Physiology of Excretion

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Excretory System

- When our cells perform their functions, certain waste products are released in to the blood stream. These are **toxic** and hence need to be removed from the body.
- The process of removal of wastes produced in the cells of the living organisms is called **excretion**. The parts involved in excretion forms the excretory system.
- Waste removal is done by the blood capillaries in the kidneys.
- When the blood reaches the two kidneys, it contains both useful and harmful substances. The useful substances are absorbed back into the blood. The wastes are removed as urine.
- From the kidneys, the urine goes into the **urinary bladder** through tube-like **ureters**. It is stored in the bladder and is passed out through the urinary opening at the end of a muscular tube called **urethra**. The **kidneys, ureters, bladder and urethra** form the excretory system.
- An adult human being normally passes about **1–1.8 L** of urine in 24 hours, and the urine consists of **95% water, 2.5 % urea and 2.5% other waste products**.

Excretory Products and their Elimination

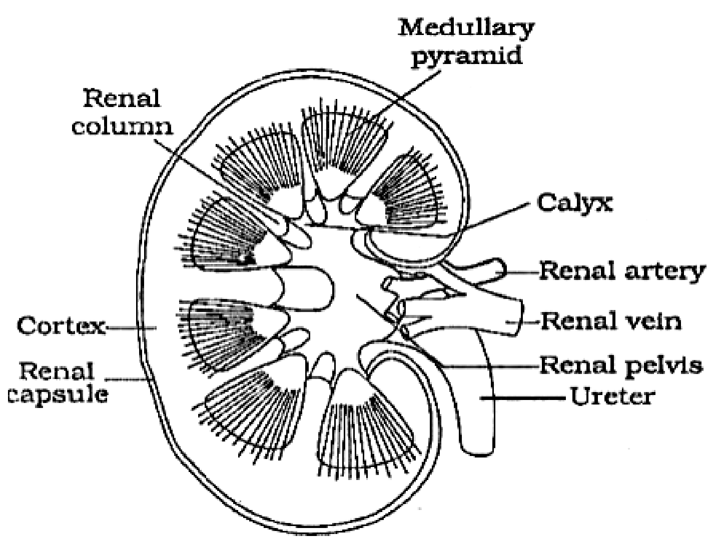
- Animals accumulate **ammonia, urea, uric acid, carbon dioxide, water and ions like Na^+, K^+, Cl^-, phosphate, sulphate**, either by metabolic activities or by other means like excess ingestion. These substances have to be removed totally or partially.
- **Ammonia, urea** and **uric acid** are the major forms of **nitrogenous wastes** excreted by the animals.
- The way in which waste chemicals are removed from the body of the animal depends on the availability of water.
- **Ammonia is the most toxic** form and requires large amount of water for its elimination, whereas **uric acid, being the least toxic**, can be removed with a minimum loss of water.
- Aquatic animals like fishes, excrete cell waste in **gaseous form (ammonia)** which directly dissolves in water.
- Some land animals like birds, lizards, snakes excrete a semi-solid, white colored compound (**uric acid**).
- The major excretory product in humans is **urea** which is excreted through urine.
- Sometimes a person's kidneys may stop working due to infection or injury. As a result of kidney failure, waste products start accumulating in the blood. Such persons cannot survive unless their blood is filtered periodically through an artificial kidney. This process is called **dialysis**.
- The process of excreting ammonia is 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 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 a desired **osmolarity [**the concentration of a solution expressed as the total number of solute particles per litre**]**.
- Reptiles, birds, land snails and insects excrete nitrogenous wastes as **uric acid** in the form of pellet or paste with a minimum loss of water and are called **uricotelic animals**.
- A survey of animal kingdom presents a variety of excretory structures. In most of the invertebrates, these structures are simple tubular forms whereas vertebrates have complex tubular organs called kidneys. Some of these structures are mentioned here.
- **Protonephridia or flame cells** are the excretory structures in Platyhelminthes (Flatworms, e.g., Planaria), rotifers, some annelids and the cephalochordate.
- Protonephridia are primarily concerned with ionic and fluid volume regulation, i.e., osmoregulation. **Nephridia** are the tubular excretory structures of earthworms and other annelids. Nephridia help to remove nitrogenous wastes and maintain a fluid and ionic balance.
- **Malpighian tubules** are the excretory structures of most of the insects including cockroaches. Malpighian tubules help in the removal of nitrogenous wastes and osmoregulation.
- **Antennal glands** or **green glands** perform the excretory function in crustaceans like prawns.

The excretory system is made up of the urinary system and a number of other organs and systems that contribute to the excretion of waste products.

- **The respiratory system** (removing CO2 from the blood)
- **Sweat glands** (remove various waste products together with the sweat)
- **Liver** (Removes products left after the breakdown of haemoglobin from old red blood cells. It also eliminates a small amount of cholesterol and some toxic substances)
- **The Urinary system** (removes CO2, urea, uric acid and other substances)

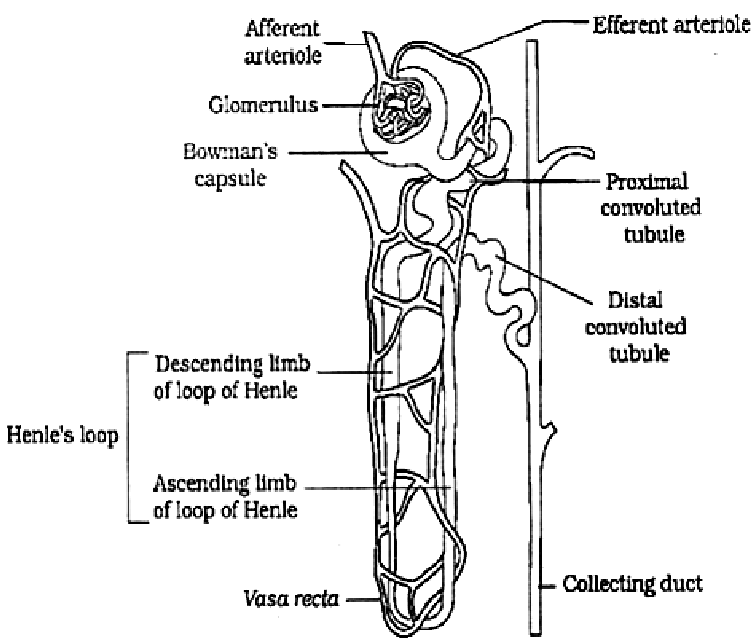
  The urinary system eliminates excretory products in the form of urine. The excretory products released include, CO2, urea, uric acid and other substances. It is necessary to keep the body's vital functions in balance. It regulates the amount of water in tissues (water homeostasis), the concentration and type of mineral salts in the blood and the blood's pH levels.



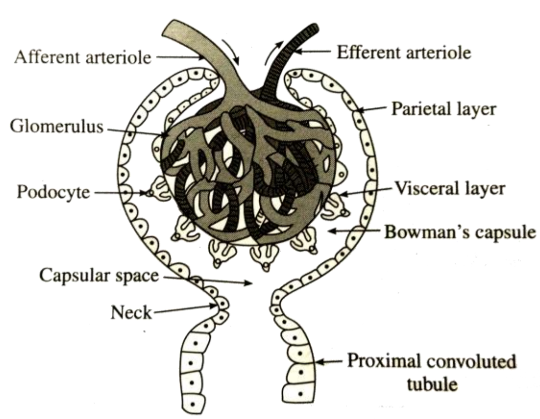
Kidneys

- 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 an 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 g.
- Towards the center 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**.
- Inside the kidney, there are two zones, an **outer cortex** and an **inner medulla**. The medulla is divided into a few conical masses (medullary pyramids) projecting into the calyces (singularity: calyx).
- Each kidney has nearly one million complex tubular structures called **nephrons**, which are the functional units.
- Each nephron has two parts – the **glomerulus** and the **renal tubule**.
- Glomerulus is a tuft of capillaries formed by the **afferent arteriole** – a fine branch of **renal artery**. Blood from the glomerulus is carried away by an **efferent arteriole**.
- The renal tubule 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.
- In 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 the Henle's loop forming a 'U' shaped vasa recta. Vasa recta is absent or highly reduced in cortical nephrons.

Urine Formation

- Urine formation involves three main processes namely, **glomerular filtration, reabsorption** and **secretion**, that takes place in different parts of the nephron.
- 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.
- 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 manner so as 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 proteins pass onto 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)**.
- A comparison of the volume of the filtrate formed per day (180 liters per day) with that of the urine released (1.5 litres), suggest that nearly 99 per cent 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.
- 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.

Function of the Tubules

Proximal Convoluted Tubule (PCT)

- PCT is lined by **simple cuboidal epithelium** which increases the surface area for reabsorption. Nearly all of the essential nutrients, and 70-80 per cent 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 HCO_3^- from it.

Henle's Loop

- Reabsorption is minimum in its ascending limb. However, this region plays a significant role in the maintenance of **high osmolarity** of medullary interstitial fluid.
- The descending limb of loop of Henle is permeable to water but almost impermeable to electrolytes. This 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 pass upward, it gets diluted due to the passage of electrolytes to the medullary fluid.

Distal Convoluted Tubule (DCT)

- Conditional reabsorption of Na^+ and water takes place in this segment. 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 blood.

Collecting Duct

- This long duct extends from the cortex of the kidney to the inner parts of the medulla.
- Large amounts of water could be reabsorbed from this region to produce a concentrated urine.
- This segment allows 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.

Mechanism of Concentration of the Filtrate

- Mammals have the ability to produce a concentrated urine. The **Henle's loop** and **vasa recta** play a significant role in this.
- 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 the 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. 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 vasa recta. NaCl is returned to the interstitium by the ascending portion of vasa recta.
- Similarly, small amounts of urea enter the thin segment of the ascending limb of Henle's loop which is transported back to the interstitium by the collecting tubule.
- The above described transport of substances facilitated by the special arrangement of Henle's loop and vasa recta is called the **counter current mechanism**. This 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 (urine). Human kidneys can produce urine nearly four times concentrated than the initial filtrate formed.

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** in the 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 [increased or excessive production of urine]**.
- 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 constrictory 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**.
- 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. ANF mechanism, therefore, acts as a check on the renin-angiotensin mechanism.

Micturition

- Urine formed by the nephrons is ultimately carried to the urinary bladder where it 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. 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 mechanisms causing it is called the **micturition reflex**.
- An adult human excretes, on an average, **1 to 1.5 litres** of urine per day. The urine formed is a light yellow coloured watery fluid which is **slightly acidic** (pH-6.0) and has a characterestic odour.
- 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 discorders 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

- Other than the **kidneys, lungs, liver** and **skin** also help in the elimination of excretory wastes.
- Our lungs remove large amounts of CO2 (approximately 200mL/ minute) and also significant quantities of water every day.
- Liver, the 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 alongwith digestive wastes.
- The sweat and sebaceous glands 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 eliminate certain substances like sterols, hydrocarbons and waxes through sebum. This secretion provides a protective oily covering for the skin. Small amounts of nitrogenous wastes could be eliminated through saliva too.

Disorders of the Excretory System

- Malfunctioning of kidneys can lead to accumulation of urea in blood, a condition called **uremia**, which is highly harmful and may lead to kidney failure. In such patients, urea can be removed by a process called **hemodialysis**.
- Blood drained from a convenient artery is pumped into a dialyzing unit after adding an anticoagulant like **heparin**. The unit contains a coiled cellophane tube surrounded by a fluid (dialyzing fluid) having 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 dialyzing 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 (kidney failure). A functioning kidney is used in transplantation from a donor, preferably a close relative, to minimise 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 crystallised salts (**oxalates**, etc.) formed within the kidney.
- **Glomerulonephritis:** Inflammation of glomeruli of kidney.