The Urinary System

The primary function of the urinary system is to maintain homeostasis by controlling the composition and volume of blood by removing and restoring selected amounts of water and solutes.

The urinary system consists of a pair of kidneys which remove substances from the blood, form urine, and help regulate various metabolic processes; a pair of tubular ureters, which transport urine away from the kidneys; a saclike urinary bladder, which serves as a urine reservoir; and a tubular urethra, which conveys urine to the outside of the body.

The kidneys are bean-shaped organs on either side of the vertebral column between the twelfth thoracic and third lumbar vertebrae. The right kidney is a little lower than the left because of the space occupied by the liver. The position of the kidneys is retroperitoneal which means they are behind the parietal peritoneum. The concave medial border faces the vertebral column and near the center of the concave border is a notch called the hilus through which the ureter exits the kidney. Blood and lymph vessels and nerves also enter and exit the kidney through the hilus. The hilus is the entrance to a cavity called the renal sinus.

Surrounding each kidney are three layers of supportive connective tissue. The layer closest to the kidney is the renal capsule which also lines the renal sinus. The renal capsule is smooth and fibrous and serves as a barrier against trauma and the spread of infection to the kidney. The middle layer is the adipose capsule which protects the kidney from trauma and holds it firmly in place in the abdominal cavity. The outermost layer, the renal fascia, is a thin layer of dense fibrous connective tissue that anchors the kidney to its surrounding structures and to the abdominal wall. It also surrounds and anchors the adrenal gland which sits atop the kidney.

The internal anatomy of the kidney consists of three distinct regions: the cortex, the medulla, and the pelvis.

The outer renal cortex forms a layer around the renal medulla and extends inward between parts of the medulla called renal pyramids to form renal columns. The renal medulla contains triangular or cone-shaped tissue masses called renal pyramids or medullary. The broader bases of the pyramids face the cortex and the apex or renal papillae face the center portion of the kidney.

Within the renal sinus is a flat, funnel-shaped tube, the renal pelvis, which is continuous with the ureter. The renal pelvis is subdivided into two or three major calyces and they, in turn, subdivide into several minor calyces which enclose the papillae of the pyramids. The minor calyces collect urine draining from the papillae and it passes into the major calyces, then into the renal pelvis and out through the ureter. The smooth muscle in the walls of the calyces, pelvis, and ureter move the urine by peristalsis.
Blood is supplied to the kidney by the renal artery which arises from the abdominal aorta and passes through the hilus. The renal arteries carry about 25% of the total cardiac output into the kidneys. The renal artery branches into lobar arteries which further divide into the interlobar artery that passes between the renal pyramids in the renal columns. At the base of the pyramid, between the cortex and medulla, the interlobar artery branches to form arcuate arteries which further subdivide to form interlobular arteries. The interlobular arteries enter the cortex and divide into afferent arterioles.

Veins are subdivided like the arteries and follow the opposite pathway and the renal vein joins the inferior vena cava in the abdominal cavity.

The nerve supply to the kidneys and the ureters is the renal plexus of the sympathetic division of the ANS. The nerves are vasomotor fibers and regulate renal blood flow in the kidney by controlling the diameter of the arterioles.

The functions of the kidney include:

1. regulate the composition and volume of blood
2. remove wastes from the blood in the form of urine
3. form renal erythropoietic factor
4. help control blood pH
5. help to regulate blood pressure by secreting renin that activates the renin-angiotensin pathway
6. participate in the activation of vitamin D.

The functional unit of the kidney is the nephron which carries out the processes of forming urine. The cortex of each kidney contains about 1 million nephrons. A nephron consists of a renal tubule and a cluster of capillaries called the glomerulus ("little ball"). A thin-walled, saclike structure, the glomerular or Bowman’s capsule surrounds the glomerulus. The glomerular capsule together with the glomerulus is the renal capsule.

The glomerular capsule has an outer parietal layer of simple squamous epithelium and a visceral layer of branching epithelial cells called podocytes which form part of the filtration membrane. The branched end of the podocytes have terminal foot processes or pedicels which cling to the basement membrane of the glomerulus. The openings between the pedicels are filtration slits or slit pores. The basement membrane of the glomerulus has no pores and serves as a dialysis membrane (diffusion of solutes). The endothelium of the glomerulus is fenestrated (contains pores).

The glomerular capsule is continuous with the renal tubule, which leads away from the capsule and becomes highly coiled. The coiled portion is the proximal convoluted tubule (PCT) which makes a hairpin turn called the loop of Henle, and then coils again to form the distal convoluted tubule (DCT). Several distal convoluted tubules from many nephrons become the collecting tubule. The collecting tubules pass through the renal pyramids and open into the minor calyces at the renal papillae as the papillary ducts.
Each region of the renal tubule has a specific filtration function which is reflected in its cellular composition. The walls of the PCT consist of cuboidal epithelium with dense microvilli which increase the surface area for reabsorption of water and solutes from the filtrate, and secretion. The loop of Henle has a descending and an ascending portion. The beginning of the descending is similar to the PCT. The rest is called a thin segment and is composed of simple squamous epithelium that is permeable to water. The ascending portion is the thick segment and consists of cuboidal or low columnar epithelium. The DCT cells are cuboidal and contain no microvilli. They secrete substances into the filtrate rather than reabsorbing substances from it.

Most nephrons are cortical nephrons. Only a small part of the loop of Henle is in the medulla; not the cortex. The second type of nephrons are the juxtamedullary nephrons which are located near the junction of the cortex and medulla. The loop of Henle has a more extensive thin segment and the loop extends deeply into the medulla. They also have thin-walled looping vessels, vasa recta ("straight vessels"), which parallel the loop of Henle in the medulla.

Each nephron is associated with a glomerulus capillary bed which produces filtrate and a peritubular capillary bed which reclaims most of the filtrate. The glomerulus is fed by afferent arterioles from the interlobular arteries and drained by the efferent arterioles. The afferent arterioles have a larger diameter than the efferent and the blood pressure in the glomerulus is high, forcing fluid and solutes out of the blood and into the glomerular capsule. 99% of the filtrate is eventually returned to the blood in the peritubular capillary bed. The peritubular capillary bed consists of capillaries that arise from the efferent arterioles. They cling closely to the renal tubule and empty into the renal venous system. The peritubular capillaries are low-pressure and porous and absorb solutes and water from the tubule cells as they are reabsorbed from the filtrate.

Near the beginning of the DCT it passes between the afferent and efferent arterioles and comes into contact with them. At the point of contact the epithelial cells of the DCT are tall, narrow and tightly packed forming the macula densa. The macula densa cells are chemoreceptors or osmoreceptors that respond to changes in the solute concentration of the filtrate in the DCT. In the walls of the afferent arterioles is enlarged smooth muscle called juxtaglomerular cells that contain granules of renin and they are mechanoreceptors that respond to blood pressure in the afferent arterioles.
Mechanisms of Urine Formation

Urine formation and the adjustment of blood composition is the function of the nephrons and involves three processes:

1. glomerular filtration
2. tubular reabsorption
3. tubular secretion

Glomerular Filtration

Filtration is the forcing of fluids and solutes through a membrane by hydrostatic pressure. When blood enters the glomerulus, the blood pressure forces water and dissolved blood components or plasma through the endothelial pores of the capillaries, basement membrane, and through the filtration slits of the visceral layer of the glomerular capsule. The resulting fluid is filtrate which consists largely of water, and components of the blood plasma, except large proteins and formed elements. Some substances include glucose, amino acids, vitamins, nitrogenous wastes, and chloride, sodium, bicarbonate and potassium ions.

The capillary pores prevent the passage of blood cells and the basement membrane restricts the passage of large proteins. The filtration slits play little or no part in restricting the passage of molecules.

The rate of glomerular filtration is directly proportional to the net filtration pressure. Glomerular hydrostatic pressure (GHP) is the main force pushing water and solutes across the filtration membrane. GHP is opposed by glomerular osmotic pressure (GOP) or colloid osmotic pressure of plasma proteins in the glomerular blood and capsular hydrostatic pressure (CHP) exerted by the fluids in the glomerular capsule. The NFP = GHP - (GOP + CHP).

Since the glomerular capillary bed is located between the afferent and efferent arterioles, any change in diameter of them causes a change in the glomerular filtration rate (GFR) or the amount of fluid filtered from the blood into the glomerular capsule each minute. If the afferent arterioles constrict, blood flow diminishes, the GHP decreases, and the filtration rate drops. If the efferent arterioles constrict, the blood backs up into the glomerulus, the GHP increases, and the filtration rate rises. Converse effects occur during vasodilation at either arteriole.

In the capillaries, the blood pressure which forces water and dissolved substances outward, is opposed by the plasma osmotic pressure that attracts water inward. As filtration occurs through the capillary walls, the proteins remaining in the plasma cause the osmotic pressure within the glomerular capillary to rise. When this pressure reaches a certain level, filtration ceases. Conditions that decrease plasma osmotic pressure (decrease in plasma proteins) cause an increase in the filtration rate.
The regulation of glomerular filtration rate involves intrinsic controls or renal autoregulation by the juxtaglomerular apparatus, and negative feedback mechanisms which are triggered when the filtration rate is decreasing and extrinsic controls by the sympathetic nervous system stimulation. As the rate decreases, the concentration of chloride ions reaching the macula densa in the DCT also decreases. The macula densa signals the smooth muscle in the wall of the afferent arteriole to relax, and vessels dilate. More blood flows into the glomerulus, increasing the glomerular pressure and the filtration rate increases. Simultaneously the macula densa stimulates the juxtaglomerular cells to release renin. Renin causes angiotensin to form angiotensin I, which is converted quickly into angiotensin II by an enzyme in the lungs and plasma. Angiotensin II is a vasoconstrictor and it stimulates the smooth muscle in the wall of the efferent arterioles to contract, causing vasoconstriction. Blood backs up into the glomerulus and the GHP increases, causing the filtration rate to increase. The two reactions maintain a stable glomerular filtration rate.

During extreme stress or emergency, blood may be shunted to the heart, brain, and skeletal muscles. Stimulation by the sympathetic nerve fibers causes the release of epinephrine by the adrenal medulla. The afferent arterioles constrict and inhibit formation of filtrate. The sympathetic nervous system also stimulates the juxtaglomerular cells to release renin which increases systemic blood pressure.

**Tubular Reabsorption**

Tubular reabsorption is the movement of the filtrate out of the glomerular filtrate through the epithelium of the renal tubule and into the blood of the peritubular capillaries or vasa recta. Tubular reabsorption begins as soon as the filtrate enters the proximal convoluted tubules, where most reabsorption occurs.

Active tubular reabsorption involves the movement of glucose, amino acids, lactate, vitamins, and most ions (Na, K, Cl, Ca) against an electrical and/or chemical gradient. Active transport has a transport maximum. Only a certain number of molecules can be transported in a given amount of time because the number of carriers is limited.

Passive tubular reabsorption includes diffusion, facilitated diffusion, and osmosis along an electrochemical gradient. The gradient is established by the active reabsorption of sodium ions from the filtrate in the PCT. As sodium ions move through the tubular wall, negatively charged ions follow (chloride, phosphate, bicarbonate ions) by electrochemical attraction. As sodium is actively transported into the peritubular capillary along with negative ions, the concentration of solutes in the peritubular blood increases. Water also moves by osmosis from the PCT into the peritubular capillary. The volume in the PCT is greatly reduced.

Sodium ions continue to be reabsorbed by active transport and water by osmosis, in the loop of Henle, DCT, and collecting tubules, and most is therefore reabsorbed before urine is formed.
Additional water may be reabsorbed if antidiuretic hormone is present which increases the permeability of the DCT and collecting tubules. Sodium reabsorption is under the control of aldosterone which increases absorption by the DCT and collecting tubules. As sodium is reabsorbed, water follows. Urea, uric acid, and creatinine, which are products of nucleic acid metabolism are not reabsorbed.

**Tubular Secretion**

Tubular secretion is the movement of substances from the blood in the peritubular capillary into the filtrate. The secreted substances include potassium and hydrogen ions, creatinine, and ammonia.

Tubular secretion rids the body of drugs (penicillin), eliminates undesirable substances (urea and uric acid), eliminates excess potassium ions, and controls blood pH. Potassium ions are removed mainly in the DCT and collecting tubules by aldosterone.

Secretion of hydrogen ions occurs through the formation of carbonic acid from the diffusion of carbon dioxide from the peritubular blood into the DCT and collecting tubules. The carbon dioxide combines with water to form carbonic acid, which then dissociates into hydrogen ions and bicarbonate ions. A low blood pH stimulates the tubule cells to secrete hydrogen ions into the urine and as they enter the urine, sodium ions or other positive ions are displaced and a weak acid or a salt of an acid is formed and it combines with the bicarbonate ion in the urine to form sodium bicarbonate. Sodium bicarbonate is absorbed into the blood. Hydrogen ions are eliminated by the body and sodium ions are conserved. As blood pH becomes alkaline, chloride ions rather than bicarbonate ions are reabsorbed and bicarbonate is formed in the urine.

Urine passes from the collecting tubules through the opening in the renal papillae to the minor calyces, the major calyces, and then through the renal pelvis and into the ureter.

The composition of urine varies due to dietary intake and physical activity. Urine is usually 95% water, and also contains urea, uric acid, creatinine, a trace of amino acids, and electrolytes (Na, K, P, sulfate, bicarbonate, Ca, and magnesium ions).

The volume of urine usually produced is 1,000 to 2,000 ml. Urine volume is influenced by blood pressure, blood concentration, diet, temperature, mental state, and general health.

Normal urine is clear to a pale yellow due to urochrome pigment derived from the metabolism of bile. The more concentrated the urine, the darker the color. Urine is slightly aromatic, has a pH of 4.5 to 8.0 and a specific gravity of 1.001 to 1.035. Specific gravity is the ratio of the weight of a volume of a substance to the weight of an equal volume of distilled water.
Ureters

Urine is carried by the ureter by peristalsis to the urinary bladder. Each ureter is a tubular organ which is an extension of the renal pelvis. They extend downward behind the parietal peritoneum (retroperitoneal) to the base of the urinary bladder.

The wall of the ureter is composed of three layers. The inner mucosa contains transitional epithelium and is continuous with the linings of the renal tubules and the urinary bladder. The middle muscularis is composed of two layers of smooth muscle: an inner longitudinal layer and an outer circular layer. The outer adventitia is fibrous connective tissue.

Peristaltic waves move the urine to the urinary bladder. When the wave reaches the bladder, it causes a jet of urine to spurt into the bladder. The opening into the bladder has a flaplike fold of mucous membrane which prevents backflow of urine.

Urinary Bladder

The urinary bladder is a hollow, collapsible, muscular sac located retroperitoneally behind the pubic symphysis. In males, it is directly anterior to the rectum. In females, it is anterior to the vagina and inferior to the uterus.

The function of the urinary bladder is to store urine. At the base of the bladder is a small triangular area called the trigone that points anteriorly. The opening to the urethra is in the apex and at the two points of the base, the ureters drain into the bladder.

The wall of the bladder has three layers: a mucosa of transitional epithelium, a muscularis layer, and a fibrous adventitia or serosa, except on the anterior surface where it is parietal peritoneum.

The muscular layer, or detrusor muscle, is composed of smooth muscle and consists of an inner longitudinal, middle circular, and outer longitudinal layers.

When the bladder is empty the wall folds and forms rugae. When the bladder fills, it becomes pear-shaped, the rugae disappear, and the bladder rises in the abdominal cavity.

Urethra

The urethra is a thin-walled muscular tube where urine from the floor of the bladder is passed to the outside of the body. In females, the urethra is 1.5 inches long and lies directly posterior to the pubic symphysis and is bound in the anterior wall of the vagina. The opening to the exterior is the external urethral orifice (meatus) which is anterior to the vaginal opening and posterior to the clitoris.

In males, the urethra is 8 inches long and immediately below the urinary bladder. It passes vertically through the prostate gland (prostate urethra), then enters the urogenital diaphragm (membranous urethra), and finally enters the penis (spongy or penile
urethra). The urethra opens at the tip of the penis through the external urethral orifice. Both urine and semen are discharged through the urethra.

The mucosal lining of the wall of the urethra is pseudostratified columnar epithelium, however near the bladder it is transitional epithelium, and near the external urethral orifice it is stratified squamous epithelium.

A portion of the detrusor circular muscle of the bladder surrounds the neck of the bladder at the junction of the urethra and forms the internal urethral sphincter. Involuntary sustained contraction prevents the bladder from emptying until the pressure in the bladder increases to a certain point. The external urethral sphincter (sphincter urethrae) surrounds the urethra. The muscle is voluntary skeletal muscle from the urogenital diaphragm.

**Micturition**

Micturition, voiding, or urination is the process by which urine is expelled or emptied from the bladder. When about 200ml of urine accumulates and distends the wall of the bladder, stretch receptors are activated. Afferent (sensory) impulses are sent to the micturition reflex centers in the sacral region of the spinal cord and efferent impulses return to the bladder by way of the parasympathetic fibers causing the detrusor muscles to contract and the internal urethral sphincter to relax. Increasing intensity of contractions force urine through the internal urethral sphincter into the upper part of the urethra. Afferent impulses are transmitted to the brain stem and cerebral cortex and the urge to void is felt. Voluntary control of the external urethral sphincter allows the postponement of voiding. When the decision to urinate is made, the external urethral sphincter relaxes and the micturition reflex is no longer inhibited and urination occurs.