24. Urinary System

I. Introduction to the Urinary System
The primary function of the urinary system is to remove waste materials from the body, by filtering the blood. Every day the kidneys filter the equivalent of about 200 liters of fluid from the bloodstream. When they are functioning normally, the kidneys eliminate toxins, metabolic wastes, and excess ions, while they retain substances useful to the body.

The kidneys also provide additional functions for the body:

A. The kidneys produce an enzyme that is necessary for the formation of the hormone calcitriol. Review the chapter on the integumentary system if you can’t remember the function of calcitriol.

B. The kidneys produce the hormone erythropoietin. You should remember this from the beginning of the semester.

C. The kidneys participate in regulation of the levels of various ions in the blood (e.g., Na⁺, K⁺, and Ca²⁺). The kidneys also help to maintain the proper pH of the blood.

D. The kidneys help regulate blood pressure by releasing renin and by adjusting the amount of fluid retained by the body.

Along with the kidneys, the urinary system includes the ureters, urinary bladder, and urethra (Fig. 24.1).

II. Gross Anatomy of the Kidney

Location and support
Kidneys are located in the upper lumbar region of the body (Fig. 24.1). Each is bean-shaped and a bit smaller than the size of your hand. The hilum (or hilus) of the kidney is the point of entry or exit for the renal artery, renal vein, and ureter (Fig. 24.3).

The kidneys occupy a dorsal position in the body, outside of the abdominopelvic cavity between the parietal peritoneum and the muscle of the dorsal body wall (Fig. 24.2).

A layer of tissue called the fibrous capsule, which consists largely of collagen fibers, surrounds each kidney (Fig. 24.2). A thick layer of adipose tissue, called the perinephric fat, surrounds the fibrous capsule. A layer of dense irregular connective tissue, called the renal fascia, encloses the perinephric fat and anchors the kidney to surrounding tissues. Finally, another layer of adipose tissue, the paranephric fat, lies outside of the renal capsule.

Sectional anatomy of the kidney
The outer portion of the kidney tissue is the cortex, and the deeper portions of tissue make up the medulla (Fig. 24.3). The medulla is divided among eight to fifteen conical structures called renal pyramids. The base of each pyramid faces the cortex, and the apex of each pyramid (the renal papilla) projects inward. Pyramids are separated from each other by extensions of cortical tissue, called renal
columns. Each pyramid and its adjacent region of the cortex make up a renal lobe. There is an internal cavity, called the renal sinus, located medially within each kidney. Blood vessels and the ureter branch within this cavity before entering or after exiting the kidney tissue proper.

Urine production occurs in each renal lobe, and urine collects in ducts that lead through each pyramid to its renal papilla. Each papilla empties into a minor calyx. A few minor calyces join together to form a major calyx, and major calyces lead to the renal pelvis, which opens to the ureter.

III. Functional Anatomy of the Kidney

Nephron
The functional unit of the kidney is the nephron (Fig. 24.4). Each nephron consists of a renal corpuscle and a renal tubule. Most of each nephron resides in the cortex of the kidney, except for the nephron loop, which extends into the medulla.

Renal corpuscle
The renal corpuscle forms one end of each nephron, and it is composed of two structures: the glomerulus and the glomerular capsule (or Bowman’s capsule). The glomerulus is a network of fenestrated capillaries that have the job of filtering blood that enters the kidney. Blood enters the glomerulus via an afferent arteriole and exits via an efferent arteriole. The glomerular capsule surrounds the glomerulus and collects fluid that is filtered out of the glomerulus. The visceral layer of the glomerular capsule is wrapped tightly around the capillaries of the glomerulus, and the parietal layer forms an outer covering. The space between these two layers is the capsular space, and this is where filtrate is initially collected.

Renal tubule
The renal tubule is a long tube that can be divided into three parts: The proximal convoluted tubule (PCT) carries fluid from the glomerular capsule. Cuboidal epithelium with microvilli lines the lumen and absorbs desired molecules from the tubular fluid back into the tissues. The nephron loop (or loop of Henle) has both descending and ascending limbs, and each limb has a thick segment and a thin segment. The distal convoluted tubule (DCT) is similar in appearance to the PCT, yet it lacks microvilli.

Collecting tubules and collecting ducts
From the DCT, urine travels to a collecting duct. From a collecting duct, urine will travel to a minor calyx, major calyx, etc. For simplicity, I will lump “collecting tubules” in with collecting ducts.

Juxtaglomerular apparatus
A portion of the DCT lies in close proximity to the renal corpuscle and the afferent and efferent arterioles (Fig. 24.7). The structure formed as a result is called the juxtaglomerular apparatus. Specialized cells of the juxtaglomerular apparatus called the macula densa will be discussed later.

IV. Blood Flow and Filtered Fluid Flow

At rest, about 20-25% of cardiac output flows through the kidneys. This is on the order of 1200 ml per minute.
Blood flow through the kidney
Each renal artery enters the renal sinus and branches into segmental arteries (Fig. 24.8). These branch into interlobar arteries, which extend through the renal columns toward the cortex. Arcuate arteries arch across the bases of the renal pyramids. Interlobular arteries extend into the cortex from the arcuate arteries.

Afferent arterioles branch off the interlobular arteries and lead to the glomeruli. Blood is filtered at the glomerulus, with some fluid leaving the glomerulus and entering the glomerular capsule. Blood that does not get filtered exits the glomerulus through an efferent arteriole. In part because the afferent arteriole has a larger diameter than the efferent arteriole, blood pressure in the glomerulus is unusually high for a capillary bed. This pressure is the force that drives filtration.

From the efferent arteriole, blood travels to the peritubular capillaries, which surround the renal tubules. Blood also travels through the vasa recta, which is a network of capillaries that surrounds the nephron loop.

Blood from the peritubular capillaries and vasa recta travels to the cortical radiate veins, arcuate veins, interlobar veins, and the renal vein.

V. Production of Filtrate Within the Renal Corpuscle

Overview of urine formation
Each day, approximately 180 liters of fluid is filtered from the blood into the nephrons. This “filtrate” contains just about everything blood does, except proteins and formed elements. By the time the filtrate reaches the collecting ducts, much of the water, nutrients, and essential ions have been reabsorbed by the body. Thus, the composition of filtrate is very different from the composition of urine that exits the body, and only about 1% of the filtrate leaves the body as urine.

One of the primary goals of urine formation is the elimination of organic wastes from the body. Three compounds in particular deserve mention:
A. Urea is the most abundant organic waste in the urine. It is produced from ammonia, which is a by-product of protein metabolism.
B. Creatinine is a product of the breakdown of creatine in the muscle cells.
C. Uric acid is generated as nitrogenous bases in RNA are recycled.

There are three main processes involved in converting filtrate into urine: (1) filtration, (2) tubular reabsorption, and (3) tubular secretion. In this section we will examine the process of filtration.

Formation of filtrate and its composition
Substances in the blood can be grouped into three categories according to how easily they pass through the filtration membrane of the glomerulus and glomerular capsule:

- Freely filtered–small substances such as water, glucose and other sugars, amino acids, ions, etc. pass freely through the filtration membrane.
- Not filtered–formed elements and large proteins normally do not pass through the filtration membrane.
• Limited filtration—medium sized proteins normally do not get filtered to a significant degree, but they might under certain circumstances, such as when blood pressure rises during exercise.

The large amount of filtrate formed contains many substances, including those shown in the table below:

<table>
<thead>
<tr>
<th>Substance</th>
<th>Molecular weight</th>
<th>Relative filterability</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>sodium</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>glucose</td>
<td>180</td>
<td>1</td>
</tr>
<tr>
<td>myoglobin</td>
<td>1,700</td>
<td>0.75</td>
</tr>
<tr>
<td>albumin</td>
<td>69,000</td>
<td>0.005</td>
</tr>
</tbody>
</table>

This table illustrates the fact that filtration is selective on the basis of size. Small molecules are filtered freely into the nephrons while larger particles are retained in the capillaries. The presence of large proteins or blood cells in the urine usually indicates damage to the kidneys.

**Regulation of glomerular filtration rate**

The rate of filtrate formation is known as the **glomerular filtration rate (GFR)**. A typical GFR for a healthy adult is about 125 ml/min, which is equivalent to about 180 liters/day. Maintaining an appropriate GFR is critical to kidney function, and GFR is generally regulated by intrinsic and extrinsic control mechanisms:

**Intrinsic controls** are as follows:

1. The **myogenic mechanism** in which a rise in pressure on the afferent arterioles leads to reflexive constriction of the afferent arterioles. Likewise, a reduction in pressure on the afferent arterioles leads to reflexive dilation of the arterioles. Is this a negative feedback or positive feedback system?

2. The **tubuloglomerular feedback mechanism** is directed by macula densa cells of the juxtaglomerular apparatus. When flow of the filtrate is low, the macula densa cells promote dilation of the afferent arterioles. When flow of the filtrate is high, the macula densa cells release chemicals that promote vasoconstriction.

**Extrinsic controls** include the following:

1. The sympathetic nervous system. Moderate sympathetic activity has little effect on the GFR. However, higher levels of sympathetic activity tend to cause strong constriction of the afferent arterioles. What effect does this have on GFR?

2. GFR is also affected by the hormone **atrial natriuretic peptide (ANP)**. ANP is released by atrial cardiac muscle cells in response to elevated blood pressure. It causes dilation of the afferent arterioles and an increase in GFR.

3. Angiotensin II affects GFR by causing vasoconstriction. **Your book conflicts with what I am saying here. For testing purposes, go with what I have here in the notes.** Angiotensin II is released when blood pressure is low, and it acts as a vasoconstrictor. In the kidneys, the vasoconstrictive effect of angiotensin II has a greater effect on the efferent arteriole than the afferent arteriole. This raises the
pressure on the glomerulus and increases GFR. This likely helps to maintain GFR under conditions of low blood pressure.

VI. Reabsorption and Secretion in Tubules and Collecting Ducts

A human cannot afford to lose 180 liters of fluid every day. Furthermore, you do not want to lose glucose, amino acids, etc. along with waste products. Whereas filtration is selective only by size, reabsorption is selective for particular molecules. For example, glucose is removed from the urine and brought back into the body at the proximal tubule. All but about 1.5 liters of water (out of about 180 liters) per day is reabsorbed.

Substances reabsorbed completely
More-or-less 100% of filtered nutrients, such as glucose and amino acids, are reabsorbed from the filtrate by the PCT. Likewise, any proteins that enter the filtrate are typically reabsorbed by the PCT.

Substances with regulated reabsorption
Various substances in the filtrate are not reabsorbed completely, but the amount that is reabsorbed can be adjusted depending upon conditions. This allows the kidneys to regulate the amount of these substances in the blood.

Sodium reabsorption
The amount of sodium reabsorbed varies between 98% and almost 100% (Fig. 24.18). While the difference between these two numbers may seem small, a large amount of sodium is filtered into the kidneys every day, so the difference between 98% and 100% is significant. Sodium is absorbed all along the renal tubule, with most being absorbed by the PCT and nephron loop. At the DCT and collecting ducts, aldosterone stimulates the synthesis of Na⁺ channels and Na⁺/K⁺ pumps to increase the reabsorption of sodium. Water follows by osmosis. ANP inhibits the reabsorption of sodium. Under what conditions are aldosterone and ANP produced?

Water reabsorption
Reabsorption of water depends upon osmosis (Fig. 24.19). Water can travel through cell membranes in two ways: (1) some water is able to move directly through the lipid bilayer by simple diffusion, and (2) water can move through channels in the cell membrane called aquaporins. The majority of water is reabsorbed by the PCT and nephron loop, largely as it follows the movement of sodium. At the DCT and collecting duct, the rate of water reabsorption is determined largely by aldosterone and antidiuretic hormone (ADH). As salt reabsorption is regulated by aldosterone, the amount of water reabsorption also varies. Increased levels. Rising levels of ADH stimulate increased reabsorption of water by the collecting ducts. ADH is released in response to dehydration, thus water is conserved in the body when needed. ADH makes the collecting ducts more permeable to water by increasing the number of aquaporins in the cells of the collecting ducts. Conversely, decreasing levels of ADH result in less water reabsorption.

Movement of potassium
Potassium is both reabsorbed and secreted (Fig. 24.20), the net result depends upon conditions. Most of the potassium in tubular fluid is reabsorbed by the PCT and nephron loop. A net reabsorption or secretion may occur in the collecting duct where some cells reabsorb potassium and others secrete it. The rate of secretion depends on aldosterone, with increasing levels of aldosterone stimulating secretion.
**Bicarbonate ions, hydrogen ions, and pH**

Nearly 100% of bicarbonate is reabsorbed by the PCT and nephron loop. In order to help regulate pH of the blood, cells of the collecting ducts can secrete or reabsorb bicarbonate. If blood is on the acidic side, bicarbonate is reabsorbed and H⁺ is secreted. This results in production of acidic urine. If blood is on the alkaline side, then bicarbonate is secreted into the filtrate and H⁺ is reabsorbed.

**Substances eliminated as waste products**

As mentioned previously, the main waste products eliminated by the blood are urea, uric acid, and creatinine. Urea and uric acid are both secreted and reabsorbed; creatinine is only secreted. In the case of urea, it is both reabsorbed and secreted as it passes through the PCT and loop, and the two process roughly even out by the time filtrate enters the DCT. Reabsorption by the collecting duct removes about 50% of the urea from the filtrate, allowing the other half to be eliminated.

**Establishing the concentration gradient**

The nephron loop is responsible for creating a concentration gradient of salts in the kidney, which allows osmoconcentration of the tubular fluid. The concentration gradient is created by a system of **countercurrent exchange** (Fig. 24.23). A positive feedback loop is established involving the descending and ascending limbs that allows the concentration of salts in the interstitial fluid of the inner medulla to reach 1200 mOsm. This positive feedback loop is referred to as the “countercurrent multiplier.”

The **vasa recta** is the portion of the peritubular capillaries that surrounds the loop of Henle (Fig. 24.23). As blood travels through the descending portion of the vasa recta, it picks up solutes from the interstitial fluid of the kidney. Some water is lost, but proteins in the blood help retain water. As blood travels through the ascending portion, it absorbs water. The net result is that blood flowing through the vasa recta has a net gain of water. Blood eventually returns to the body via the renal vein.

**Formation of dilute urine**

Tubular fluid enters the DCT at an osmotic concentration of about 100 mOsm/l. How does this concentration compare to the normal concentration of body fluids?

When the body wishes to get rid of excess water, fluid from the DCT is simply allowed to pass through the collecting ducts and out of the body. When levels of ADH are low, the collecting ducts are impermeable to water, so as fluid travels through the collecting ducts water is not reabsorbed into the tissues. Because cells of the DCT and collecting ducts can remove ions from the tubular fluid, the concentration of urine can be reduced to levels as low as about 50 mOsm/l.

**Formation of concentrated urine**

Permeability of the collecting duct and the DCT to water is regulated by ADH. If the body wishes to conserve water, ADH levels will increase and the duct becomes permeable to water. Osmosis leads to reabsorption of water from the collecting ducts as urine passes through the medulla and its increasing interstitial osmolarity. Urine osmotic concentrations may rise as high as 1400 mOsm/l. How does the volume of urine relate to the concentration?

Caffeine and alcohol are both inhibitors of ADH. How do these chemicals affect the volume and concentration of urine?
VII. Urine Characteristics, Transport, Storage, and Elimination

Urinary tract (ureters, urinary bladder, urethra)

_Ureters_

After urine has been produced in the kidneys it travels through the ureters to the urinary bladder. A muscular layer of tissue in the ureter walls can produce peristaltic waves to propel urine toward the bladder.

_Urinary bladder_

The urinary bladder can typically hold up to about a liter of urine (Fig. 24.26). Like the stomach, the urinary bladder has folds, called rugae, which allow expansion. The bladder has three openings: one opening for each ureter and one internal urethral orifice. These three openings form a triangle at the bottom of the bladder, which is referred to as the trigone.

The lining of the bladder has three tissue layers:
A. The mucosa is the innermost layer. It is made of transitional epithelial tissue.
B. The detrusor muscle forms the middle layer. This consists of multiple layers of smooth muscle.
C. The peritoneum is the outermost layer on the superficial surface, and the adventitia is the outermost layer on the remainder of the bladder.

_Urethra_

Urine passes from the bladder to the outside of the body via the urethra. Passage of urine from the bladder into the urethra is controlled by two sphincters (Fig. 24.27): (1) The internal urethral sphincter is made of smooth muscle, and it is under involuntary control. This sphincter is located at the base of the bladder. (2) The external urethral sphincter is made of skeletal muscle, and it is under voluntary control. This sphincter is located inferior to the internal urethral sphincter.

Micturition

Micturition is another word for urination. Micturition involves three basic processes that can be described as the “micturition reflex”: (1) contraction of the detrusor muscle, (2) relaxation of the internal urethral sphincter, and (3) relaxation of the external urethral sphincter. The first two processes are stimulated by the parasympathetic nervous system and inhibited by the sympathetic. The external urethral sphincter, being a skeletal muscle, is controlled by the somatic nervous system. Stretching of the bladder by urine stimulates parasympathetic signals to the bladder. A person can then exercise choice over whether or not to urinate. If the person does not, then the parasympathetic signals subside for a time.