6 Location and structure of nephrons.

- Fenestrated endothelium of the glomerulus
- Apical microvilli
- Cortex
- Medulla
- Podocyte
- Basement membrane
- Apical side
- Basolateral side
- Highly infolded basolateral membrane
- Proximal convoluted tubule
- Distal convoluted tubule
- Thick segment
- Collecting duct
- Intercalated cell
- Principal cell
- Thin segment
- Proximal convoluted tubule cells
- Glomerular capsule: parietal layer
- Glomerular capsule: visceral layer
- Distal convoluted tubule cells
- Nephron loop (thin segment) cells
- Collecting duct cells
- Renal cortex
- Renal medulla
- Renal pelvis
- Ureter
- Kidney
- Renal corpuscle
- • Glomerular capsule
- • Glomerulus
- Renal corpuscle and nearby tubules
- Histology of corpuscle and nearby tubules
- Renal corpuscle
  - Squamous epithelium of parietal layer of glomerular capsule
  - Glomerular capillary space
  - Glomerulus
- Proximal convoluted tubule
  - (fuzzy lumen due to long microvilli)
- Distal convoluted tubule
  - (clear lumen)

Figure 25.12a The filtration membrane.

- Glomerular capillary covered by podocytes that form the visceral layer of glomerular capsule
- Filtration Membrane:
  - Fenestrated capillaries
  - Visceral layer glomerular capsule with filtration slits
  - Produce solute rich, virtually protein free filtrate
- Parietal layer of glomerular capsule
- Proximal convoluted tubule
- Efferent arteriole
- Afferent arteriole
- Glomerular capillary space
Figure 25.12b The filtration membrane.

Glomerular capillary endothelium (podocyte covering and basement membrane removed)

Podocyte cell body

Fenestrations (pores)

Cytoplasmic extensions of podocytes

Filtration slits

Foot processes of podocyte

(a) Glomerular capillary surrounded by podocytes

Figure 25.12c The filtration membrane.

Capillary

Filtration membrane

- Capillary endothelium
- Basement membrane
- Foot processes of podocyte of glomerular capsule

Filtration slit

Plasma

Filtrate in capsular space

Slit diaphragm

Fenestration (pore)

Foot processes of podocyte

(d) Three layers of the filtration membrane

Figure 25.10 Juxtaglomerular complex (JGC) of a nephron.

Glomerulus

Glomerular capsule

Afferent arteriole

Efferent arteriole

Red blood cell

Podocyte cell body (visceral layer)

Foot processes of podocytes

Parietal layer of glomerular capsule

Proximal tubule cell

Lumens of glomerular capillaries

Endothelial cells of glomerular capillary

Gloysis

Gloster

Glomerular capillary surrounded by capillary endothelium

Filtration Membrane:
- Fenestrated capillaries
- Visceral layer glomerular capsule with filtration slits
- Produce solute rich, virtually protein free filtrate

Blood pressure in glomerulus high because:
- Afferent arterioles are larger in diameter than efferent arterioles
- Arterioles are high-resistance vessels

Plasma proteins remain to maintain colloid osmotic pressure

Prevents loss of all water to capsular space

Proteins in filtrate indicate membrane problem

Allows molecules smaller than 3 nm to pass:
- Water, glucose, amino acids, nitrogenous wastes, most solutes
- Normally no cells can pass

Prevents loss of all water to capsular space

Proteins in filtrate indicate membrane problem
Renal Tubules and Collecting Duct

- **Renal tubule** is about 3 cm (1.2 in.) long
- Consists of single layer of epithelial cells in 3 major parts
  1. **Proximal convoluted tubule** (closest to renal corpuscle)
     - Cuboidal cells with dense microvilli that form **brush border**, confined to cortex
     - high surface area to interact with filtrate
     - large mitochondria to support active transport functions
     - Functions in reabsorption and secretion
  2. **Nephron loop** – formerly loop of Henle – thick and thin limbs
  3. **Distal convoluted tubule**
     - Distal, farthest from renal corpuscle, confined to cortex
     - Cuboidal cells with very few microvilli
     - Function more in secretion than reabsorption
     - drains into **collecting duct**
Renal Tubule and Collecting Duct (cont.)

- **Collecting ducts**
  - Cells lining ducts participate in fine-tuning of water, sodium ion, and acid-base balance between blood and urine
  - Receive filtrate from many nephrons
  - Run through medullary pyramids
    - Give pyramids their striped appearance
  - Ducts fuse together to deliver urine through papillae into minor calyces

Nephron Capillary Beds

- Renal tubules are associated with two capillary beds
  - Glomerulus
  - Peritubular capillaries
    - Low-pressure, porous capillaries adapted for absorption of water and solutes
    - Arise from efferent arterioles
    - Cling to adjacent renal tubules in cortex
    - Empty into venules
- Juxtaglomerular nephrons are associated with Vasa recta
  - Long, thin-walled vessels parallel to long nephron loops of juxtaglomerular nephrons
  - Arise from efferent arterioles serving juxtaglomerular nephrons
  - Instead of peritubular capillaries
  - Function in formation of concentrated urine
Juxtaglomerular Complex (JGC)

- Each nephron has one
- Modified portions of distal portion of ascending limb of nephron loop and Afferent arteriole
- Regulates rate of filtrate formation and blood pressure
- Three cell populations are seen in JGC:
  1. Ascending limb macula densa contains chemoreceptors that sense NaCl content of filtrate
  2. Granular cells (or JG cells) act as mechanoreceptors to sense blood pressure in afferent arteriole
     Enlarged, smooth muscle cells of arteriole
     Contain secretory granules that contain enzyme renin
  3. Extraglomerular mesangial cells may be autoregulatory smooth muscle cells, may also contribute to renin secretion and perhaps EPO

Steps in Urine Production

- Three processes are involved in urine formation and adjustment of blood composition:
  1. **Glomerular filtration**: produces cell- and (mostly) protein-free filtrate
  2. **Tubular reabsorption**: selectively returns 99% of substances from filtrate to blood in renal tubules and collecting ducts
  3. **Tubular secretion**: selectively moves substances from blood to filtrate in renal tubules and collecting ducts
Urine Production
Step 1: Glomerular Filtration

- **Glomerular filtration** is a passive process
  - No metabolic energy required
- Hydrostatic pressure forces fluids and solutes through *filtration membrane* into glomerular capsule
- Control over systemic blood pressure very important to this process - necessitates kidney’s role in BP control

Pressures That Affect Filtration

- **Outward pressures promote filtrate formation**
  - Hydrostatic pressure in glomerular capillaries (HPgc)
    - Essentially glomerular blood pressure
    - 55 mm Hg compared to ~ 26 mm Hg seen in most capillary beds
    - Efferent arteriole
      - High-resistance vessel
      - Diameter smaller than afferent arteriole
- **Inward Pressures inhibit filtrate formation**:
  - Hydrostatic pressure in capsular space (HPcs)
    - 15 mm Hg capsule filtrate “back” pressure
  - Colloid osmotic pressure in capillaries (OPgc)
    - “pull” of proteins in blood; 30 mm Hg

- **Net filtration pressure (NFP): sum of forces**
  - 55 mm Hg forcing out minus 45 mm Hg opposing = net outward force of 10 mm Hg
  - Pressure responsible for filtrate formation
  - Main controllable factor determining glomerular filtration rate (GFR)

Figure 25.13 Forces determining net filtration pressure (NFP).

Normal Glomerular Filtration Rate (GFR) = 120–125 ml/min
Dependent on glomerular hydrostatic pressure and surface area for filtration
Step 2: Tubular Reabsorption

- **Tubular reabsorption** quickly reclaims most of tubular contents and returns them to blood
  - Whole volume of plasma enters proximal convoluted tubule every 22 minutes
- **Selective transepithelial process**
  - Almost all organic nutrients are reabsorbed
    - Like glucose and amino acids
  - Water and ion reabsorption is hormonally regulated and adjusted
  - Peritubular capillaries nearby to accept diffusing/facilitated substances
    - Contain blood that just left the glomerulus
- **Includes active and passive tubular reabsorption**
  - Primary and secondary active transport
  - Diffusion, facilitated diffusion, osmosis

Transcellular and paracellular routes of tubular reabsorption.

Reabsorption by PCT cells
Tubular Reabsorption of Nutrients, Water, and Ions

- **Passive tubular reabsorption of water**
  - Movement of Na⁺ and other solutes creates osmotic gradient for water
  - Water is reabsorbed by osmosis, aided by membrane pores called aquaporins
    - Obligatory water reabsorption
    - Aquaporins are always present in PCT
    - Facultative water reabsorption
    - Aquaporins are inserted in collecting ducts only if ADH is present

- **Passive tubular reabsorption of solutes**
  - Solute concentration in filtrate increases as water is reabsorbed
    - Creates concentration gradients for solutes, which drive their entry into tubule cell and peritubular capillaries

Transport Maximum

- Transcellular transport systems are specific and limited
  - Transport maximum ($T_m$) exists for almost every reabsorbed substance
    - Reflects number of carriers in renal tubules that are available
  - When carriers for a solute are saturated, excess is excreted in urine
    - Example: hyperglycemia leads to high blood glucose levels that exceed $T_m$, and glucose spills over into urine

Hormonal Control Over Reabsorption

- **Antidiuretic hormone (ADH)**
  - posterior pituitary gland
  - Causes principal cells of collecting ducts to insert aquaporins in apical membranes, increasing water reabsorption

- **Aldosterone**
  - Targets collecting ducts and distal DCT
  - Promotes synthesis of apical Na⁺ and K⁺ channels, and basolateral Na⁺-K⁺ pumps for Na⁺ reabsorption
  - As a result, most Na⁺ reabsorbed (and water follows)

- **Atrial natriuretic peptide**
  - Reduces blood Na⁺, resulting in decreased blood volume (water remains in filtrate with Na⁺) and blood pressure
  - Inhibits Na⁺ reabsorption from collecting ducts
  - Released by cardiac atrial cells if blood volume or pressure elevated
Step 3: Tubular Secretion

- Occurs mostly in PCT with 'fine-tuning' in DCT and collecting duct
- Selected substances are moved from peritubular capillaries through tubule cells out into filtrate
  - K⁺, H⁺, NH₄⁺, creatinine, organic acids and bases
- Substances synthesized in tubule cells also are secreted (example: HCO₃⁻)
- Important for:
  - Disposing of substances, such as drugs or metabolites
  - Eliminating undesirable substances that were passively reabsorbed (example: urea and uric acid)
  - Ridding body of excess K⁺ (aldosterone effect)
  - Controlling blood pH by altering amounts of H⁺ or HCO₃⁻ in urine

Summary of tubular reabsorption and secretion.

Cortex

<table>
<thead>
<tr>
<th>Reabsorption</th>
<th>Secretion</th>
</tr>
</thead>
<tbody>
<tr>
<td>65% of filtrate volume reabsorbed</td>
<td>H₂O, Na⁺, HCO₃⁻, and many other ions</td>
</tr>
<tr>
<td>All glucose, amino acids and other nutrients</td>
<td>Regulated reabsorption</td>
</tr>
<tr>
<td>H⁺ and NH₄⁺</td>
<td>Some drugs</td>
</tr>
<tr>
<td>Regulated secretion</td>
<td>K⁺ (by aldosterone)</td>
</tr>
<tr>
<td>Regulated secretion</td>
<td>Reabsorption or secretion to maintain blood pH described in Chapter 26; involves H⁺, HCO₃⁻, and NH₄⁺</td>
</tr>
<tr>
<td>Regulated reabsorption</td>
<td>H₂O (by ADH)</td>
</tr>
<tr>
<td>Na⁺ (by aldosterone; Cl⁻ follows)</td>
<td>Urea (increased by ADH)</td>
</tr>
<tr>
<td>Na⁺, K⁺, Cl⁻</td>
<td>Urea</td>
</tr>
<tr>
<td>H₂O</td>
<td>Na⁺, K⁺, Cl⁻</td>
</tr>
<tr>
<td>Ca²⁺ (by parathyroid hormone)</td>
<td>No solutes can leave the descending limb</td>
</tr>
<tr>
<td>No water can leave the ascending limb</td>
<td></td>
</tr>
<tr>
<td>No stimulus needed - automatic</td>
<td></td>
</tr>
<tr>
<td>No stimulus can leave the ascending limb</td>
<td></td>
</tr>
</tbody>
</table>

Regulation of Urine Concentration and Volume

- Kidneys make adjustments needed to maintain body fluid osmotic concentration at around 300 mOsm
- Same as plasma
- Limits osmosis between cells and fluids = balance, no cells swell or shrink
- Osmolality is a measure of the osmoles (Osm) of solute per kilogram of solvent (osmol/kg or Osm/kg)
- Osmolarity is defined as the number of osmoles of solute per liter (L) of solution (osmol/L or Osm/L)
- Body fluids have much smaller amounts, so expressed in milliosmoles (mOsm) = 0.001 osmol
  - 1 mole NaCl/L = 2 osmoles NaCl/L
- Urine volume and concentration vary based on
  - Your hydration status: drinking, sweating
  - Small amount of concentrated urine if the body is dehydrated
  - Large amount of dilute urine if overhydrated
Regulation of Urine Concentration and Volume

- Accomplish this by using countercurrent mechanism
- Fluid flows in opposite directions in two adjacent segments of same tube
- Countercurrent mechanisms work together to:
  - Establish and maintain medullary osmotic gradient from renal cortex through medulla
    - Gradient runs from 300 mOsm in cortex to 1200 mOsm at bottom of medulla
  - Countercurrent multiplier creates gradient
  - Countercurrent exchanger preserves gradient
  - Collecting ducts can then use gradient to vary urine concentration

Juxtamedullary nephrons create an osmotic gradient within the renal medulla that allows the kidney to produce urine of varying concentration.
Formation of Dilute or Concentrated Urine

- Established medullary osmotic gradient can now be used to form dilute or concentrated urine
  - Without gradient, would not be able to raise urine concentration > 300 mOsm to conserve water
- Overhydration produces large volume of dilute urine
  - ADH production decreases; urine ~100 mOsm
  - If aldosterone present, additional ions can be removed, causing water to dilute to ~50 mOsm
- Dehydration produces small volume of concentrated urine
  - Maximal ADH is released; urine ~1200 mOsm
  - Severe dehydration: 99% water reabsorbed
Urine

- **Chemical composition**
  - 95% water and 5% solutes
- **Nitrogenous wastes**
  - Urea (from amino acid breakdown): largest solute component
  - Uric acid (from nucleic acid metabolism)
  - Creatinine (metabolite of creatine phosphate)
- Other normal solutes found in urine
  - Na⁺, K⁺, PO₄³⁻, and SO₄²⁻, Ca²⁺, Mg²⁺ and HCO₃⁻
- Abnormally high concentrations of any constituent, or abnormal components may indicate pathology
- **pH**
  - Urine is slightly acidic (~pH 6, with range of 4.5 to 8.0)
Urinary Bladder (cont.)

- **Urine storage capacity**
  - Collapses when empty
  - *Rugae* appear
  - Expands and rises superiorly during filling without significant rise in internal pressure
  - Moderately full bladder is ~12 cm long (5 in.) and can hold ~ 500 ml (1 pint)

**Micturition**, also called urination or voiding

Three simultaneous events must occur

1. Contraction of detrusor by ANS
2. Opening of internal urethral sphincter by ANS
3. Opening of external urethral sphincter by somatic nervous system