EXCRETORY PRODUCTS AND THEIR ELIMINATION

- Excretory products are produced during metabolism of substances like carbohydrates, fats, amino acids or proteins and nucleic acids.
- Metabolism of carbohydrates and fats produces CO_2 and H_2O which are easy to remove. Their excretion is effected through **lungs** (expired air), **skin** (sweat) or **kidneys** (urine).
- Metabolism of proteins and nucleic acids produce nitrogenous waste materials such as **ammonia, urea** and **uric acid.**
- Ammonia is the basic nitrogenous catabolite of protein, formed by breakdown of amino acids. Removal of the amino group (NH_2) is known as **deamination** and it converts the amino acid into a keto acid. **In vertebrates, deamination takes place in the liver.**
- Ammonia thus produced is highly toxic and cannot be stored within the body. It needs to be eliminated immediately.
- Depending upon the excretory product, animals show the following types of nitrogenous excretion
  - **Ammonotelism :** 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.
  - **Ureotelism :** Excretion of urea is known as ureotelism. **Urea is less toxic** and less soluble in water than ammonia. Mammals, many terrestrial amphibians and marine fishes mainly excrete urea and are called ureotelic animals.
  - **Uricotelism :** Excretion of uric acid, is known as uricotelism. Animals which live in **dry conditions** have to **conserve water** in their bodies. Therefore, they synthesize crystals of uric acid from ammonia. Uric acid crystals are non-toxic and almost insoluble in water. 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.

Some animals perform two modes of excretion. That is called **dual excretion.** Earthworms excrete ammonia when sufficient water is available while they excrete urea instead of ammonia in drier surroundings. When lung fishes and *Xenopus* (African toad) live in water they are normally ammonotelic but they become ureotelic when they lie immobile in moist air or mud during their metamorphosis. Crocodiles spend most of their time in water and are normally ammonotelic but when kept out of water the excretion of urea and uric acid increases.

HUMAN EXCRETORY SYSTEM

- **Human excretory system** or **ureotelic system** consists of paired kidneys, paired ureters, urinary bladder and urethra.
- **Kidney** is paired, bean, shaped, dark red in colour, measuring 10 cm long × 5 cm broad × 4 cm thick and weighing about 150 grams in adult male and about 135 gms in adult female.
- Kidney is surrounded by an **adipose tissue capsule** which keeps it in place and protects it from external shocks and injuries.
- **Ureters** are paired **smooth muscled tubes** (about 28 cm long) opening independently into the urinary bladder and **carrying urine** from the kidney.
- **Urinary bladder** is a chamber made of smooth muscles and consists of a **body** where urine collects, and a funnel – shaped extension of the body called **neck.**
- **Urethra** is 18-20 cm long in human male and 4 cm long in female and opens by **urethral orifice** or **urinary aperture.** Muscular **urethral sphincters** keep the urethra closed except during the act of passing urine out.
- Towards the centre of the inner concave surface of the kidney is a notch called **hilus** or **hilum** through which blood vessels, lymphatics vessels, nerves and ureters enter or leave the kidney.
- The glandular part of the kidney surrounds a large cavity called **renal sinus** which extends from the hilus and contains the **renal pelvis.** The renal pelvis is funnel-shaped expansion of the upper end of ureter and forms 2-3 outpockets called **calyces.**
- There are two distinct zones in kidney-an outer, darker, reddish brown **renal cortex** and an inner, lighter **renal medulla** which is made of 8-10 conical subdivisions called **renal pyramids.** The lateral boundary of each renal pyramid is delineated by darker **cortical tissue** called **renal column of Bertini.** A portion of each nephron is located in both the **cortex** and **medulla** although the major part of each nephron is found in the **cortex.**

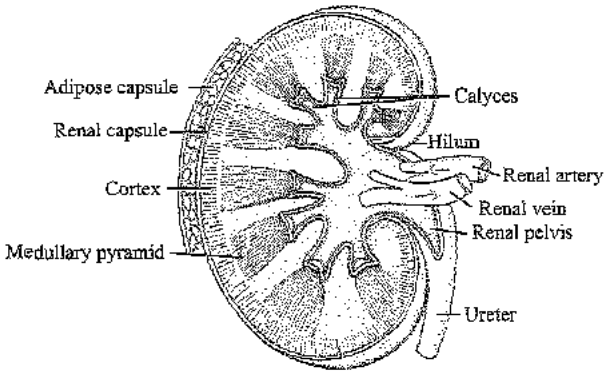

Fig.: L.S. of human kidney

- The **structural** and **functional unit** of human kidney is **nephron.** Approximately one million (= 10 lacs) nephrons are present in each kidney.
- It is of two types : **(i) Cortical nephron** (about 80-90%) which are superficial and originate in cortex, having relatively **short loops of Henle** (deals with the control of blood volume), **(ii) Juxtamedullary nephrons** (10-20%) are present at the junction between cortex and medulla and have **long loops of Henle** (deals with increased water retention, when water is in short supply).

- Each nephron is made up of **Bowman's capsule** with **glomerulus** and **tubules** formed of **proximal convoluted tubule** (PCT), **Henle's loop, distal convoluted tubule** (DCT) and **collecting tubule** (CT) or **duct**.
- The glomerulus is formed by the branches of **afferent arteriole** which interconnect to form tuft of capillaries capped by **Bowman's capsule**. Glomerular membrane consists of–**capillary endothelium, basement membrane** and an **epithelium made of podocytes** which has split pores that restrict passage of colloids. The efferent arteriole from the glomerulus forms a fine capillary network around renal tubule, a minute vessel of thin network the runs parellel to the Henle's loop forming a U-shaped **vasa recta.** PCT is continuous with **Bowman's capsule** and is lined by highly cuboidal epithelial cells. The cells bear **microvilli** on the free surface (luminal side) and rest on a **basement membrane** (high absorptive function).
- **Loop of Henle** consists of a thin walled **descending tubule** that makes a sharp hairpin bend in the **upper medulla** for the **cortical nephron**, and deeper in the **medulla** for the **juxtamedullary nephron. Distal convoluted tubule (DCT)** commences as a short, highly convoluted tubule in the cortex of **juxta medullary region. Collecting tubule (CT)** drains a number of ducts of DCT in the cortex. It descends to the tip of **medulla** to form the **collecting ducts of Bellini** which empty *via* **calyces** into renal pelvis.
- The smooth muscle cells of both the afferent and efferent arterioles are swollen and contain **dark granules**. These cells are called **juxtoglomerular cells**. The granules are composed mainly of **inactive renin**. Renin converts **angiotensinogen** (present in the blood) into **angiotensin**. The latter increases blood pressure.
- The epithelial cells of the distal convoluted tubule that come in contact with the afferent and efferent arterioles are more dense than the other tubular cells and are collectively called the **macula densa**. The cells of macula densa may function as **chemoreceptors**; feeding information to the **juxtaglomerular cells**. The juxtaglomerular cells and macula densa together form the **juxtaglomerular apparatus or complex**.

FORMATION OF URINE

- The formation of urine is the result of the following process:
  - **Glomerular filtration or ultra filtration** of the blood plasma by the glomeruli.
  - **Selective reabsorption** by the tubules (useful substances such as sugar, salts, water are selectively reabsorbed from the glomerular filtrate to maintain the constant internal environment).
  - **Secretion by the tubules** (the tubules secrete certain substances like urea, uric acid, anions, etc., from the blood into the tubular lumen for excretion into the urine).

Glomerular filtration or ultrafiltration of blood

- The first step in urine formation is the filtration of blood, which is carried out by the glomerulus. 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 **ultrafiltration.**
- Glomerular filtration occurs because the pressure of the blood flowing in the glomerular capillaries is higher than the pressure of the filtrate in Bowman's capsule. **Glomerular filtration does not require the expenditure of energy by kidney cells.**
- 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 **glomerular filtration rate (GFR)** can activate the JG cells to release **renin** which can stimulate the glomerular blood flow and thereby the GFR back to normal.

Selective tubular reabsorption

- As much as 99 per cent of the material in the filtrate is reabsorbed, preventing the loss of water, nutrients, and ions from the body
- Reabsorption occurs within three regions of the nephron and in the collecting duct, but most of it takes place within the proximal convoluted tubule.
- Depending upon the types of molecules being reabsorbed, movements into and out of epithelial cells occur by **passive transport** or **active transport.**
- **Water and urea,** for example, are reabsorbed by passive transport, by which they move from regions of higher concentration to regions of lower concentration (water is reabsorbed by osmosis and urea by simple diffusion). Glucose and amino acids are reabsorbed by active transport. The reabsorption of Na^+ occurs by both passive and active transport.
- Water is reabsorbed in all parts of the tubules except the ascending limb of loop of Henle. **About 70-80% of electrolytes and water are reabsorbed in PCT.** This is called **obligatory water reabsorption,** *i.e.*, it occurs irrespective of hydration state of body.
- 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. The filtrate in PCT becomes **isotonic** to blood plasma.
- Reabsorption in Henle's loop **is minimum**, however, this plays a **significant role in maintaining high osmolarity of medullary interstitial fluid**.

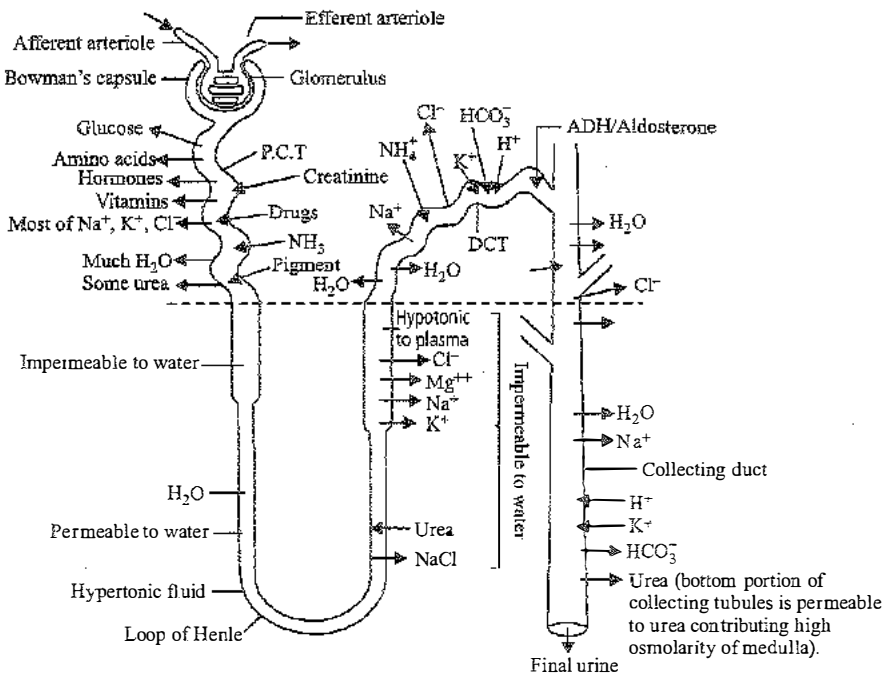

Fig.: Process of ultrafiltration, selective reabsorption and tubular secretion in mammalian nephron

- Descending limb of loop of Henle is **permeable** to **water** but is almost **impermeable** to **electrolytes**. This concentrates the filtrate as it moves down. The filtrate become **hypertonic** to blood plasma.
- Ascending limb of loop of Henle is impermeable to water but permeable to K^+, Cl^- and Na^+ and partially permeable to urea. The filtrate becomes **hypotonic** to blood plasma. Therefore as the concentrated filtrate pass **upward**, it gets **diluted** due to the passage of electrolytes to the medullary fluid.
- In **distal convoluted tubules**, there is active reabsorption of sodium ions from the filtrate under the influence of **aldosterone** (hormone secreted by cortex of adrenal glands). Water is reabsorbed here under the influence of **antidiuretic hormone (ADH)** secreted by posterior lobe of pituitary gland. This makes the filtrate **isotonic** to blood plasma.
- In **collecting duct**, further reabsorption of water takes place. Now the filtrate becomes more concentrated which makes the filtrate **hypertonic** to blood plasma. The entire duct is permeable to water. Thus a considerable amount of water is reabsorbed in the collecting duct under the influence of ADH. Sodium is reabsorbed in the collecting duct under the influence of **aldosterone**. The filtrate is now called **urine**. Thus, **urine is hypertonic to blood plasma.**

Tubular secretion

- Tubular secretion (clearance rate) refers to the addition of selected materials from the blood to the ultrafiltrate and thus increasing its volume. It occurs mainly by **active transport**. It takes place in **DCT** and **PCT**.
- The chemicals removed by tubular secretion include foreign bodies and ions and molecules that are toxic at elevated levels.
- After entering the proximal or distal convoluted tubules, these chemicals are mixed with the glomerular filtrate and are eliminated from body with the urine.

COUNTER-CURRENT MECHANISM

- Flow of filtrate in the limbs of Henle's loop is in **opposite direction**, and thus forms **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 helps in maintaining an increased 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 **vasa recta**. NaCl is returned to the interstitium by the ascending portion of **vasa recta**. Small amounts of urea enter the **thin segment** of the ascending limb of Henle's loop which is transported back to the interstitum by the collecting tubule.
- 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

- **Osmoregulation is the regulation of water and solute contents of the body fluids by the kidneys.** This is brought about by controlling the amount of **water** with the help of the hormone **ADH (vasopressin)** and of **sodium (salt)** with the help of the hormone **aldosterone** and proteins **renin** and **angiotensin.**

Antidiuretic hormone (ADH) or vasopressin

- **Excessive loss of fluid** from the body activates **osmoreceptors**, which stimulate the **hypothalamus** to release ADH or vasopressin form **neurohypophysis**. ADH facilitates water reabsorption from **latter parts of the tubule**, thereby preventing **diuresis**. An increase in body fluid volume switches off the **osmoreceptors** and **suppresses the ADH release** to complete the feedback.
- Alcohol inhibits the release of ADH and caffeine interferes with ADH action and sodium reabsorption thus, both these artificially dilute the urine.

- Under the **deficiency of ADH**, a disease called **diabetes insipidus** is caused in which the output of urine may reach 20–25 litre/day in place of normal 1.2–1.8 litre/day. Frequent urination and thirst are the symptoms of the disease.

Angiotensin-II

- As blood pressure decreases, the cells of the **juxtaglomerular apparatus** release the enzyme **renin** and activate the **renin-angiotensin-aldosterone pathway (RAAS).**
- Renin converts **angiotensinogen** into **angiotensin I. Angiotensin converting enzyme (ACE)** then converts angiotensin I into **angiotensin II,** a peptide hormone that is the active form. Angiotensin II has the following effects:
  - Raises blood pressure directly by constricting blood vessels (being powerful vasoconstrictor).
  - Increases the synthesis and release of **aldosterone.**
  - Aldosterone causes sodium and water reabsorption by the distal part of the tubules. This also leads to an increase in blood pressure and GFR.
  - May stimulate the posterior pituitary to release ADH.
- These changes assist in restoring extracellular fluid volume and in stabilizing blood pressure.

Atrial natriuretic peptide (ANP)

- ANP hormone produced by the atria of heart, increases sodium excretion and decreases blood pressure and blood volume. ANP is released into the blood stream in response to stretching of the atrial muscle cells by increased blood volume.
- ANP has the following physiological effects:
  - Increases **glomerular filtration** rate by dilating afferent arterioles.
  - Inhibits the collecting ducts from reabsorbing sodium, both directly and indirectly (by inhibiting aldosterone secretion).
- **Atrial natriuretic peptide** (ANP) works opposite to RAAS. When there is higher blood volume, ANP inhibits renin secretion by juxtaglomerular cells and ADH by pituitary gland. It inhibits NaCl reabsorption and concentration of urine.
- The renin-angiotensin system and ANP function anatogonisitically in the maintenance of fluid/electrolyte balance and blood pressure.

ROLE OF OTHER ORGANS IN EXCRETION

- Our **lungs** remove large amounts of CO_2 (18 litres/day) 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. 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. **Sebaceous glands** eliminate certain substances like sterols, hydrocarbons and waxes through sebum.

HAEMODIALYSIS/DIALYSIS/ARTIFICIAL KIDNEY

- When the kidneys are completely damaged and do not function, the patient often receives **haemodialysis** (treatment with an artificial kidney). Haemodialysis is the separation of certain substances from blood by use of a selectively permeable membrane. The pores in the membrane allow some substances to pass through, however, prevent others. The patient is connected to the machine by a tube attached to an artery often the **radial artery.** Blood from the artery is pumped into a tube that runs through the **dialyser.** The dialyzer is filled with dialysis fluid which contains the same quantities of electrolytes and nutrients as normal plasma but contains no waste products. The **cellophane tube** (a tube bounded by thin membrane) is kept in the dialysis fluid. The membrane of the cellophane tube is impermeable to blood cells and proteins but permeable to urea, uric acid, creatinine and mineral ions. So these wastes diffuse from the blood to the dialysis fluid across the cellophane membrane. Thus the blood is cleared of nitrogenous waste products without losing plasma proteins. Such a process of separating small solutes from macromolecular colloids with the help of a selectively permeable membrane is called **dialysis.** Now the blood is returned to the patient's body through a vein usually the **radial vein.** Haemodialysis saves and prolongs the life of many patients.

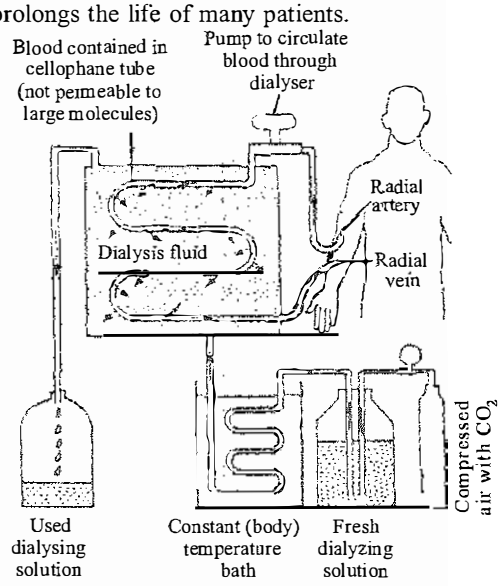

Fig.: A schematic diagram to show the working of an artificial kidney

DISORDERS OF THE EXCRETORY SYSTEM

- **Kidney stone** (Renal calculus) – formed by precipitation of uric acid or oxalate stone may pass into the ureter and bladder.
- **Haematuria** – passing of blood in urine.
- **Diabetes insipidus** – excessive urination, and drinking of fluids = polydipsia.
- **Pyelonephritis** – inflammation of renal pelvis, calyces and interstitial tissue.

- **Glomerulonephritis** – inflammation of glomeruli due to injury, bacterial toxins, drugs, etc.
- **Uraemia** – accumulation of urea in blood due to malfunctioning of kidney. It is highly harmful and may lead to **kidney/renal failure.**

CONCEPT MAP

Nitrogenous Excretion

Depending upon the excretory product, animals show the following types of nitrogenous excretion.

Ammonotelism

- Excretion of ammonia. It is readily soluble, excreted by diffusion.
- Bony fishes, aquatic amphibians, aquatic insects.

Ureotelism

- Excretion of urea. It is less toxic.
- Mammals, terrestrial amphibians and marine fishes.

Uricotelism

- Excretion of uric acid. Its crystals are non-toxic and almost insoluble in water and hence excreted as pellets with minimum loss of water.
- Reptiles, birds, land snails and insects.

Human Excretory System

Kidney

- Paired, bean-shaped, dark red in colour.
- Two distinct zones– **(i) renal cortex,** outer and darker; **(ii) renal medulla,** inner and lighter, it is made up of 8-10 conical **renal pyramids.**

Ureters

- Ureters are paired smooth muscle tubes.
- They open into urinary bladder and carry urine from the kidney.

Urinary bladder

- Urinary bladder is a chamber of smooth muscles.
- It collects urine.

Urethra

- Urethra is the duct that conveys urine from the bladder to be discharged to the outside of the body.
- Muscular urethral sphincters keep the urethra closed.

Regulation of kidney

- **Juxtaglomerular apparatus (JGA)** is special region formed by cellular modifications in the DCT and afferent arteriole supplying Bowman's capsule.
- JG cells contain granules of the proteolytic enzyme renin which activates renin – angiotensin – aldosterone pathway (RAAS) that leads to the activation of angiotensin - II.
- Angiotensin - II increases the synthesis and release of aldosterone.
- Aldosterone causes sodium and water reabsorption by the distal part of the tubules.
- Antidiuretic hormone (ADH) or vasopressin from posterior pituitary facilitates water reabsorption from DCT and CT.

Nephron

- Nephron is the structural and functional unit of kidney. Each nephron is made up of Bowman's capsule and tubules.

Bowman's capsule

- Bowman's capsule encloses a tuft of a glomerular capillaries.
- The epithelial cells called podocytes of Bowman's capsule form filtration slits through which ultrafiltration is carried out.
- Glomerular filtration occurs due to the pressure gradient between glomerular capillaries and Bowman's capsule.

Tubules

Proximal Convoluted Tubules (PCT)

- PCT is continuous with Bowman's capsule and is lined by cuboidal epithelial cells.
- About 70-80% of electrolytes and water are reabsorbed in PCT.
- It helps in maintaining pH and ionic balance.
- Filtrate is **isotonic.**

Henle's loop

- **Descending limb** is permeable to water and impermeable to electrolytes. Filtrate becomes **hypertonic.**
- **Ascending limb** is impermeable to water but permeable to K^+, Cl^- and Na^+. Filtrate becomes **hypotonic.**

Distal Convoluted Tubules (DCT)

- DCT absorbs sodium chloride and other inorganic salts while retaining water.

Collecting Tubule (CT)

- The entire duct is permeable to water is reabsorbed.
- It drains into the renal pelvis which leads to the ureter.