CHAPTER-19

EXCRETORY PRODUCTS AND THEIR ELIMINATION

Introduction

In living, cell's different metabolic reactions are taking place during which several toxic by-products are produced. Animals accumulate ammonia, urea, uric acid, carbon dioxide, water, and ions like Na+, K+, Cl–, phosphate, sulphate, etc., either by metabolic activities or by other means like excess ingestion. These substances have to be removed totally or partially. The removal of these waste materials is known as excretion. In this chapter, we will emphasize especially on the elimination of nitrogenous waste material.

The excretory system is not only responsible for the elimination of waste products from our body, but it is also responsible for maintaining the ionic and pH balance of body fluid.

Types of excretory materials and classification of animals

Though several kinds of toxic materials are produced in our living cells which all are eliminated from our body. But in true sense elimination of nitrogenous substances is known as excretion. Ammonia, urea, and uric acid are the major forms of nitrogenous wastes excreted by the animals. Ammonia is the most toxic form and requires a large amount of water for its elimination, whereas uric acid, being the least toxic, can be removed with a minimum loss of water.

The process of excreting ammonia is Ammonotelism. Many bony fishes, aquatic amphibians, and aquatic insects are ammonotelic in nature. Ammonia, as it is readily soluble, is generally excreted by diffusion across body surfaces or through gill surfaces (in fish) as ammonium ions. Kidneys do not play any significant role in its removal.

Terrestrial adaptation necessitated the production of lesser toxic nitrogenous wastes like urea and uric acid for the conservation of water.

Mammals, many terrestrial amphibians, and marine fishes mainly excrete urea and are called ureotelic animals. Ammonia produced by metabolism is converted into urea in the liver of these animals and released into the blood which is filtered and excreted out by the kidneys. Some amount of urea may be retained in the kidney matrix of some of these animals to maintain the desired osmolarity.

Reptiles, birds, land snails, and insects excrete nitrogenous wastes as uric acid in the form of a pellet or paste with a minimum loss of water and are called uricotelic animals.

Excretory organs in different animal groups

Different animals inhabit in different environments and their metabolic waste, as well as their requirement, is different. Accordingly, different types of excretory structures have developed. Here we are mentioning the excretory organs in some of the different animals. In higher classes you will study about comparative development of excretory structures in different animals and animal groups.

In most of the invertebrates, these structures are simple tubular forms whereas vertebrates have complex tubular organs called kidneys.
Some of these structures –

a. Protonephridia or flame cells are the excretory structures in Platyhelminthes like- Flatworms, e.g., *Planaria*, rotifers, some annelids and the cephalochordate – *Amphioxus*. Protonephridia are primarily concerned with ionic and fluid volume regulation, i.e., osmoregulation.

b. Nephridia are the tubular excretory structures of earthworms and other annelids. Nephridia help to remove nitrogenous wastes and maintain a fluid and ionic balance.

c. Malpighian tubules are the excretory structures of most of the insects including cockroaches. Malpighian tubules help in the removal of nitrogenous wastes and osmoregulation.

d. Antennal glands or green glands perform the excretory function in crustaceans like prawns.

Excretory system in human beings

In humans, the excretory system consists of a pair of kidneys, one pair of ureters, a urinary bladder and a urethra. Kidneys are reddish-brown, bean-shaped structures situated between the levels of last thoracic and third lumbar vertebra close to the dorsal inner wall of the abdominal cavity. Each kidney of adult human measures 10-12 cm in length, 5-7 cm in width, 2-3 cm in thickness with an average weight of 120- 170 gm, toward the centre of the inner concave surface of the kidney is a notch called hilum through which ureter, blood vessels and nerves enter. Inner to the hilum is a broad funnel-shaped space called the renal pelvis with projections called calyces.

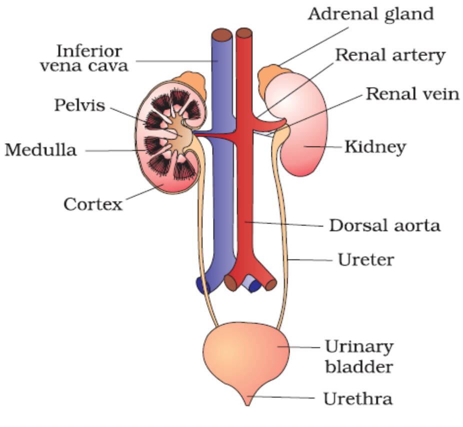


Figure Human Urinary system

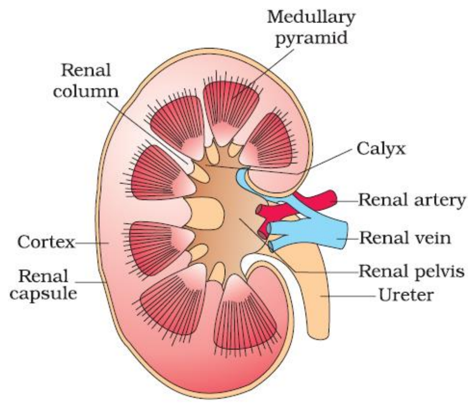


Figure Longitudinal section (Diagrammatic) of Kidney

The outer layer of the kidney is a tough capsule. Inside the kidney, there are two zones, an outer *cortex,* and an inner *medulla*. The medulla is divided into a few conical masses which may also be known as medullary pyramids projecting into the calyces. The cortex extends in between the medullary pyramids as renal columns called Columns of Bertini. Each kidney consists of nearly one million complex tubular structures called nephrons. The nephron is known as the functional unit of the human kidney. Each nephron has two parts – the glomerulus and the renal tubule.

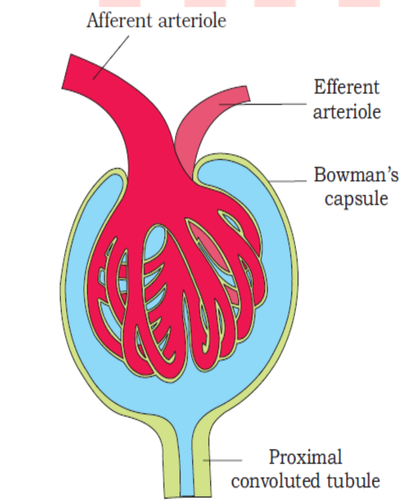


Figure Malpighian body (renal corpuscle)

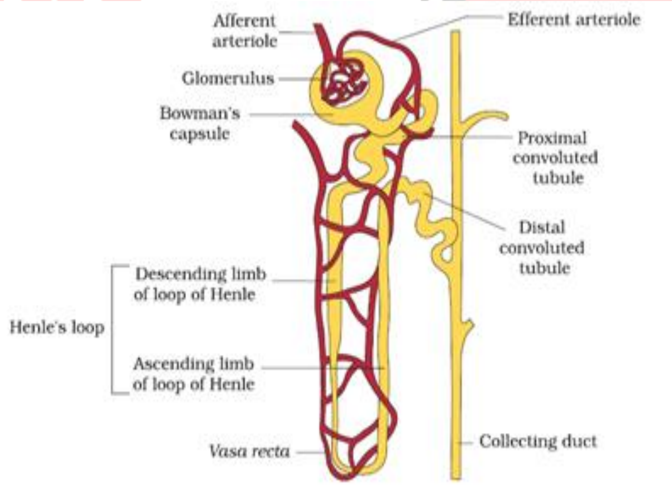


Figure A diagrammatic representation of a nephron showing blood vessels, duct and tubule

Glomerulus

● It is a tuft of capillaries formed by the afferent arteriole – a fine branch of the renal artery. Blood from the glomerulus is carried away by an efferent arteriole.

Renal tubule

● It begins with a double-walled cup-like structure called Bowman's capsule, which encloses the glomerulus. Glomerulus along with Bowman's capsule is called the Malpighian body or renal corpuscle.
● The tubule continues further to form a highly coiled network – proximal convoluted tubule (PCT).
● A hairpin shaped Henle's loop is the next part of the tubule which has a descending and an ascending limb.
● The ascending limb continues as another highly coiled tubular region called distal convoluted tubule (DCT).
● The DCTs of many nephrons open into a straight tube called *collecting duct*, many of which converge and open into the renal pelvis through medullary pyramids in the calyces.
● The Malpighian corpuscle, PCT, and DCT of the nephron are situated in the cortical region of the kidney whereas the loop of Henle dips into the medulla.

Collecting Duct:

● The long duct extends from the cortex of the kidney to the inner parts of the medulla. Distally it opens in the pelvis region of the kidney.

Cortical and Juxta medullary nephron

● In the majority of nephrons, the loop of Henle is too short and extends only very little into the medulla. Such nephrons are called cortical nephrons. In some of the nephrons, the loop of Henle is very long and runs deep into the medulla. These nephrons are called juxta medullary nephrons.
● The efferent arteriole emerging from the glomerulus forms a fine capillary network around the renal tubule called the peritubular capillaries. A minute vessel of this network runs parallel to Henle's loop forming a 'U' shaped vasa recta. Vasa recta are absent or highly reduced in the cortical nephron.

Urea synthesis

In humans, being urea is the main excretory material. The amino-containing compounds or nitrogen-containing compounds undergo in the metabolic processes like delamination and transamination, producing ammonia as chief excretory material. Since ammonia is highly toxic so immediately it requires its elimination from our body. But there are two problems with ammonia. The first one is that since ammonia is a highly toxic material so it immediately requires its elimination from our body. But in human beings, it is not possible to excrete all the time through-out life. At the same time, ammonia is soluble in water so its excretion requires a lot of water which may lead to dehydration. So to get rid of all these problems the ammonia is first converted in urea. Urea is a less toxic material. Urea can be stored temporarily in our body at the same time urea excretion requires a very small amount of water, this person will not suffer from dehydration due to excretion.

In the human body, the ammonia produced during amino acid metabolism or metabolism of any nitrogen-containing compound is at first converted in urea. Most of the synthesis of urea is taking place in the liver. Synthesis of urea occurs through a metabolic pathway known as "Ornithin cycle or Urea cycle or Krebs Henselit cycle". This cycle involves ammonia, Co2, and ATP. The urea synthesis may also take place in brain cells as well as in kidney cells in a very small quantity. After synthesis urea is transported to kidney for its excretion.

Urine synthesis

Urine formation involves three main processes namely, glomerular filtration, reabsorption, and secretion, which take place in different parts of the nephron.

(1) Glomerular filtration or ultrafiltration

- The first step in urine formation is the filtration of blood, which is carried out by the glomerulus and is called glomerular filtration.
- On an average, 1100-1200 ml of blood is filtered by the kidneys per minute which constitute roughly 1/5th of the blood pumped out by each ventricle of the heart in a minute.
- The glomerular capillary blood pressure causes filtration of blood through 3 layers, i.e., the endothelium of glomerular blood vessels, the epithelium of Bowman's capsule and a basement membrane between these two layers.
- The epithelial cells of Bowman's capsule called podocytes are arranged in an intricate to leave some minute spaces called filtration slits or slit pores. Blood is filtered so finely through these membranes, that almost all the constituents of the plasma except the lumen of the Bowman's capsule. Therefore, it is considered as a process of ultra filtration. The amount of the filtrate formed by the kidneys per minute is called Glomerular filtration rate (GFR).
- GFR in a healthy individual is approximately 125 ml/minute, i.e., 180 liters per day. The kidneys have built-in mechanisms for the regulation of glomerular filtration rate.
- One such efficient mechanism is carried out by juxta glomerular apparatus (JGA). JGA is a special sensitive region formed by cellular modifications in the distal convoluted tubule and the afferent arteriole at the location of their contact. A fall in GFR can activate the JG cells to release renin which can stimulate the glomerular blood flow and thereby the GFR back to normal.

(2) Tubular resorption

- A comparison of the volume of the filtrate formed per day i.e.180 liters per day with that of the urine released i.e. 1.5 liters per day suggest that nearly 99 percent of the filtrate has to be reabsorbed by the renal tubules. This process is called reabsorption.
- The tubular epithelial cells in different segments of nephron perform this either by active or passive mechanisms. For example, substances like glucose, amino acids, Na+, etc., in the filtrate are reabsorbed actively whereas the nitrogenous wastes are absorbed by passive transport. Reabsorption of water also occurs passively in the initial segments of the nephron.

(3) Tubular secretion

- During urine formation, the tubular cells secrete substances like H+, K+ and ammonia into the filtrate. Tubular secretion is also an important step in urine formation as it helps in the maintenance of ionic and acid-base balance of body fluids.

The function of renal tubule

- **The function of Proximal convoluted tubule (PCT)-** It is lined by simple cuboidal brush border epithelium which increases the surface area for reabsorption. Nearly all of the essential nutrients and 70-80 percent of electrolytes and water are reabsorbed by this segment. PCT also helps to maintain the pH and ionic balance of the body fluids by selective secretion of hydrogen ions, ammonia and potassium ions into the filtrate and by absorption of HCO3 – from it.
- **The function of Henle's Loop:** Henle's loop has three regions the descending limb, loop, and ascending limb. The descending limb is permeable for water only. The loop itself is impermeable for any kind of material. The ascending limb has two parts, the first part is narrow which is passively permeable only for NaCl however later part is wide, which is permeable actively for NaCl. Reabsorption in Henle's loop is minimum. However, this region plays a significant role in the maintenance of high osmolarity of medullary interstitial fluid. The descending limb of the loop of Henle which is permeable to water but almost impermeable to electrolytes concentrates the filtrate as it moves down. The ascending limb is impermeable to water but allows transport of electrolytes actively or passively. Therefore, as the concentrated filtrate passes upward, it gets diluted due to the passage of electrolytes to the medullary fluid.

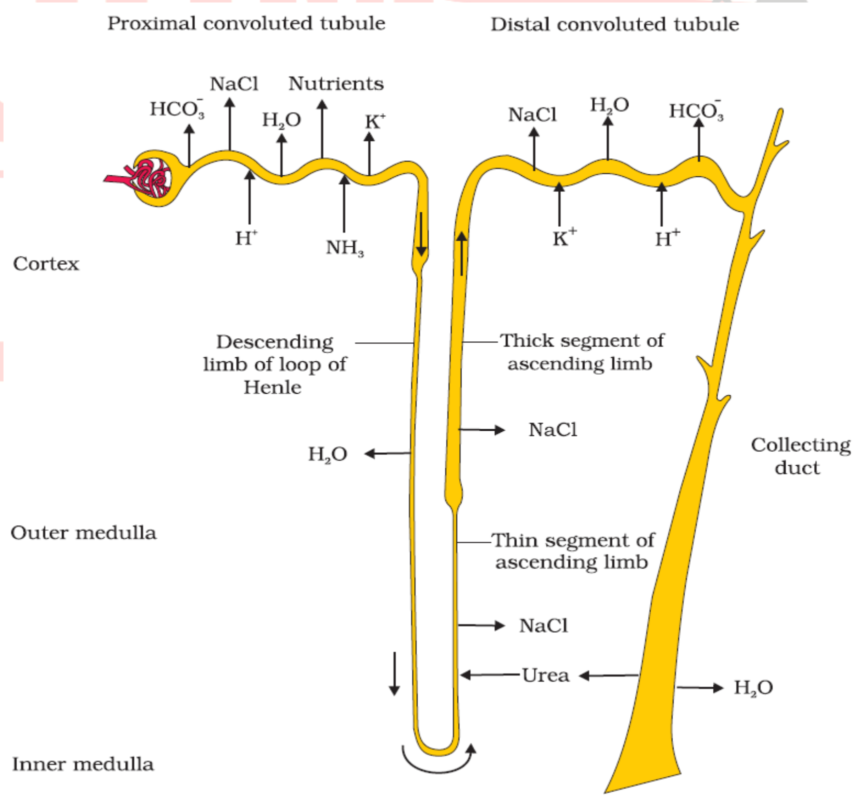


Figure Reabsorption and secretion of major substances at different parts of the nephron (Arrows indicate direction of movement of materials.)

- **The function of Distal Convoluted Tubule (DCT):** Conditional reabsorption of Na+ and water takes place in this segment. In normal conditions, its wall is impermeable for water and salt but in the presence of the ADH hormone, its wall becomes permeable for water while in the presence of hormone mineralocorticoids its wall becomes permeable for NaCl. DCT is also capable of reabsorption of HCO_3^- and selective secretion of hydrogen and potassium ions and NH_3 to maintain the pH and sodium-potassium balance in the blood.

- **The function of collecting duct-** Large amounts of water could be reabsorbed from this region to produce concentrated urine. This segment allows the passage of small amounts of urea into the medullary interstitium to keep up the osmolarity. It also plays a role in the maintenance of pH and ionic balance of blood by the selective secretion of H^+ and K^+ ions.

Counter current mechanism

Human beings and other mammals excrete concentrated hypertonic urine. The mechanism by which the human body can produce hypertonic urine is known as a counter-current mechanism. Loop Henle and vasa recta play a significant role in the excretion of hypertonic urine. The mechanism of the counter current mechanism is as following-

- The flow of filtrate in the two limbs of Henle's loop is in opposite directions and thus forms a counter current.
- The flow of blood through the two limbs of *vasa recta* is also in a counter-current pattern.
- The proximity between Henle's loop and *vasa recta*, as well as the counter-current in them, help in maintaining an increasing osmolarity towards the inner medullary interstitium, i.e. from 300 $mOsmolL^{-1}$ in the cortex to about 1200 $mOsmolL^{-1}$ in the inner medulla. This gradient is mainly caused by NaCl and urea. NaCl is transported by the ascending limb of Henle's loop which is exchanged with the descending limb of the vasa recta. NaCl is returned to the interstitium by the ascending portion of the vasa recta.

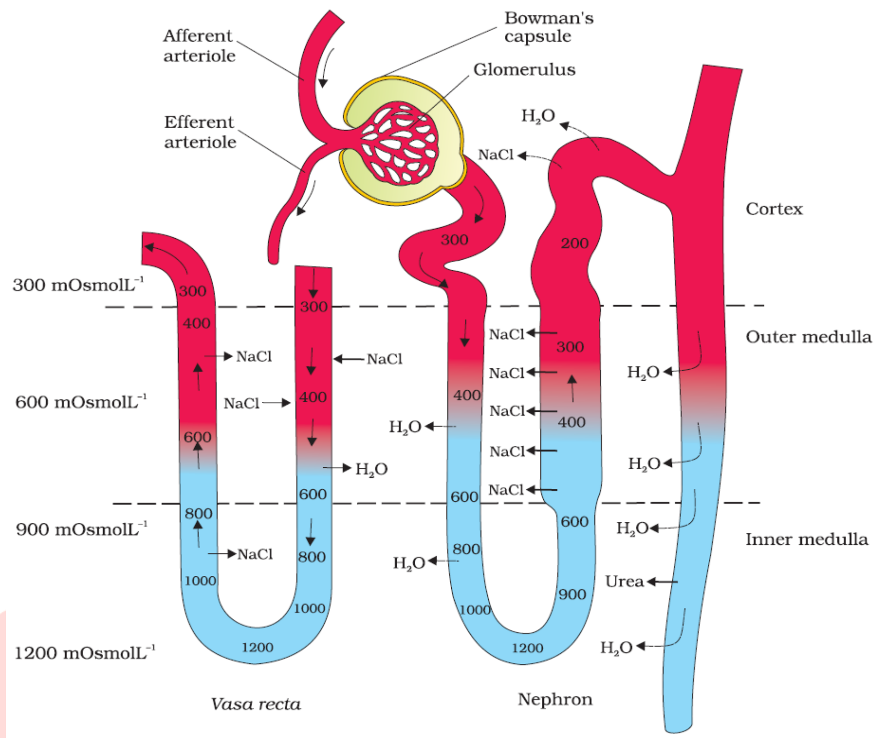


Figure Diagrammatic representation of a nephron and *vasa recta* showing counter current mechanisms

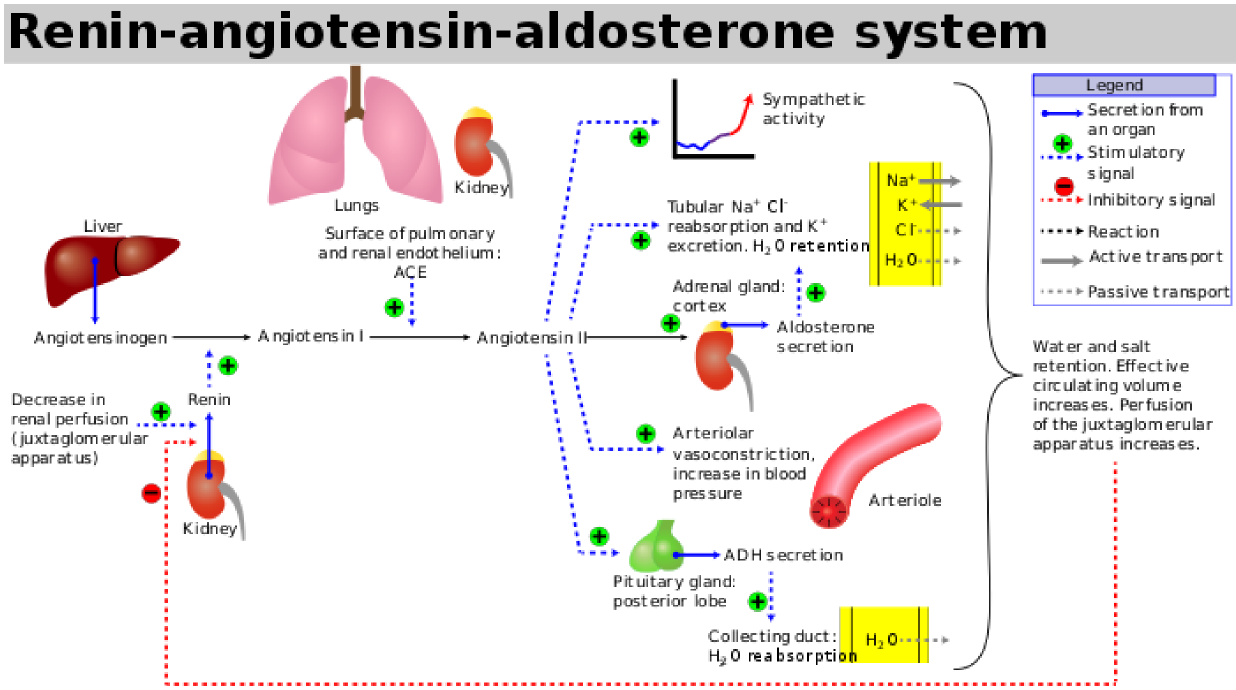
- A small amount of urea enters the thin segment of the ascending limb of Henle's loop which is transported back to the interstitium by the collecting tubule. All these described transport of substances facilitated by the special arrangement of Henle's loop and *vasa recta* is called the counter current mechanism
- The counter current mechanism helps to maintain a concentration gradient in the medullary interstitium. Presence of such interstitial gradient helps in an easy passage of water from the collecting tubule thereby concentrating the filtrate i.e. urine.
- With help of this mechanism human kidneys can produce urine nearly four times concentrated than the initial filtrate formed.

Regulation of kidney function

Regulation of kidney function may occur at several levels like- Neural level (by sympathetic nerves), muscular level as well as at hormonal level. Here in this topic we will focus mainly on the regulation of kidney function at hormonal level. In higher classes you will study more about the regulation of kidney function at neural level as well as on muscular level.

Hormonal regulation of kidney function

- The functioning of the kidneys is efficiently monitored and regulated by hormonal feedback mechanisms involving the hypothalamus, JGA and to a certain extent, the heart.
- Osmoreceptors present at different places in our body are activated by changes in blood volume, body fluid volume and ionic concentration.



- An excessive loss of fluid from the body can activate these receptors which stimulate the hypothalamus to release antidiuretic hormone (ADH) or vasopressin from the neurohypophysis. ADH facilitates water reabsorption from latter parts of the tubule, thereby preventing diuresis.
- An increase in body fluid volume can switch off the osmoreceptors and suppress the ADH release to complete the feedback.
- ADH can also affect the kidney function by its constrictor effects on blood vessels. This causes an increase in blood pressure. An increase in blood pressure can increase the glomerular blood flow and thereby the GFR.
- The JGA plays a complex regulatory role. A fall in glomerular blood flow/glomerular blood pressure/GFR can activate the JG cells to release renin which converts angiotensinogen in blood to angiotensin I and further to angiotensin II. Angiotensin II, being a powerful vasoconstrictor, increases the glomerular blood pressure and thereby GFR.
- Angiotensin II also activates the adrenal cortex to release Aldosterone. Aldosterone causes reabsorption of Na+ and water from the distal parts of the tubule. This also leads to an increase in blood pressure and GFR. This complex mechanism is generally known as the Renin-Angiotensin mechanism.

Regulation of kidney function by heart

- An increase in blood flow to the atria of the heart can cause the release of Atrial Natriuretic Factor (ANF).
- ANF can cause vasodilation (dilation of blood vessels) and thereby decrease the blood pressure. Thus ANF mechanism acts as a check on the renin-angiotensin mechanism.

Micturition

Mechanism of passage of urine is known as micturition. After formation, urine is transported from kidney to urinary bladder by ureter. In urinary bladder urine is stored till a voluntary signal is given by the central nervous system (CNS). This signal is initiated by the stretching of the urinary bladder as it gets filled with urine. The average capacity of urinary bladder is 600 to 800 ml. When a urinary bladder is half filled, the person fells urge of urination.
Mechanism of urination- The wall of urinary bladder has several stretch receptors. When the urinary bladder is filled with urine these receptors get stretched. In response, the stretch receptors on the walls of the bladder send signals to the CNS. The CNS passes on motor messages to initiate the contraction of smooth muscles of the bladder and simultaneous relaxation of the urethral sphincter causing the release of urine. The process of release of urine is called micturition and the neural mechanism of micturition is called the micturition reflex.

Composition of urine- An adult human excretes, on an average, 1 to 1.5 liters of urine per day. The urine formed is a light yellow colored watery fluid which is slightly acidic, i.e. pH-6.0 and has a characterestic odour. The characteristic color of urine is due to urochrome and characteristic odor is due to ammonia present in it. On an average, 25-30 gm of urea is excreted out per day.
Various conditions can affect the characteristics of urine. Analysis of urine helps in clinical diagnosis of many metabolic disorders as well as malfunctioning of the kidney. For example, presence of glucose (Glycosuria) and ketone bodies (Ketonuria) in urine are indicative of diabetes mellitus.

Role of other organs in excretion

Usually expulsion of nitrogenous waste material from our body is known as excretion. But several other kinds of waste materials are produced in our body, which all need to eliminate out. The kidney is mainly responsible for elimination of nitrogenous waste material as well as it is also responsible for ionic balance, maintenance of pH and water balance. The ionic and water balance is known as osmoregulation. Despite of these functions kidney also produces a hormone known as erythropoietin hormone. This hormone acts on red bone marrow and stimulates it to produce RBC. Since kidney is responsible for elimination of nitrogenous waste material so other waste materials are also involved in process of elimination of other waste materials. Some organs involved in this process are as following-

- **Lungs-** Our lungs remove large amounts of CO_2 (18 liters/day) and also significant quantities of water every day.
- **Liver-** Liver is largest gland in our body, secretes bile-containing substances like bilirubin, biliverdin, cholesterol, degraded steroid hormones, vitamins and drugs. Most of these substances ultimately pass out along with digestive wastes.
- **Sweat-** This gland is found in the skin can eliminate certain substances through their secretions. Sweat produced by the sweat glands is a watery fluid containing NaCl, small

amounts of urea, lactic acid, etc. Though the primary function of sweat is to facilitate a cooling effect on the body surface, it also helps in the removal of some of the wastes mentioned above.

- **Sebaceous glands-** It is also present in skin. It eliminates certain substances like sterols, hydrocarbons and waxes through sebum. This secretion provides a protective oily covering for the skin.
- **Salivary gland-** It is found in oral cavity. Mainly responsible for secretion of saliva. Saliva contains enzyme ptylin which is involved in starch digestion. Saliva contains several other materials at the same time it also contains a small amounts of nitrogenous wastes. Hence salivary gland may also take part in excretion.

Disorders of excretory system

There may be several disorders associated with excretory system. Some of the important disorders in human beings are as following

- **Uremia-**Accumulation of urea in our body is uremia. It occurs due to malfunctioning of kidney. Malfunctioning of kidneys can lead to accumulation of urea in blood. The normal blood urea level in healthy adult human being is 25-30 mg/ml of blood. Uremia if not treated it may lead in kidney failure. In these persons the excess of urea and high level of creatinin is removed out by a process known as hemodialysis.

In hemodialysis, blood drained from a convenient artery is pumped into a dialysing unit after adding an anticoagulant like heparin. The unit contains a coiled cellophane tube surrounded by a fluid, known as dialysing fluid which has the same composition as that of plasma except the nitrogenous wastes. The porous cellophane membrane of the tube allows the passage of molecules based on concentration gradient. As nitrogenous wastes are absent in the dialysing fluid, these substances freely move out, thereby clearing the blood. The cleared blood is pumped back to the body through a vein after adding anti-heparin to it. This method is a boon for thousands of uremic patients all over the world. Kidney transplantation is the ultimate method in the correction of acute renal failures or kidney failure. A functioning kidney is used in transplantation from a donor, preferably a close relative, to minimize its chances of rejection by the immune system of the host. Modern clinical procedures have increased the success rate of such a complicated technique.

- **Renal calculi-**Stone or insoluble mass of crystallized salts like oxalates, etc. formed within the kidney.
- **Glomerulonephritis-** Inflammation of glomeruli of kidney due to some kind of infection of injury or due to accumulation of urine in the ureter (Hydroglomerulonephritis)

IMPORTANT TERMS

Sl No.	Terms	Explanation
1	**ADH**	Antidiuretic hormone. Secreted from posterior pituitary gland. Acts on DCT of nephron make it permeable for water. So increases the blood volume and blood pressure.

2	**Afferent renal arteriole**	The arteriole enters in malpighian corpuscle.
3	**Ammonotelic organism**	The organism excrete ammonia
4	**ANF**	Atrial Natriuretic Factor. A potent vasodilator secreted by auricles of heart. Acts on blood vessels dilate them hence overall it decreases the systemic blood pressure.
5	**Bowman's capsule**	A cup like structure of proximal part of nephron. It contains glomerulus
6	**Calyces**	Renal pyramid opens in pelvis through small duct like structure is calyces.
7	**Colloidal pressure**	The pressure generated in blood flowing through glomerulus. It opposes the filtration of blood in it. In human being it is about 30 mm Hg.
8	**Capsular pressure**	The pressure of filtrate in Bowman's capsule. It opposes the filtration of blood. In human being it is about 20 mm Hg.
9	**Effective filtration pressure (EFP)**	The net pressure generated in malpighian corpuscle through which ultra filtration takes place. In human being it is near about 10 mm Hg. EFP= GFP- (Colloidal pressure + Capsular pressure).
10	**Efferent renal arteriole**	The arteriole leaving the malpighian corpuscle.
11	**Glomerular filtration pressure or glomerular pressure**	The pressure generated in glomerular capillaries due to differences in diameter of afferent renal arteriole and efferent renal arteriole. It promotes the filtration.
12	**Glomerulonephritis**	A disease cause due to swelling in glomerulus.
13	**Glomerulus**	A tuft of blood capillary found in Bowman's capsule. At least 5 capillaries are present. It consists of afferent renal arteriole and efferent renal arteriole.
8	**Hilum**	The concave region of kidney through which blood vessels, lymph vessels, nerves enter and leaving the kidney as well as from which ureter arises.
9	**JGA**	Juxta glomerular apparatus. It is associated with muscle layer of renal afferent arteriole at the place where it enters in malpighian capsule. It is mainly involved in regulation of kidney function especially when blood pressure, blood volume etc decreases. It releases an enzyme Renin (At some place Renin is considered as hormone. But actually it is an enzyme)

10	**Angiotensinogen**	An inactive protein synthesized and secreted by liver. When blood pressure, blood volume etc decreases in our body, renin is released which converts it in angiotensin with help of another enzyme catalaze.
11	**Renal cortex**	Proteins are large biomolecules, or macromolecules, consisting of one or more long chains of amino acid residues.
12.	**Renal plasma flow**	The amount of blood flows through kidney in a minute. In human being it is about 1100-1200 ml.