Chapter 14

HUMAN URINARY SYSTEM

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Outline different organs of the (human) urinary system.
- Describe the structure of the kidney.
- Relate the structure of the kidney with its function.
- Explain the detailed structure of a nephron.
- Explain the processes of glomerular filtration, selective re-absorption and tubular secretion as the events in kidney functioning.
- Explain regulatory mechanism involved in concentration of urine
- Justify the functioning of kidneys as both excretion and osmoregulation.
- Compare the function of two major capillary beds in kidneys i.e., glomerular capillaries and peritubular capillaries.
- List urinary tract infections and the bacteria responsible.
- Explain the causes and treatments of kidney stones.
- Outline the causes of kidney failure.
- Explain in detail the mechanism and problems related to dialysis.
- Describe the principles and the problems associated with kidney transplant.

In this chapter, we will explore the remarkable architecture and functioning of the kidneys. We will also study the life-saving technologies used when this vital system weakens.

14.1- HUMAN URINARY SYSTEM

The urinary or excretory system is responsible for excretion. In biological terms, **excretion** is the process by which an organism eliminates the metabolic wastes. The metabolic wastes include nitrogenous wastes, extra water, and extra salts etc. The urinary system performs three essential roles simultaneously:

Critical Thinking
Given the definition of *excretion*, why the large intestine is not classified as a major excretory organ?

1. **Nitrogenous Waste Removal:** Filtering out urea, a nitrogenous waste of protein breakdown in the liver.
2. **Osmoregulation:** Maintaining the "water-to-salt" balance of the blood by adjusting how much water is reabsorbed or excreted.
3. **pH and Ion Regulation:** Balancing levels of sodium, potassium, and hydrogen ions to keep blood slightly basic (around pH 7.4).

The human urinary system consists of two kidneys, two ureters, one urinary bladder, and one urethra. Kidneys are located high in the abdominal cavity, one on each side of the vertebral column, between the 12th thoracic and 3rd lumbar vertebrae. Due to the position of liver, the right kidney is slightly lower and smaller than the left one. The upper parts of both kidneys are partially protected by the 11th and 12th ribs. The **ureters** are about 25 cm long tubes. A ureter begins at the funnel-shaped renal pelvis in kidney. Ureters from both kidneys extend downward and open in a single urinary bladder. Ureters transport urine from the kidney to the **urinary bladder**. The urinary bladder is a hollow and distensible muscular organ. It is located within the pelvic cavity. It serves as urine reservoir. The **urethra** is a tube that carries urine from urinary bladder to the outside of the body.

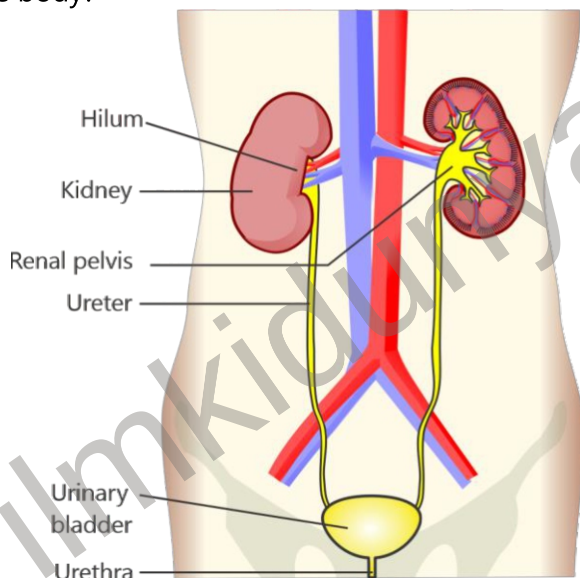

Figure 14.1: Human excretory (urinary) system

14.1.1- Structure of Kidney

A kidney is a reddish brown, bean shaped organ. Each kidney, has an adrenal gland on its top. The kidney and its adrenal gland are surrounded by a fibrous **renal capsule**. Each kidney has a convex and a concave side. A depressed area on the concave side is the **renal hilum** (also called hilus). At this point, the renal artery enters the kidney and the renal vein and ureter leave.

Internally, a kidney consists of two portions. The outer portion is called **renal cortex**. It makes up about a third of the kidney's mass. The inner portion is called **renal medulla**. It makes two-thirds of the kidney. The **renal pelvis** is a funnel-shaped structure in the centre of kidney. Blood enters the kidney through a renal artery and leaves through a renal vein. The renal medulla consists of a number of cone-shaped **renal pyramids**. Urine is collected in the renal pelvis and exit the kidney through ureter.

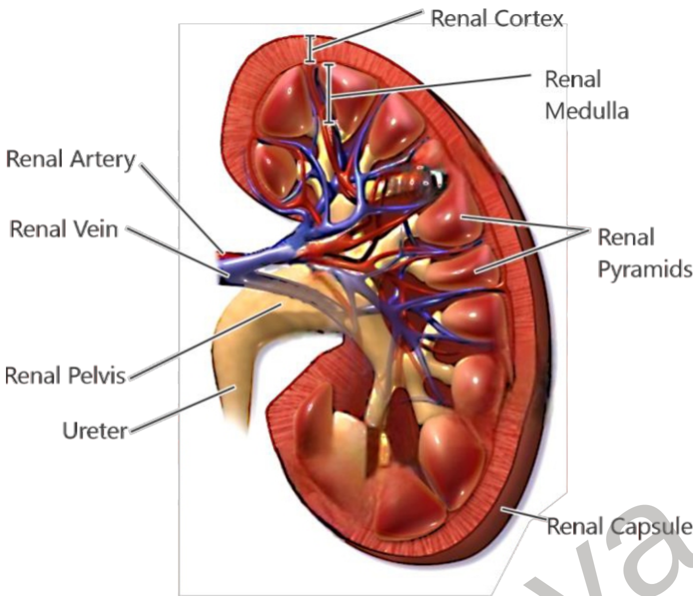

Figure 14.2: The internal structure of kidney

Structure of Nephron

Each kidney contains about one million microscopic tubular structures called nephrons. These are the functional units of kidney. A nephron consists of two main portions i.e., a renal corpuscle and a renal tubule.

Renal corpuscle consists of two associated structures. **(i) Glomerulus** is a capillary network derived from an afferent renal arteriole. **(ii) Bowman's capsule** is a cup-shaped, double-walled sac that surrounds the glomerulus.

Renal tubule is a long tubule that leads away from the Bowman's capsule. It consists of three connected portions. **(i) The proximal convoluted tubule** is the beginning portion and is highly coiled. It dips into the medulla. **(ii) The Loop of Henle** is a U-shaped hairpin turn. It consists of two limbs. The descending limb continues toward the medulla. The ascending limb returns toward the cortex and reaches parallel to renal corpuscle. Here, it opens in **(iii) the distal convoluted tubule** which is highly coiled again.

The distal convoluted tubules of multiple nephrons drain into a single **collecting duct**. As these ducts descend through the medulla, they merge to form larger **papillary ducts**, which ultimately discharge into the renal pelvis.

Nephrons are categorized into two types based on their location within the kidney: **(i) Cortical nephrons** make the majority (about 85%) of nephrons. These are located primarily within the renal cortex. They possess relatively short loops of Henle. **(ii) Juxtamedullary nephrons** originate deep in the cortex, near the medulla. They have long loops of Henle that extend deep into the renal medulla.

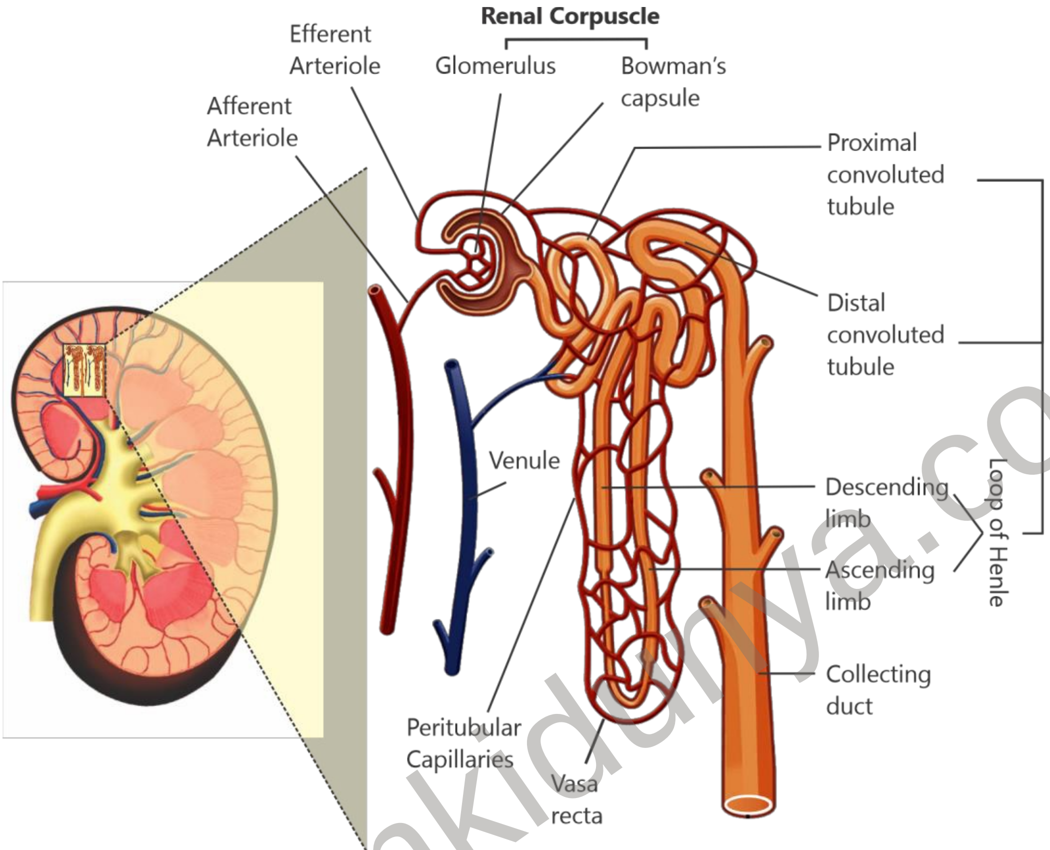

Figure 14.3: Structure of nephron

14.1.2- Blood Supply of the Kidney

> The kidneys are highly vascularized organs, receiving approximately 20–25% of the total cardiac output.

The pathway of blood inside kidney begins with the **renal artery**, which enters the kidney at the hilum. It divides into branches which give rise to **afferent arterioles**. Each afferent arteriole leads into the capillary bed i.e., glomerulus. Unlike most capillary beds in the body that drain into venules, the glomerular capillaries drain into an efferent arteriole.

The **efferent arteriole** branches into **peritubular capillaries**. These capillaries form a dense network around the proximal and distal convoluted tubules in the renal cortex. In juxtamedullary nephrons, the efferent arterioles also give rise to **vasa recta**. These are long and straight capillary networks in medulla that run parallel to the loops of Henle.

After the exchange of materials, the capillaries converge to form **venules**. These venules merge into larger veins, eventually opening into the **renal vein**. The renal vein exits the kidney at the hilum and drains into the inferior vena cava. Here it returns the filtered, "clean" blood to the heart.

14.1.3- Functioning of Kidney

Kidneys filter metabolic wastes and extra water from blood and excrete them in the form of urine. The process of urine formation comprises three major steps that take place in the nephron: glomerular filtration, selective reabsorption, and tubular secretion.

While doing the excretory function, kidneys also work as osmoregulatory organs. Kidneys control the salt concentrations of body fluids by forming dilute urine (when body fluids are hypotonic) and concentrated urine (when body fluids are hypertonic and there is dehydration).

(i)- Glomerular Filtration

The first step in the formation of urine is a physical process known as glomerular filtration (or **ultrafiltration**). The efferent arteriole is narrower than the afferent arteriole. Due to this difference, the blood within the glomerular capillaries remains under relatively high pressure. This high-pressure in glomerulus forces water, urea, glucose, amino acids, vitamins, and various salts ((Na^+, K^+, Cl^-) from blood into the Bowman's capsule. About one-fifth (20%) of the fluid portion of the blood filters into the Bowman's capsule and is called **glomerular filtrate**. Plasma proteins (e.g., albumin and globulins) and blood cells are too large to pass through the capillary walls. So, these structures remain in the blood.

(ii)- Selective Reabsorption

The glomerular filtrate contains not only wastes but also vital nutrients that the body cannot afford to lose. Selective reabsorption is the process by which useful materials are transported from renal tubule back into the peritubular capillaries. Most reabsorption occurs in the proximal convoluted tubule. In this region, about 75% of the water returns from the filtrate to the capillaries by osmosis. Glucose, amino acids, and salts (sodium, potassium, and calcium) are returned from proximal tubule to the blood by active transport. As the filtrate moves further, more water is reabsorbed in the descending limb of the loop of Henle. Ascending limb is impermeable to water but actively transports salts out of the tubule. Some water and salts are also absorbed from distal convoluted tubule. Collecting duct is the final site for water reabsorption.

(iii)- Tubular Secretion

Tubular secretion is opposite to reabsorption. In this process, the epithelial cells of the distal convoluted tubule take some materials from surrounding blood and secrete them into the filtrate. Secreted substances include hydrogen ions, ammonium, potassium ions, and various metabolic toxins or drug residues (like penicillin). Through tubular secretion of hydrogen ions, the kidneys play role in maintaining the acid-base balance (pH) of the blood.

Elimination of Urine

From the collecting ducts, urine flows through the renal pelvis into a ureter. Ureter leads to the urinary bladder. Muscular contractions of the bladder force urine out of the body through urethra. A normal adult eliminates from 1 to 2 L of urine a day. This amount is highly variable and depends on several factors. The more water or hydrating fluids we consume, the higher is the urine output. Diets with high salt trigger water retention and decrease urine production. Physical exercise leads to water loss through respiration and perspiration, which generally decreases urine volume.

Tidbit

In hot weather, the body loses more water through sweat, leading the kidneys to conserve water and produce a smaller volume of concentrated urine.

14.2- Regulation of the Urine Concentration

14.2.1- Counter-current Mechanism

For the reabsorption of water from the loop of Henle and collecting duct, nephrons create and maintain higher concentration of salts (NaCl) in the surrounding fluid. It is done by **counter-current mechanism**.

- The descending limb is permeable to water but not to salts.
- The ascending limb is impermeable to water but actively transports salts out of tubule.

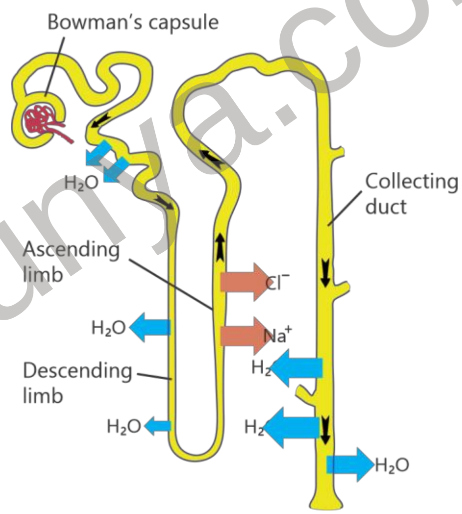

Figure 14.4: Formation of urine

When filtrate flows through the descending limb, water is reabsorbed into the surrounding fluid because the surrounding fluid has more salts. When fluid flows through the ascending limb, it actively transports sodium ions from the filtrate to the surrounding fluid. The chloride ions follow sodium ions. So, the salt concentration of the fluid remains high As urine passes down the collecting duct through this salty fluid, water moves out by osmosis and enters blood via the vasa recta.

14.1.2- Hormonal Control of Kidney Functions

When body needs to conserve water, kidneys excrete a hypertonic urine.When there is much water in body, kidneys excrete a hypotonic urine. These functions of kidneys are coordinated by the following hormones.

1- Antidiuretic Hormone (ADH)

ADH is the body's primary tool for water conservation. It is produced by the **hypothalamus** and secreted by the **posterior pituitary gland**

When the body is dehydrated or has taken salty food, the higher concentration of salts in blood is detected by osmoreceptors present in the hypothalamus. The hypothalamus sends signals to the posterior pituitary to create a sensation of thirst and to release ADH. ADH acts on the walls of the collecting ducts and make them more permeable to water. So, more water moves from the filtrate into the hypertonic fluid and then into blood. In this way, concentrated urine is produced and water is conserved.

When the concentration of salts falls in blood, the hypothalamus stops ADH secretion. The walls of the collecting duct become less permeable to water. So, less water is reabsorbed, resulting in the excretion of dilute urine. As a result, the blood volume and blood pressure decrease.

Tidbit
ADH increases the blood volume. It results in an increase in blood pressure. ADH also causes the blood vessels to constrict or narrow. This constriction further increases blood pressure.

A person who cannot produce enough ADH due to pituitary damage constantly excretes a large volume of dilute urine. This disorder is known as *diabetes insipidus*. Such a person is in danger of becoming severely dehydrated with very low blood pressure.

2- Aldosterone

Aldosterone is the hormone responsible for regulating sodium and potassium levels of urine. It is produced by the **adrenal cortex** (the outer layer of adrenal gland present on the top of kidney).

Aldosterone is secreted when blood pressure drops or sodium levels in the blood are too low. It acts on the walls of the distal convoluted tubule and the collecting duct. It increases sodium ions reabsorption from the filtrate into the blood. Due to higher concentration of sodium ions in blood, water also moves from filtrate into the blood.

Tidbit
Aldosterone also promotes the excretion of potassium ions in the urine. It helps to prevent hyperkalaemia, a condition in which the blood potassium levels become too high and can lead to dangerous cardiac arrhythmias.

Two capillaries Beds in Kidneys
In kidney, two distinct capillary beds work in sequence to process blood.
1. **Glomerular capillaries** are located within the Bowman's capsule. These capillaries are designed for filtration. They operate under high blood pressure which forces water and small solutes out of the blood and into the nephron.
2. **Peritubular capillaries** surround the renal tubules. Their primary role is reabsorption and secretion. They operate under low hydrostatic pressure and pull essential nutrients (glucose, ions) and water back into the bloodstream from the tubules. They also secrete specific toxins into the tubule.

14.3- Disorders of Urinary Tract

A variety of disorders can affect the structure and function of kidneys and urinary tract. Common disorders include urinary tract infections, kidney stones, kidney failure, and polycystic kidney disease.

14.3.1- Urinary Tract Infections

Urinary tract infections (UTIs) are usually caused by bacteria, most commonly *Escherichia coli*. These bacteria enter the urinary system through urethra and infect the bladder, ureters, or kidneys.

The symptoms of a UTI include a frequent and urgent need to urinate, pain or burning during urination, cloudy or strong-smelling urine, lower abdominal pain, and sometimes fever or chills. Treatment involves a course of antibiotics to kill the causative bacteria. Drinking plenty of water and urinating frequently can also help to flush out the bacteria and alleviate symptoms.

14.3.2- Kidney Stones

Urinary stones are hard, crystalline mineral materials that-stick together to form small "pebbles" within the kidney or urinary tract. They may stay in kidneys or travel out of the body through the urinary tract.

70% of kidney stone patients have stones of calcium oxalate. These stones are formed due to **hypercalciuria** (high calcium in urine) and **hyperoxaluria** (increased level of oxalate level in urine). 10% of patients may have stones of uric acid. **Hyperuricemia** (increased amount of uric acid in blood) is the cause of such stones. High concentration of cysteine and phosphates in urine also cause kidney stones. Continuous dehydration in the body increases the chances of kidney stone formation. Treatment of kidney stones usually involves lithotripsy i.e., breaking of stones. There are two methods of lithotripsy.

Tidbit
Doctors diagnose the nature of kidney stone by studying the urine test of patient.
When urine is acidic, the stone is of calcium oxalate.
When the urine is alkaline, the stone is of calcium phosphate.
When urine is persistently acidic, the stone is of uric acid type.

In **Extracorporeal Shockwave Lithotripsy (ECSWL)**, an instrument called **lithotripter** generates shockwaves from outside the patient's body. These shockwaves break the stone into small pieces. Most of pieces then pass out through urine.

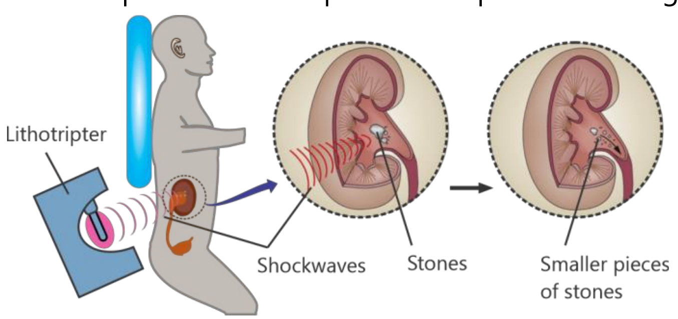

Figure 14.5: Extracorporeal shockwave lithotripsy

In case of larger stones, **Percutaneous Nephrolithotripsy** (PNL) is used. In this technique, a tube is inserted from the patient's back into the kidney. A small camera called **nephroscope** is inserted through the tube to visualize the stone. Ultrasound equipment is then inserted to break the stone. The stone pieces can be grasped with special equipment and pulled out from the kidney.

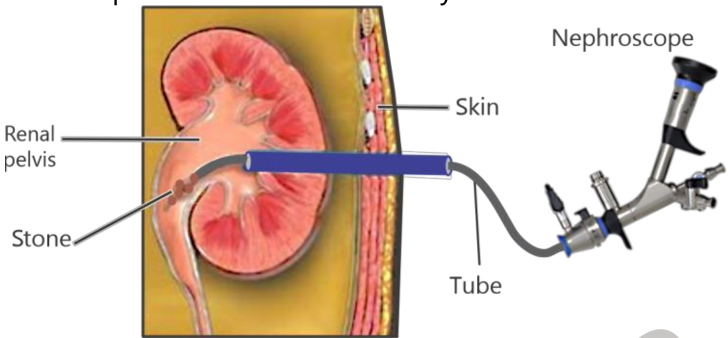

Figure 14.6: Percutaneous Nephrolithotripsy

14.3.3- Kidney Failure

Kidney/renal failure is a condition in which the kidneys lose their ability to filter wastes from the blood and regulate fluid and salt balance in the body. Chronic kidney failure develops over a longer period of time and is irreversible. It is often caused by underlying conditions like diabetes, high blood pressure, or kidney disease (chronic infection, inflammation of glomeruli etc.).

Acute kidney failure (also called kidney injury) occurs suddenly and often resolves with treatment. It may be due to kidney infection, blockage in urinary tract (due to kidney stones, bladder cancer, or enlarged prostate), certain medications such as NSAIDs, and blood clots in renal arteries or arterioles.

Renal dialysis is the treatment of renal failure in which the metabolic wastes are filtered from blood by artificial methods. There are two general types of renal dialysis i.e., haemodialysis & peritoneal dialysis.

1- Haemodialysis

In haemodialysis, the wastes are removed by circulating the blood outside the body through an equipment called dialyzer. This equipment is a type of filter and contains a semipermeable membrane (made of cellulose).

In this treatment, a catheter is inserted into an artery, usually in the arm. The blood is then circulated through dialyzer which also contains a special fluid called **dialysate**. As the blood passes through the dialyzer, the dialysate attracts the wastes, water, and salts to move out from blood, the filtrates passes through semipermeable membrane and dissolves in dialysate. The clean blood then returns to the body through a second catheter inserted in a vein.

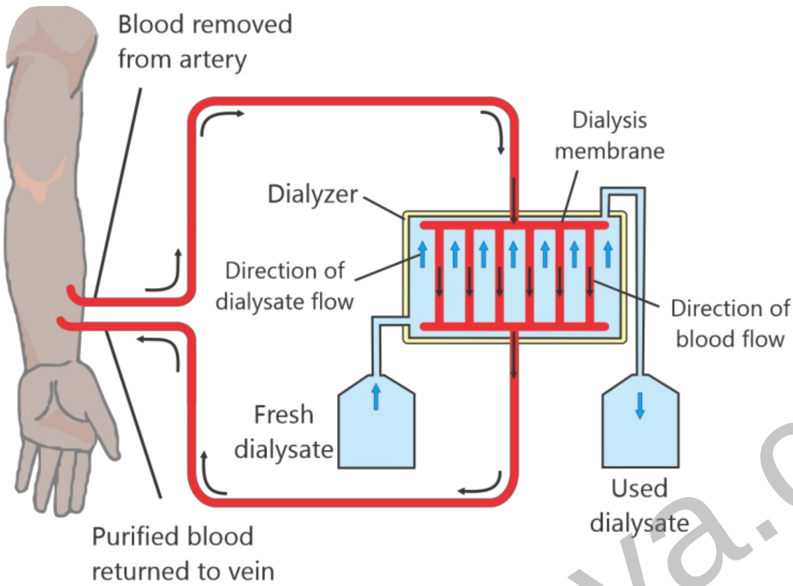

Figure 14.7: Haemodialysis

2- Peritoneal Dialysis

Peritoneal dialysis involves the use of peritoneal membrane that lines the abdominal cavity. In this process, 1.5 to 2 litre of dialysate is infused into the patient's abdomen through a catheter. The dialysate is left in abdomen for 4 to 6 hours. Waste products and excess fluid from the blood capillaries of peritoneum pass into the dialysate. Then, the dialysate is drained out of the abdomen and discarded. This process is repeated several times a day, to achieve adequate clearance of waste products and excess fluid.

Problems associated with dialysis

While dialysis can be life-saving for people with kidney failure, there are several problems associated with this treatment.

- Dialysis requires access to the bloodstream, which increases the risk of infections.
- Hypotension, or low blood pressure, is a common complication of haemodialysis.
- Muscle cramps can occur during dialysis due to changes in salt levels.
- Dialysis can cause anaemia, which can lead to fatigue and weakness.
- If too much fluid is removed too quickly, it can lead to dehydration or low blood pressure.
- Dialysis treatments can be emotionally challenging. Patients may feel anxious, depressed, or overwhelmed by the demands of the treatment.

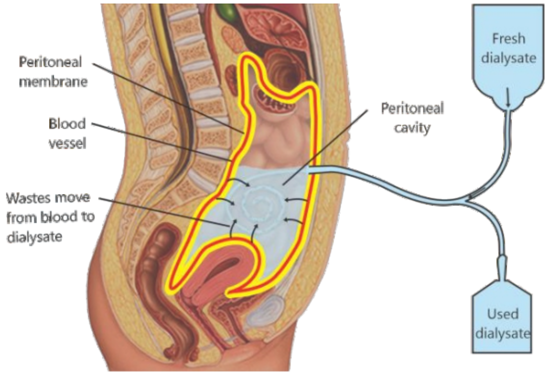

Figure 14.8: Peritoneal Dialysis

14.3.4- Kidney Transplant

Kidney transplant is a surgical procedure in which a person's non-functioning kidney is replaced with a healthy kidney from a donor. This treatment is offered to individuals with end-stage kidney failure. Kidney transplant process requires careful evaluation, matching, and monitoring to ensure the best results for both the recipient and the donor.

Potential Donors for Kidney Transplant

Related donor: A person who is genetically related to the recipient, such as a parent, sibling, or child can be the best donor of kidney.

Unrelated donor: The donor cannot be genetically related to the recipient, such as a spouse, friend, or co-worker. This type of donation is less common but can still be successful if the donor's and recipient's blood group and tissue type match.

Deceased donor: Many people register with hospitals for donation of their organs after their death. Their organs, including the kidneys, can be donated to individuals in need of a transplant. Deceased donor's kidneys are carefully matched to recipients based on blood group, tissue type, and immune system compatibility.

Tidbit

Kidney donation can be a life-saving gift for someone with end-stage kidney disease.

Donating a kidney does not have significant long-term health risks for the donor. Studies have shown that kidney donors generally experience no negative impact on their overall health or lifespan.

For Information

Pakistan's first kidney transplant centre was established in 1985 at the Sindh Institute of Urology and Transplantation (SIUT) in Karachi. It is one of the largest and most successful transplant centres in the world.

The Pakistan Kidney and Liver Institute & Research Center (PKLI&RC) was established in 2017. It is a tertiary-care hospital located in Lahore. It was established to address the massive national crisis of kidney and liver diseases, serving as a specialized center for medical care, transplantation, and research

Problems associated with kidney transplant

There are some potential complications and risks associated with kidney transplant. For example;

- The recipient's immune system may recognize the transplanted kidney as a foreign object and attack it, leading to organ rejection. This can occur even if the patient is taking immunosuppressant medications to prevent rejection.
- Patients with a suppressed immune system are at a higher risk of developing infections after a transplant.
- Recipients are given immunosuppressant medications to prevent organ rejection. Such medicines can have side effects such as high blood pressure, weight gain, and increased risk of infections and cancers.

EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. Which one of these is not a part of single nephron?
   (a) Distal convoluted tubule (b) Collecting duct
   (c) Bowman's capsule (d) Loop of Henle
2. In a healthy person, glucose is present in blood but not in urine. This is because glucose molecules are;
   (a) Reabsorbed from the proximal convoluted tubule to blood
   (b) Oxidised in kidneys
   (c) Stored in kidneys
   (d) Too large to enter Bowman's capsule
3. The sizes of molecules present in Bowman's capsule are smaller than the sizes of molecules present in;
   (a) Afferent renal arteriole (b) Collecting duct
   (c) Loop of Henle (d) Proximal tubule
4. If a drug reduces mitochondrial activity in nephrons, which chemical will be present in increased amounts in the urine?
   (a) Ammonia (b) Glucose (c) Uric acid (d) Urea
5. The water content of blood is regulated by ADH. In which part of the nephron this regulation occurs?
   (a) Bowman's capsule (b) Proximal convoluted tubule
   (c) Loop of Henle (d) Collecting duct
6. In kidneys, glucose is reabsorbed into blood. Where does this reabsorption occur?
   (a) Bowman's capsule (b) Glomerulus
   (c) Proximal convoluted tubule (d) Collecting duct
7. In normal conditions, which one is completely reabsorbed from renal tubule into blood?

(a) Urea (b) Water (c) Salts (d) Glucose

8. If the loops of Henle are absent in all nephrons, what would happen?
(a) No urine formation
(b) Formation of urine with normal concentration
(c) Formation of concentrated urine
(d) Formation of dilute urine

9. In peritoneal dialysis, the lining of which part of the body acts as a filter?
(a) Stomach (b) Intestine (c) Lungs (d) Abdomen

10. During which of these treatments, the patients are prescribed immunosuppressant drugs?
(a) Lithotripsy (b) Haemodialysis
(c) Kidney transplant (d)Peritoneal dialysis

SECTION 2: SHORT QUESTIONS

1. Justify the functioning of kidneys as both excretion and osmoregulation.
2. List the organs of the urinary system.
3. Define glomerular filtration.
4. Compare the function of glomerular capillaries and peritubular capillaries.
5. What are the three main processes involved with urine formation?
6. What are the causes of kidney failure?
7. Why do blood and dialysate flow in opposite direction?
8. Differentiate between:
   - Afferent and efferent arterioles
   - Chronic and acute renal failure
   - Haemodialysis and peritoneal dialysis
   - Renal cortex and renal medulla

SECTION 3: LONG QUESTIONS

1. Describe the structure of kidney and relate it with its function.
2. Explain the detailed structure of nephron.
3. Explain the main processes in kidney functioning.
4. Explain that concentration of urine is regulated by counter-curent and hormonal mechanisms.
5. Explain the causes and treatments of kidney stones.
6. Explain in detail the mechanism and problems related to dialysis.
7. Describe the principles and the problems associated with kidney transplant.

INQUISITIVE QUESTIONS

1. Hypothesize kidney stone by studying the urine test of relevant patients.
2. Describe the importance of kidney donation for the benefit of kidney failure patients.
3. Name the important kidney transplant centres in your city.