Definitions of terms:

Term	*Definition*	*Examples*
Excretion	Expulsion from the body of the waste products of metabolism	CO_2, urea, uric acid, ammonia, excess water, excess mineral salts, bile pigments, oxygen (plants) etc.
Homeostasis	Maintenance by the body of internal environment within narrow range of conditions, regardless of the conditions in the external environment.	Concentration of blood glucose, core body temperature, blood PH (acid-base balance), concentration of oxygen and Carbon dioxide.
Osmoregulation	Control of water and salt balance so that the concentration of dissolved substances in the body fluids remains constant.	Osmotic conditions, especially concentration of various ions e.g. Na^{2+}, K^{+}, Cl^{-} and water content.
Secretion	The production of substances useful to the body by cells.	Release of hormones, digestive juices
Egestion	The removal from the body of undigested food and other substances, which have never been involved in	Elimination of faeces from the gut (defaecation) and undigested food

	the metabolic activities of cells.	from the food vacuole of amoeba

Importance of excretion

1. Enables removal of unwanted by-products of metabolic pathways to prevent unbalancing the chemical equilibria of reactions. This leads to chemical reactions proceeding in the desired direction.
2. Removes toxic wastes that if accumulated would affect the metabolic activities of organisms and would damage the cells eg. may act as enzyme inhibitors.

Importance of osmoregulation/osmotic control

1. It regulates ionic concentration of body fluids to facilitate efficiency of cell activities e.g nervous coordination, protein synthesis, hormone production, muscle contraction, enzyme activity.
2. It regulates the water content of body fluids.
3. Enables regulation of ions that have a major influence on pH of the body fluids eg. hydrogen ions and hydrogen carbonate ions .
4. Enables removal of excess nutrients that are taken in that if all allowed to accumulate would interfere with cell activities.
5. Gives increased environmental activities.

The different environments and their problems

Environment	*Salinity and problems faced by organisms*
Sea water	The solute concentration is extremely variable, but average salinity is 34.5 $^0/00$ (parts per thousand). *Problems*: **(1)** osmotic water loss **(2)** salt gain by diffusion
Fresh water	Water freshness varies but any water with salinity of less than 0.5 $^0/00$ may be considered as fresh. *Problems*: **(1)** osmotic water gain **(2)** salt loss by diffusion

Brackish water	This is water with salinity between 0.5 and 30 $^0/00$ (between fresh water and sea water). It includes estuarine water and intertidal zones. ***Problems***: variable
Terrestrial environment	This land environment. ***Problems***: Water loss by evaporation

EXCRETION IN PLANTS

The following account for the absence of complex/elaborate excretory systems in plants as those in animals:

(1) Toxic wastes do not accumulate because they are utilized by the plant e.g. carbon dioxide and water are raw materials for photosynthesis while oxygen participates in respiration.

(2) Extra gaseous wastes are removed from plant bodies by simple diffusion through the stomata and lenticels.

(3) Most of the organic waste substances formed in plants are not harmful and can be stored in the plant tissues which are removed periodically e.g. leaves and bark.

(4) Some plants store other wastes such as resins in organs that later fall off e.g. leaves.

(5) Excess water and dissolved gases are removed by transpiration through the stomata.

(6) Some plants remove waste products by exudation. e.g. gums, resins, latex and rubber.

(7) In some plants, guttation occurs i.e. excess water with dissolved salts ooze out through hydathodes at leaf surfaces.

(8) Organic acids which would be harmful to plants often combine with excess cations and precipitate as insoluble crystals which can be safely stored in plant cells. E.g. excess Ca^{2+} combines with oxalic and pectic acids to form the non-toxic calcium oxalate and calcium pectate.

(9) Plants synthesize all their organic requirements according to demand, leaving no excess of protein hence very little excretion of nitrogenous waste substances occurs.

(10) The rate and amount of catabolism is much slower and much less than that of animals of similar weight, and as a result the waste products accumulate more slowly.

Excretory products in plants

- Carbon dioxide, water and oxygen from respiration and photosynthesis respectively.
- Anthocyanins stored in petals, leaves, fruits, barks.
- Tannins deposited in dead tree tissues like wood and barks.
- Calcium oxalates, calcium carbonates and Latex (rubber).
- Alkaloids like quinine, cannabis, cocaine, caffeine, morphine etc.

OSMOREGULATION IN PLANTS:

Depending on how much water is available in their natural environment, plants can be categorized into the following groups:

a) **Hydrophytes:** plants living completely or partially submerged in fresh water. They have water in plenty and the2efore there is no problem of obtaining it e.g. water lilies, water hyacinth, water lettuce, etc.

b) Mesophytes: plants inhabiting normal well-watered soils.

c) **Xerophytes:** plants inhabiting dry areas e.g. desert.

d) **Halophytes:** plants inhabiting areas of high salinity e.g. estuaries, salt marshes. The Australian saltbush *(Atriplex spongiosa)* excretes excess salts by actively depositing the salt in special epidermal bladder cells, which eventually fall off or burst.

Adaptations of xerophytes for surviving unfavourable water balance (more loss than uptake from soil).

Structural adaptations	*Physiological adaptations*
• Possession of extremely deep roots so as to obtain water from deep down below the water table e.g. acacia and Oleander. • Shallow root system for absorbing moisture even after slight showering e.g. cactus • Possession of fleshy succulent stems and leaves that store water in large parenchyma cells e.g. bryophylum and cactus. • Reduction in stomata number to reduce on transpiration. • Possession of sunken stomata. • Hairy leaf surface to trap air and reduce on transpiration. • Rolling / curling / folding of leaves to reduce transpiration e.g. marram grass (*Ammophila)* • Hairy epidermis for reflecting solar radiation and trapping humid air next to leaf surface and reduce transpiration. • Possession of thick cuticle, which is impermeable to water e.g. Prickly pear *(Opuntia).*	• Reversal of the normal stomatal rhythm in some plants e.g. opening stomata at night and closing during day time so as to reduce on water evaporation. • Increased levels of abscisic acid, which induces stomatal closure so as to reduce water loss. • Possession of tissues tolerant to desiccation e.g. low solute potential of cytoplasm and production of resistant enzymes. • Leaf fall in deciduous trees so as to cut down transpiration • Survival of drought as seeds or spores that are highly dehydrated and protected within a hard coat

• Reduction of surface area over which transpiration has to occur by having small leaves.	

Note: Other than unfavorable water balance, terrestrial plants are faced with other challenges that result from environmental variables like temperature, ionic concentrations (nutrients), water/ moisture, light, wind/air currents. Accordingly, plants have developed mechanisms that enable successful reproduction, gaseous exchange, nutrition, propagation (dispersal), support, loss of excess water and salts etc.

EXCRETION AND OSMOREGULATION IN ANIMALS

Excretory and homeostatic organs in various animals

Animal	Excretory and homeostatic structures
Platyhelminthes e.g. planaria, liverfluke, tapeworm	Flame cells (solenocytes)
Annelids	Nephridia
Insects, millipedes	Malpighian tubules
Arachnids	Book lungs
Fish	Gills and kidneys
Amphibians	Lungs, kidneys, liver and gills
Birds and Reptiles	Lungs, kidneys and liver
Mammals	Lungs, kidneys, liver and skin
Unicellular organisms	Cell surface membrane
Crustaceans	Antennal glands

Roundworm	Excretory cell

Summary of the relationship between excretory products and habitats of some animal groups

Excretory product	Nature of waste	Habitat	Animals
Urea	Nitrogenous waste	Terrestrial	Mammal
Ammonia		Aquatic	Fresh water bony fish and protozoa
Uric acid		Terrestrial	Birds and Terrestrial insects
Guanine		Terrestrial	Spiders
Trimethylamine oxide		Aquatic	Marine bony fish
Creatine		Aquatic	Some marine fish
Carbondioxide	Non Nitrogenous waste	Terrestrial	Mammals, birds and protozoa
Excess water and mineral salts		Terrestrial	Mammals, birds, reptiles
Bile salts		Terrestrial	Mammals

Animals are placed in **two main** categories with regard to their osmoregulation:

a) Osmotic conformers (Osmo conformers**):** Animals whose Osmotic concentration of body fluids fluctuates according to that of the environment. E.g. fresh water lower animals.

Euryhaline animals: are those that tolerate wide variations in salt concentration of water. They usually live in brackish water.

Stenohaline animals: are those with narrow tolerance to environmental variation of salt concentration in water e.g. Maia, Arenicola.

(i) **Euryhaline osmotic conformers (tissue tolerant species):** species that tolerate wide external and therefore internal osmotic fluctuations.

(ii) **Stenohaline osmotic conformers:** species that tolerate only limited external and therefore internal osmotic fluctuations. Such organisms' habitats are limited to environments of constant concentration e.g. the hagfish is strictly marine and stenohaline, its body fluids are iso-osmotic (have same concentrations as sea water)

b) Osmotic regulators (Osmo regulators): Animals that maintain or regulate within narrow limits the internal body osmolarity despite environmental changes. E.g. Most marine vertebrates, higher fresh water animals (they remain hyperosmotic)

(i) **Euryhaline Osmotic regulators:** species that maintain within narrow limits the internal body osmolarity over a wide range of environmental changes. E.g. migratory fish like eel *(Anguilla bengalensis)* which migrate from fresh wter to sea water, Salmon (*Salmo fario)* which migrate from sea to fresh water for spawning,

(ii) **Stenohaline osmotic conformers:** species that regulate the internal body osmolarity over a narrow range of external environmental changes.

FACTORS THAT INFLUENCE EXCRETION OF NITROGENOUS WASTES

<u>Note:</u> nitrogenous wastes are produced by the breakdown of proteins, nucleic acids and excess amino acids

- **<u>Ammonia</u>** is highly toxic hence its excretion requires a lot of water for dilution. Being highly soluble and readily difusable, it is excreted by fresh water bony fish, protozoa, porifera, Cnidarians which live in abundance of water. Such animals are said to be ***ammoniotelic***.
- **<u>Urea</u>** is relatively toxic and very soluble hence can be easily diluted before elimination, so it is excreted by some terrestrial animals like

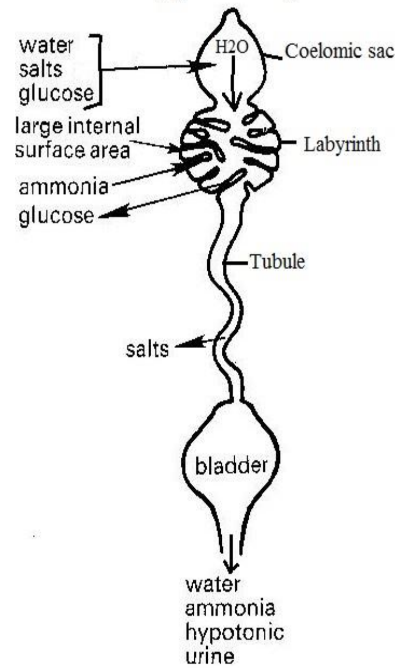
mammals and marine ones whose body fluids are hypotonic to seawater. Animals that excrete mainly urea are said to be ***ureotelic***

- **Uric acid** is almost non-toxic and highly insoluble, requiring very little water for its elimination so it is excreted by animals living in very arid conditions e.g. birds, insects and reptiles, which live in water shortage. These animals are said to be ***uricotelic***
- **Trimethylamine oxide** is soluble but non-toxic, requiring relatively less water for its elimination, so is excreted by marine bony fishes suffering from water shortage.
- **Guanine** is less soluble than uric acid and requires no water for its elimination, hence is excreted by terrestrial spiders that live in scarcity of water.

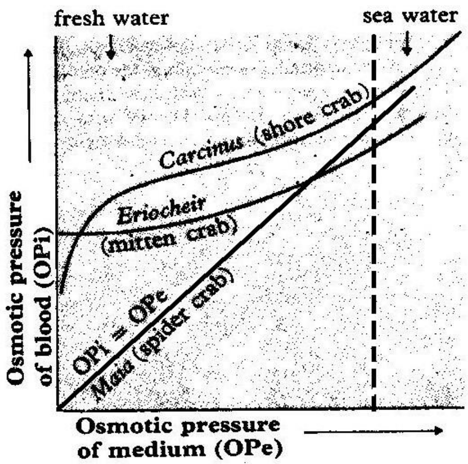
OSMOREGULATION IN SEA WATER

Animals first evolved in the sea, and most marine invertebrates are osmoconfromers.

Shore crab (Carcinus maenas)	***Mitten crab (Eriocheir)***	*Fig. 14.11* **B** *Roberts MBV: Biology a functional approach, 4th ed. P. 222* **or** Colin Clegg (1981) p.195
-**Antennal glands** at the base of the antennae excrete excess water and nitrogenous wastes. - Antennal glands are incapable of holding back salts (they eliminate salts and water alike), resulting	What happens in the shore crab also happens in the ***Mitten crab (Eriocheir)*** except that here the inward secretion of salts is sufficient enough to enable the animal to flourish in fresh water.	

into production of urine isotonic with blood. -**Gills** absorb salts from the surrounding medium and secrete them into blood against a concentration gradient so as to maintain an internal osmotic pressure (opi) higher than external osmotic pressure (ope).	*Crayfish* Here antennal glands are capable of eliminating excess water but reabsorb salts, resulting into production of urine hypotonic with blood and an internal osmotic pressure (opi) higher than external osmotic pressure (ope). Reabsorption of salts occurs as the urine flows along the coiled tubule	**Antennary gland of crayfish** 

The graph below shows changes in internal osmotic pressure of blood (opi) with external osmotic pressure in the surrounding medium (ope) in marine invertebrates.



[Figure 14.9 Roberts MBV: Biology a functional approach, 4th ed. Page 220 **or** *Colin Clegg (1981), Biology for schools and colleges, page 186]*

Explanation for the variations in internal pressure

In the body fluids of marine invertebrates, the concentrations of the various ions are usually different from those in the surrounding sea water.

Carcinus **Variation:** Opi of carcinus is low in fresh water *(fw)*, increases rapidly with slight increase in Ope, then increases slowly thereafter with increase of external concentration. Osmoregulation breaks down and opi increases rapidly with transition into highly concentrated external medium / sea water *(sw)*.

Explanation: Marine Crustacea experiencing reduced salinities are subjected to osmotic influx of water from the surrounding medium. In *Carcinus maenas,* urine production increases with progressive dilution of the medium to prevent increase in internal volume and hydrostatic pressure which would rise to a lethal level. E.g. transfer of crabs from 100 % to 50% sea water results in increased urine production within 5 minutes of dilution of the medium. ***Likely habitat*:** estuarine / brackish water (neither fresh water nor sea water)

Eriocheir: **Variation:** Opi of Eriocheir is relatively constant in ***fw,*** slightly increases with salinity, save with too much concentration.

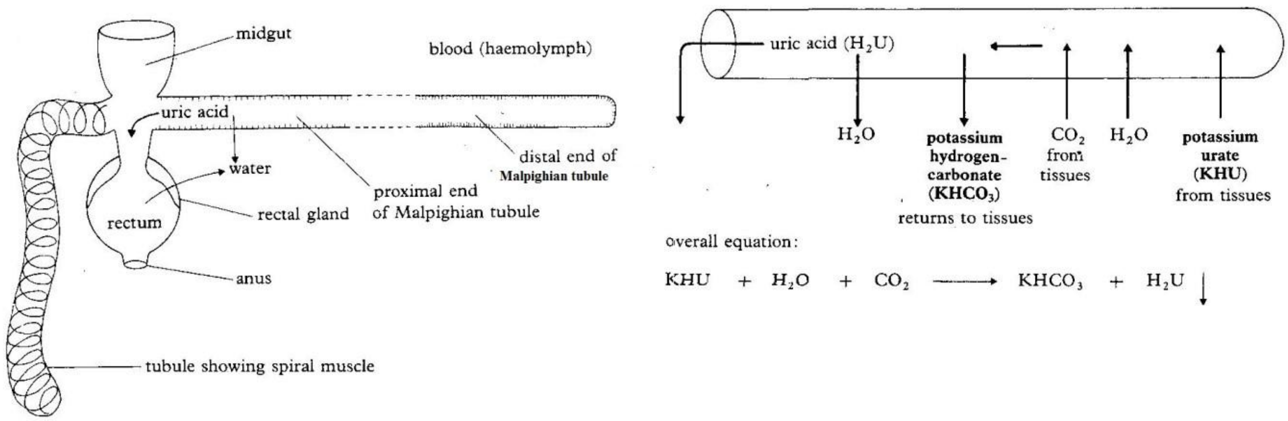
Explanation: Eriocheir has osmoregulatory abilities even with much dilution except in highly concentrated external medium. ***Likely habitat*:** fresh and brackish water.

Maia: **variation**: A change in ope results in a similar change in opi of blood, which is an indicator that Maia cannot osmoregulate at all. Likely habitats include fresh water, sea water and brackish water.

Description of excretion and osmoregulation in a terrestrial insect

Osmoregulation	Excretion
A terrestrial insect is liable to water loss, which is minimized by: -An impermeable cuticular covering coated with wax -Production of non-toxic and almost insoluble waste product, uric acid which requires little water for its elimination being almost no toxic. -Reabsorption of water by malpighian tubules and rectal glands, resulting in very concentrated urine. -Laying cleidoic eggs such that water loss is prevented during embryo development by a relatively impermeable shell. -Possession of valve-like structures and hair in the spiracles to reduce on water loss	-The peristaltic movements of **malpighian tubules** stir up the coelomic fluid (blood) enabling epithelial cells to absorb nitrogenous wastes like **sodium and potassium urate**. -Within the tubule cells, Water and CO2 react with potassium urate to form potassium hydrogen carbonate and **uric acid.** -Potassium hydrogen carbonate is absorbed back into blood while uric acid is deposited in the tubule lumen. -As the uric acid moves from distal to proximal end of the malpighian tubule, water is vigorously back into blood while solid crystals of uric acid are deposited in the lumen and later rectum to be passed out.

Draw figures 14.14 **A** *and* **B** *Roberts MBV: Biology a functional approach, 4th ed. Page 226*



Description of osmoregulation in fresh water protozoa e.g. amoeba or paramecium

- Contractile vacuoles carry out osmoregulation in fresh water protozoa.

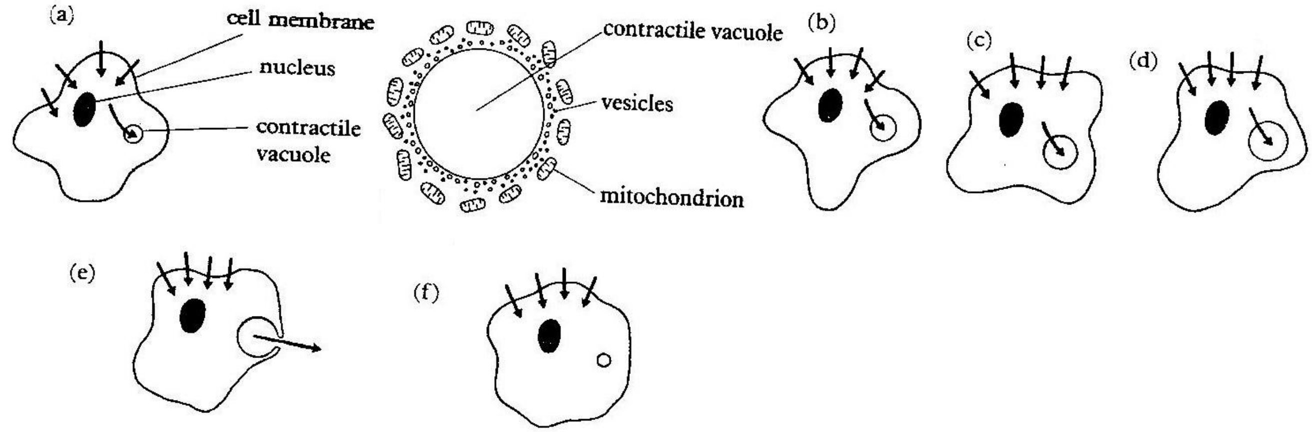
-Since the cell contents are hypertonic to the surrounding, and the cell membrane is partially permeable, there is constant influx of water into the cytoplasm by osmosis.

-Small vesicles in the cytoplasm fill up with fluid from the cytoplasm and pump salts back into the cytoplasm by active transport, using energy provided by ATP from the numerous mitochondria surrounding the vesicles.

-The vesicles, now containing water fuse with the contractile vacuole which gradually expands.

-The impermeability of the vacuolar membrane to water prevents osmotic out flow of water.

-On reaching critical size, the contractile vacuole fuses with the cell surface membrane, contracts suddenly and releases its water. ***Roberts MBV:*** *Biology a functional approach, 4th ed. Page 221, also read* ***Taylor DJ*** *etal: Biological science pg676-678*



Attempt this question:

Two species of amoeba were transferred from their natural habitats to different dilutions of sea water, and each individual was given time to adjust to its new environment. The table below shows data about the rate of vacuolar contractions with varying solute concentrations. **[Susan & Glenn Toole (1991), 2nd edition, pg.527]**

	Number of vacuolar contractions per hour	
Sea water concentration in % (normal sea water = 100%)	***Species A***	***Species B***
5	82	20
10	74	63
15	65	64
20	58	56
30	34	31
40	14	13
50	0	6
60	0	0

(a) Plot the results of the experiment as a graph

(b) Describe the functioning of the contractile vacuole.

(c) Explain by reference to the data, the difference in vacuolar contraction in the two species of Amoeba when placed in the higher concentrations of seawater.

(d) What information may be deduced about the natural habitats of the two species from the rates of vacuolar contractions?

OSMOREGULATION AND EXCRETION IN FRESH WATER BONY FISH (TELEOSTS), MARINE TELEOSTS, MARINE ELASMOBRANCHS AND MIGRATORY FISHES.

Fresh water teleosts (bony fish) *e.g. tilapia, stickle back, trout, etc* (Opi > Ope)	Marine teleosts *e.g. cod, mackerel* (Opi < Ope)	Marine elasmobranchs (cartilaginous fish) *e.g. dog fish, sharks, rays*	Migratory fishes *e.g. salmon and eels*
The excretory and osmoregulatory organs are the gills and kidneys. Internal body fluids being hypertonic to the surrounding water, there is: i) Osmotic influx of water across the gills, lining of mouth and pharynx. ii) Efflux of solutes (ions and ammonia) into water by diffusion. -Problem (i) is addressed by not	The excretory and osmoregulatory organs in marine teleosts are the gills and kidneys. Internal body fluids being hypotonic to the surrounding water, there is osmotic extraction of water from the body leading to dehydration of the tissues, a situation described as '**physiological drought'**. This is overcome by: -Drinking large amounts of seawater and having a kidney with low filtration	Their tissue fluid is slightly hypertonic to seawater, causing slight influx of water, which is readily expelled by the kidneys. • Hypertonic tissue fluid results from urea retention, which is facilitated by: -Impermeability of gills to urea. -Urea reabsorption from the nephron	These are fish that keep moving from one extreme osmotic environment (sea) to another (fresh water) during lifetime. This is achieved through adjustments like: -Changes in kidney

drinking water and production of large volume of dilute (hypotonic) urine. -Problem (ii) is addressed by reabsorbing ions across the nephron tubules, from the glomerular filtrate back into blood. The high glomerular filtration rate is enabled by numerous large glomeruli in the kidneys. In addition, there is active uptake of salts from water by chloride secretory cells in the gills.	rate enabled by few small sized glomeruli. - The ions Ca^{2+}, Mg^{2+} and $SO4^{2-}$ (divalent ions) in the seawater a marine fish drinks are eliminated through the anus while K^+, Na^+, and Cl^- (monovalent ions) are absorbed into blood and are actively transported out of blood across the gills, reverse to the direction in fresh water fish.. The divalent ions that enter blood are secreted into the nephron tubules and excreted in urine. -Excreting trimethylamine oxide, which is soluble but non-toxic requiring little water for elimination	tubules, maintaining its concentration at over 100 times higher than that in mammals. -Tolerance of tissues and enzymes to high urea concentration. -The highly toxic urea is detoxified by TriMethylamine Oxide (TMAO)	filtration rate. -Reversal of the direction in which the chloride secretory cells transfer salt i.e. in fresh water they take in salt and may move them outwards in seawater.

OSMOREGULATION IN TERRESTRIAL VERTEBRATES:

Terrestrial animals are liable to water loss to the atmosphere and must overcome this to be able to survive.

How terrestrial animals gain water	***How terrestrial animals lose water***
(1) By drinking directly **(2)** taken along with food **(3)** from metabolic by-product e.g. respiratory product	**(1)** In urine **(2)** Faeces **(3)** Sweating **(4)** Evaporation from lungs **(5)** External secretions e.g. tears

Physiological adaptations against water loss	Structural / morphological adaptation	Behaviuoral adaptations
• Reduction in glomerular filtration rate e.g. the desert frog, *chiroleptes* has few and smaller glomeruli than its relatives living in moist temperate regions. • Production of non-toxic nitrogenous waste e.g. the insoluble uric acid (reptiles, birds and insects) and the relatively less toxic urea (mammals and amphibians) that require little water for removal. • Extensive water reabsorption from glomerular filtrate	Possession of waterproof integuments, which include the keratinous scales of reptiles, cornified epithelium of mammals and the waxy cuticle of insects.	• Change of habitat depending on the weather conditions. • Some animals e.g. African lungfish **aestivate.** **Aestivation** is seasonal response by animals to drought or excessive heat during which they become dormant, body temperature and metabolic rate fall to the

(mammals and birds) and rectum (insects). E.g. kangaroo rat has an extra long loop of Henle enabling it to produce hypertonic urine. • Use of metabolic water from fat through respiration. This explains why desert animals like kangaroo rat (*Dipodomys*) mostly metabolise fat, which yields more water (1 gm yields 1.1gm of water) on oxidation than carbohydrate (1 gm yields 0.6 gm of water) and protein (1 gm yields 0.3 gm of water). *Dipodomys* may spend its entire life without drinking water. • Possession of tissues tolerant to dehydration. E.g. a Camel can survive for a week without drinking water, but can gulp 80 litres in 10 minutes. • Ability to sweat at abnormally higher temperature e.g. a camel begins sweating at 41^0C from its normal body temperature of 34^0C • Ability to reduce the need for nitrogenous excretion e.g. a camel secretes urea into the lumen of alimentary canal		minimum required for maintaining the vital activities of the body. It is an adaptation for temperature regulation as well as water conservation. During aestivation, the African lungfish burrows down and encases in a cocoon of hard mud lined with mucus

where bacteria convert it to protein, which is then utilized as food.		

OSMOREGULATION IN AMPHIBIANS AND REPTILES

Amphibians being the first terrestrial vertebrates, their kidney is identical to that of fresh water fishes.

(1) Body fluids of amphibian are hypertonic to fresh water resulting in

(i) osmotic influx of water which is readily lost by the kidneys expelling large volumes of urine.

(ii) Salt loss by diffusion which are replaced actively across the skin.

(2) During aestivation, amphibia instead of the usual ammonia form urea, which is less toxic and therefore can be retained until water is available for excretion.

(3) Amphibia never drink water hence water gain is osmotic via the skin or in food consumed.

Reptiles on the other hand live in diverse habitats:

- Those living mainly in fresh water e.g. some crocodiles possess kidneys like those of fresh water fishes and amphibians.
- Marine reptiles e.g. some crocodiles, turtles, sea snakes and some lizards e.g. iguana possess kidneys similar to those of their fresh water relatives. However, since these kidneys reabsorb salt, marine reptiles cannot excrete a great deal of salt in their urine. Instead, they eliminate excess salt by means of **salt secreting glands** located near the nose or the eye, hence 'the turtle shedding tears. Terrestrial reptiles reabsorb much of the salt and water in the nephron tubules of kidneys, helping somewhat to conserve blood volume in dry environments. Like amphibians and fishes, though, they cannot produce urine that is more concentrated than the blood plasma.

Reptiles minimize water loss by

(1) Laying cleidoic eggs with waterproof embryonic membranes and supporting shell.

(2) Possession of waterproof keratinized skin and scales.

(3) Possession of kidneys with reduced glomeruli hence low rate of glomerular filtration.

(4) Production of insoluble uric acid which is almost non-toxic and therefore requires little water for elimination.

(5) Absorption of water by the cloaca from faeces and nitrogenous wastes.

EXCRETION AND OSMOREGULATION IN MAMMALS AND BIRDS

Mammals and birds are the only vertebrates with loops of Henle, enabling their kidneys to produce urine that has a higher osmotic concentration than their body fluids. This enables them to excrete waste products in a small volume of water, so that more water can be retained in the body. E.g. Human kidneys can produce urine that is 4.2 times as concentrated as their blood plasma, the camel, gerbil and pocket mouse can excrete urine 8, 14 and 22 times as concentrated as their blood plasma, respectively.

Birds, however, have relatively few or no nephrons with long loops, so they cannot produce urine that is as concentrated as that of mammals. Marine birds e.g. penguins, gulls and cormorants drink salt water and then excrete the excess salt from **salt secreting nasal glands** near the eyes, giving an impression that these birds have runny noses.

Mammalian excretory organs include the lungs, skin, liver and kidneys, which are the main excretory organs.

AN OUTLINE OF THE FUNCTIONS OF THE KIDNEYS

(1) Excretion of metabolic waste products such as urea, excess water, uric acid, ammonia, creatine etc

(2) Regulation of water and solute content of blood (osmoregulation)

(3) Maintenance of pH of body fluids at 7.4 (acid-base balance by removing or neutralizing excess acidity / alkalinity.

(4) Regulation of blood levels of ions such as Na^+, K^+, Cl^-, Ca^{2+}

(5) Secretion of the hormone **erythropoietin**, which stimulates red blood cell production for transporting oxygen.

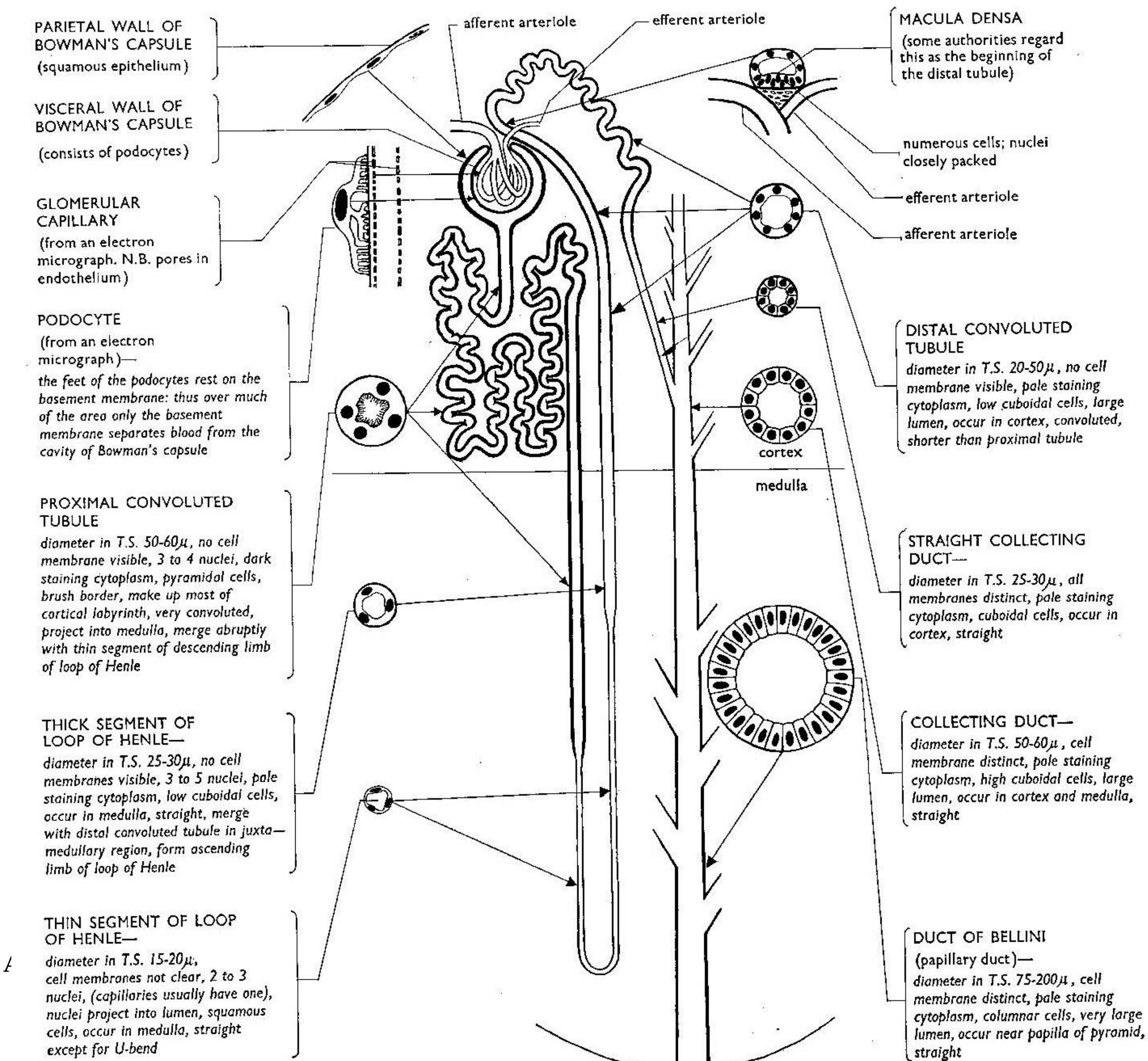
(6) Retention of important nutrients such as glucose and amino acids through reabsorption from glomerular filtrate into blood.

Structure of mammalian kidney *(Figure 14.1* **A, B** ***and*** **C** ***Roberts MBV****: Biology a functional approach, 4th ed. Page 211 & fig. 51.3 Raven*

GHS S6

EXCRETION AND OSMOREGULATION

Peter .H and Johnson George .B: biology, 4th ed. Page 1148) **or** *Freeman W.H. & B. Bracegirdle (1984), Atlas of histology, P77*



A nephron consists of **(1)** Bowman's capsule **(2)** glomerulus **(3)** proximal tubule **(4)** loop of Henle **(5)** distal tubule

Homeostatic function	How it occurs
Maintenance of PH of body fluids at 7.4 (acidbase balance) to avoid denaturing of enzymes and other proteins, which would result into death	The body produces more acids than bases, causing the blood pH usually to lower (become acidic) from the normal pH of 7.4 due to high concentration of H^+ ions that result from metabolic processes. In the cells of **distal convoluted tubules**, the carbon dioxide from aerobic respiration, catalysed by carbonic anhydrase enzyme reacts with water to form carbonic acid, which dissociates into H^+ and HCO_3^- ions. The H^+ ions are pumped into the lumen where they are buffered by **hydrogen phosphate** (HPO_4^{2-}) as it takes up H^+ ions to form sodium dihydrogen phosphate (NaH_2PO_4), which is excreted in urine while the HCO_3^- ions are absorbed and retained in blood. Exceptional lowering of PH causes the cells lining the **distal tubule** to **deaminate** glutamine amino acid to form ammonia, which on combining with H^+ ions forms ammonium ions, which are excreted. Blood pH rises (becomes less acidic) due to absorption of HCO_3^- that result from dissociation of carbonic acid. In order to control pH, the HCO_3^- are excreted while H^+ ions are retained. ***NOTE:*** 1. *Within plasma, hydrogen carbonate (*HCO_3^-*),* *protein and hydrogen phosphate (*HPO_4^{2-}*)act as PH buffers by temporarily taking up any excess* H^+ *ions and at the same time keeping the PH constant.* 2. *The body maintains constant PH by (i) lungs expelling* CO_2*, which would accumulate and react with water to form carbonic acid (ii) the buffering mechanism*

	involving plasma protein in blood (iii) the kidneys expelling H^+ and retaining HCO_3^- Therefore pH (acid-base balance) is controlled by the lungs, blood and kidneys.

Homeostatic function	**How it occurs**
Regulation of water and solute content of blood (Osmotic regulation)	Increased concentration of solutes in blood (little water relative to salts) is detected by osmoreceptors in the hypothalamus which stimulate the posterior pituitary gland to secrete antidiuretic hormone (ADH)/vasopressin and at the same time triggering the sensation of thirst resulting in drinking of water. ADH increases the permeability of distal convoluted tubule and collecting duct to water, allowing the osmotic flow of water from the glomerular filtrate into the cortex and medulla hence reducing the osmotic pressure of blood but increasing that of urine. ADH also increases the permeability of the collecting duct to urea, enabling its diffusion from urine into the medulla tissue fluid where it increases the osmotic pressure resulting in osmotic extraction of water from the descending limb. Low solute concentration in blood (too much water relative to salts) inhibits ADH release, tubule walls and collecting duct become impermeable to water, less water is reabsorbed from glomerular filtrate into blood and large volume of dilute urine is passed out hence raising the osmotic pressure of blood. ***NOTE:*** 1. *Diuresis is the production of copious dilute urine, antidiuresis being the opposite.* 2. *Insufficient production of ADH leads to a condition known as diabetes inspidus, characterised by frequent copious urination.*

Regulation of blood levels of ions such as Na^+, K^+, Cl^-, Ca^{2+}	The concentration of any particular type of ion in blood and tissue fluid is regulated in three ways: i) Hormones control the uptake of the ions into bloodstream from the gut. ii) Hormones control the removal of ions from the blood by kidneys and elimination in the urine. iii) Hormones control the release of ions into the bloodstream from reservoirs like organs / tissues e.g. bones in which they are at high concentrations. **Regulation of calcium ions (Ca^{2+}):** Low blood calcium level stimulates the **parathyroid glands** (surrounding the thyroid gland) to secrete the **parathormone (parathyroid) hormone** which increases the calcium level and decreases the hydrogen phosphate (HPO_4^{2-}) level through promoting: -Bone breakdown by osteoclasts -Calcium retention by kidneys -Excretion of hydrogen phosphate (HPO_4^{2-}) in urine by kidneys -Activation of vitamin D, which in turn stimulates the absorption of calcium from the gut. High blood calcium level stimulates the **thyroid gland** to secrete **calcitonin hormone**, which increases bone buildup by osteoblasts so as to reduce calcium level. ***NOTE:*** 1. *Calcium plays an important role in nervous conduction, muscle contraction and blood clotting.*

	2. *Deficiency of parathyroid hormone results in* *<u>tetany</u> (shaking of body due to continuous muscle contraction caused by increased excitability of the nerves, which fire spontaneously and without rest)* **<u>Regulation of sodium ions (Na^+):</u>** A decrease in blood sodium leads to decreased blood volume and reduced blood pressure because less water is drawn into blood by osmosis. *Low levels of sodium in blood are detected by the hypothalamus, which stimulates the anterior pituitary gland to secrete the hormone adrenocorticotropic hormone (ACTH), which stimulates* the juxtaglomerular complex (situated between the distal convoluted tubule and afferent arteriole) to release the enzyme **<u>Renin</u>** (don't confuse it with the digestive enzyme **rennin**). Renin catalyses the conversion of **<u>angiotensinogen,</u>** a plasma protein into a hormone **<u>angiotensin</u>** which stimulates the adrenal cortex to secrete the **<u>hormone Aldosterone.</u>** Aldosterone has the following effects: -Stimulates the **<u>active uptake of sodium ions</u>** from the glomerular filtrate into the plasma of capillaries surrounding the nephron. This induces osmotic uptake of water into blood thus increasing both the blood volume and sodium level back to the norm, accompanied by loss of potassium ions. -Stimulates sodium absorption in the gut and decreases loss of sodium in sweat so as to raise sodium levels to cause an osmotic inflow of water thus increasing the blood volume and pressure -

	Stimulates the brain to increase the sensation of thirst. Increased sodium level in blood causes increased blood volume and pressure, less production of renin and angiotensin resulting in less secretion of aldosterone by the adrenal cortex hence less uptake of sodium from the glomerular filtrate occurs, restoring sodium level to the norm.

	3. *Increase in blood osmotic pressure (BOP) results from ingestion of little water, much sweating, ingestion of large amount of salt while a decrease in BOP may be due to little sweating, ingestion of large volume of water and low salt intake.*
Homeostatic function	**How it occurs**
Regulation of water and solute content of blood (Osmotic regulation)	Increased concentration of solutes in blood (little water relative to salts) is detected by osmoreceptors in the hypothalamus which stimulate the posterior pituitary gland to secrete antidiuretic hormone (ADH)/vasopressin and at the same time triggering the sensation of thirst resulting in drinking of water. ADH increases the permeability of distal convoluted tubule and collecting duct to water, allowing the osmotic flow of water from the glomerular filtrate into the cortex and medulla hence reducing the osmotic pressure of blood but increasing that of urine. ADH also increases the permeability of the collecting duct to urea, enabling its diffusion from urine into the medulla tissue fluid where it increases the osmotic pressure resulting in osmotic extraction of water from the descending limb. Low solute concentration in blood (too much water relative to salts) inhibits ADH release, tubule walls and collecting duct become impermeable to water, less water is reabsorbed from glomerular filtrate into blood and large volume of dilute urine is passed out hence raising the osmotic pressure of blood. ***NOTE:***

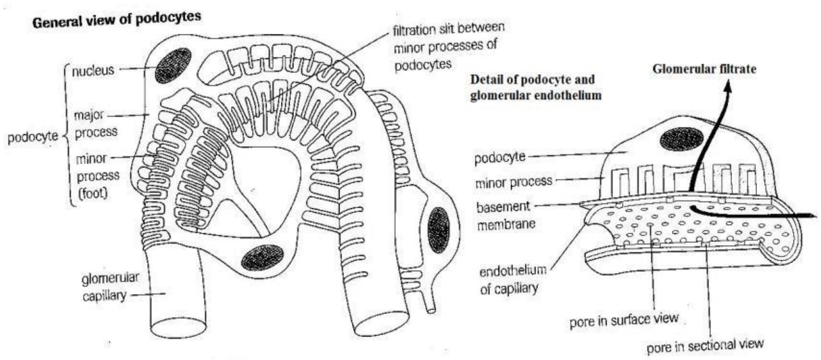
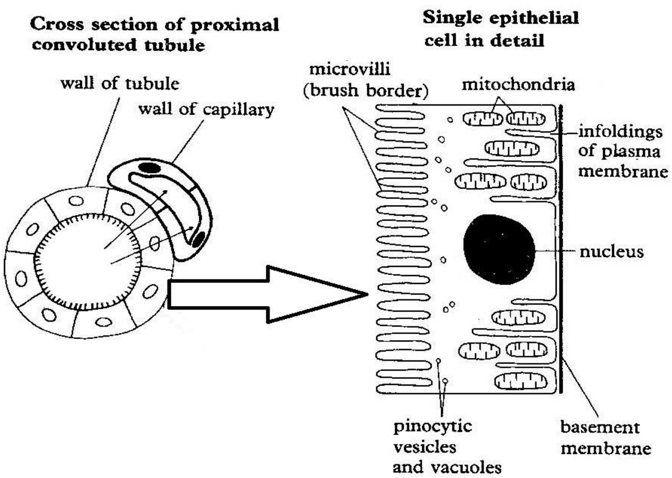
	4. *Diuresis is the production of copious dilute urine, antidiuresis being the opposite.* 5. *Insufficient production of ADH leads to a condition known as diabetes inspidus, characterised by frequent copious urination.* 6. *Increase in blood osmotic pressure (BOP) results from ingestion of little water, much sweating, ingestion of large amount of salt while a decrease in BOP may be due to little sweating, ingestion of large volume of water and low salt intake.*

EXCRETORY FUNCTION OF THE KIDNEY:

The nephron accomplishes its excretory function by these separate processes which occur at the different regions of the:

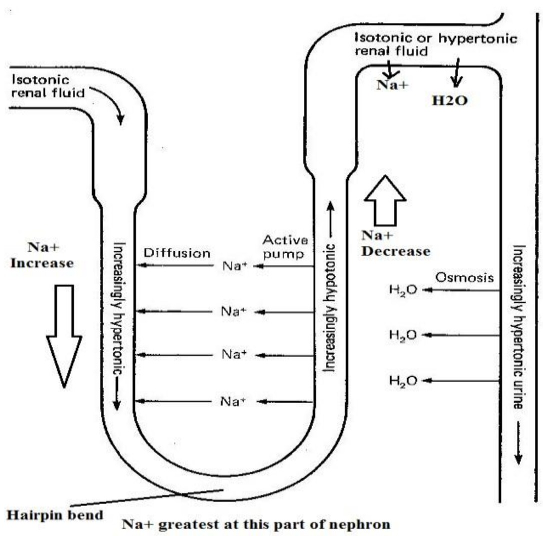
(i) **Ultra filtration (pressure filtration)** at the glomerulus of Bowman's capsule.
ii) **Selective reabsorption** in the tubules.
iii) Tubular secretion at the proximal and distal convoluted tubule.
iv) Counter current multiplier effect in the loop of Henle.
V) Water reabsorption in the distal convoluted tubule and collecting duct.

(v) Water reabsorption in the distal convoluted tubule and collecting duct.

Process	Explanation and Description
Ultra filtration (pressure filtration) in the bowman's capsule *(Fig 17.5* **A** *and* **B** ***Michael Roberts & Reiss, etal*** *Advanced Biology 1st ed. 2000 Page 283)*  	This is the first stage of urine formation at the glomerular capillary wall of kidney nephrons during which hydrostatic pressure forces small molecules in blood of glomerular capillaries to pass across the basement membrane into the capsular space but large molecules are held back. The substances that are forced by pressure to pass passively across the fine basement membrane filter include small molecules like water, glucose, amino acids, vitamins, urea, uric acid, ions, creatine, and some hormones while the large substances retained in blood include red blood cells, platelets, white blood cells and large sized plasma proteins. Although filtration occurs through three layers of glomerular capillary, the endothelium is a coarse screen retaining only blood cells, the negatively charged basement membrane retains negatively charged large sized protein, while the selective filtration occurs at the diaphragms of slit pores formed by foot-like projections of supporting cells called podocytes The high hydrostatic pressure of blood in the glomerulus which facilitates ultrafiltration results from the afferent arteriole having a larger diameter than the efferent arteriole.
Selective reabsorption from the tubules [***MBV Roberts (4th ed)***]  	Because particle size rather than their importance determines the substances to pass through the basement membrane during ultra filtration, useful substances such as glucose enter the capsular space to form glomerular filtrate and have to be reabsorbed later. As the glomerular filtrate (renal fluid) flows along the tubule of the nephron, all the glucose, 85% of the water, Na^+, Cl^-, amino acids, vitamins, hormones, 50% of urea are reabsorbed from the proximal convoluted tubule into the surrounding blood capillaries. Glucose, amino acids and Na^+, $H_2PO_4^-$ and HCO_3^- diffuse into proximal tubule cells and then actively transported into the blood capillaries. The active uptake of Na^+ followed by the passive uptake of Cl^- raises the osmotic pressure in the cells enabling entry of water into capillaries by osmosis. 50% of urea is reabsorbed by diffusion but the small sized proteins in the renal filtrate are removed by pinocytosis. As a result of all this activity, the tubular filtrate is isotonic with blood in the surrounding capillaries
Tubular secretion at the proximal convolulated tubule	Finally, active secretion of unwanted substances like creatine, some urea, ammonia, uric acid, H^+, and K^+ occurs from blood capillaries into the proximal tubule

NB: Only birds and mammals have loops of Henle in their Kidneys enabling production of hypertonic urine

Process	Definition, Explanation and Descriptio
Counter current multiplier effect in the loop of Henle	



A system of parallel and opposite flow of renal fluid in the descending and ascending limbs of the loop of Henle in the kidney with active salt concentration in the medullary interstitial tissue, an increase in salt concentration in the renal fluid of the descending limb and a decrease in salt concentration in the ascending limb to cause production of hypertonic urine.

The loop of Henle is the **counter current multiplier** and the vasa recta is the **counter current exchanger**. If the vasa recta did not exist, the high concentration of solutes in the medullary interstitium (the tissue surrounding the loop of Henle in the medulla) would be washed out.

The ascending limb of the loop of Henle is relatively impermeable to water while the descending limb is freely permeable to water but relatively impermeable to salt and urea.

Na^+ and Cl^- are actively pumped out of the upper part of ascending limb, but diffuse from the lower part, raising the solute concentration in the interstitial region and lowering the concentration in the ascending limb.

Water is osmotically drawn from the descending limb and collecting duct and carried away by blood in the vasa recta, resulting into a slightly higher solute concentration in the **descending** limb than the adjacent ascending limb and hypertonic urine to form.

The concentrating effect is multiplied such that the fluid in and around the loop of Henle becomes saltier with the saltiest region being the hairpin bend.

The glomerular filtrate becomes less salty as it goes up the ascending limb

This is under the influence of hormones as discussed on page 8 under osmotic regulation

- **Water reabsorption** in the distal convoluted tubule and collecting duct.

  As the fluid flows down the collecting duct, water is drawn out of it osmotically into the interstitium, resulting in hypertonic urine production

How the proximal convoluted tubule cells are adapted for reabsorption (How structure is related to function):

- Bear numerous microvilli at the free end to increase the surface area for reabsorption of substances like glucose, amino acids, vitamins, NaCl, water.
- Contain numerous mitochondria to form ATP that provide energy required in active transport of glucose, amino acids, Na^+, $H2PO4^-$ and $HCO3^-$ into the blood capillaries
- The cell surface membrane is indented to form a large area of intercellular spaces bathed with fluid.

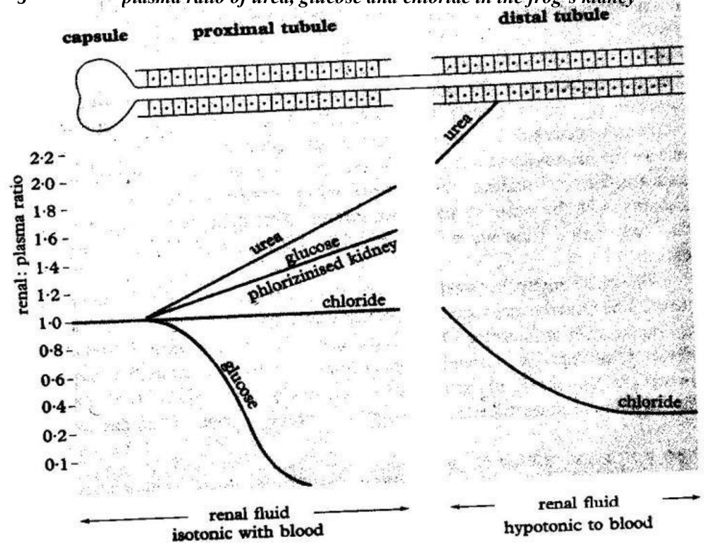
- Contain numerous pinocytic vesicles, which enable the digestion of

Table 20.4 Taylor DJ etal: Biological science 3 edition pg693 also check Table 20.1 Phillips W. D and Chilton T.:JA-level Biology, revised ed.pg154

Table 20.4 The composition of plasma and urine and changes in concentration occurring during urine formation in humans.

	Plasma %	*Urine %*	*Increase*
water	90	95	–
protein	8	0	–
glucose	0.1	0	–
urea	0.03	2	67×
uric acid	0.004	0.05	12×
creatinine	0.001	0.075	75×
Na^+	0.32	0.35	1×
NH_4^+	0.0001	0.04	400×
K^+	0.02	0.15	7×
Mg^{2+}	0.0025	0.01	4×
Cl^-	0.37	0.60	2×
PO_4^{3-}	0.009	0.27	30×
SO_4^{2-}	0.002	0.18	90×

Changes in renal-plasma ratio of urea, glucose and chloride in the frog's kidney



small protein molecules from the renal filtrate. □ Form a thin thickness of one cell layer to ease reabsorption of substances.

WHAT IS RENAL-PLASMA RATIO?

The ratio obtained after dividing the concentration of substances in renal fluid by the concentration of same substances in blood plasma.

Observations from the graph	**Explanation for the observations**
(i) The concentration of all components is the same in the renal fluid (glomerular filtrate) and the blood plasma at **Bowman's capsule,** thus the ratio of 1.	Re-absorption has not yet occurred.

Chloride concentration remains almost constant in the renal fluid and the blood plasma at the capsular space of the and at the proximal tubule	
(ii) Renal-plasma ratio of more than 1 for urea and glucose in the phlorizinised kidney.	The concentration of the component is greater in the renal fluid (glomerular filtrate) than in the plasma. ●Urea's concentration in the renal fluid increases rapidly mainly because **(1)** large volume of water is reabsorbed into capillaries **(2)** Urea is actively secreted into tubules from blood. ● Glucose concentration in the phlorizinised kidney increases in the proximal tubule yet phlorizin inhibits reabsorption of glucose. This is because large volume of water is reabsorbed into capillaries.
(iii) Renal-plasma ratio of less than 1 for glucose in the non-phlorizinised proximal tubule of kidney and chloride in the distal tubule.	The concentration of the component is lower in the renal fluid (glomerular filtrate) than in the plasma. ● The glucose concentration in the proximal tubule decreases rapidly to zero (0) because all the glucose is actively reabsorbed into blood capillaries surrounding the proximal tubule. The process is active (uses energy) because when the tubule cells are treated with

	a metabolic poison e.g. cyanide, glucose reabsorption is inhibited or slowed down. ● The chloride concentration decreases rapidly and remains at a low constant because Cl^- are reabsorbed passively following the active reabsorption of Na^+

<u>The glomerular filtration rate and its determinants:</u>

Glomerular filtration rate **(GFR)** is the net rate of formation of filtrate by the two kidneys. GFR is equal to the **renal plasma flow** (RPF) rate, the rate of plasma flow through the renal arteries, multiplied by the fraction of this plasma flow that is filtered (**the filtered fraction, FF),** so GFR = (RPF) x (FF)

FF is determined by three factors: **(i)** filtration pressure across the glomerular capillary walls **(ii)** permeability of the renal filter to fluid **(iii)** the total surface area available for filtration.

The kidneys receive a large part of the total cardiac output: for a typical cardiac output of 5.6 litres per minute, the kidneys might receive about 1.2 litres per minute, or about 20%.

GFR increases **(i)** if the mean glomerular capillary pressure rises as a result of either dilation of the afferent arterioles or constriction of efferent arterioles, or **(ii)** if the concentration of plasma proteins falls, because this reduces the force favouring reabsorption.

GFR falls if **(i)** the hydrostatic pressure in bowman's capsule rises (e.g. if the ureters are occluded) or **(ii)** plasma proteins escape into Bowman's capsule, because protein in Bowman's capsule makes net osmotic force across the glomerular wall smaller.

As a consequence of net reabsorption of solute, the volume of fluid in the nephrons decreases, until only about 1% or 2% of the original filtrate volume reaches the ureters as final urine.

The adaptive significance of formation of urine by filtration in the glomerulus followed by reabsorption and secretion in the later parts of the nephrons **is to enable the kidney excrete soluble chemicals that might enter the body, e.g. drugs and bacterial toxins but for which there are no specific tubular reabsorption pathways.**

Why urine production almost stops after serious bleeding:

The amount of urine produced is proportional to the amount of blood flowing through the kidneys. The total blood volume in the body reduces if serious bleeding occurs, resulting into diversion of blood from other tissues (including the kidneys) to the brain to maintain life. Therefore the volume of blood flowing through the kidneys reduces greatly to the extent that less ultrafiltration and hence formation urine occurs.

Q. a) Outline the main features of the kidney nephron.

b) ***Explain how the mammalian kidney produces urine that is hypertonic to blood***

c) ***Describe how the nephron regulates the PH of blood.***

HOW THE STRUCTURES OF THE MAMMALIAN NEPHRONE ARE RELATED TO THE FUNCTIONS THEY PERFORM / ADAPTATIONS OF THE MAMMALIAN NEPHRONE TO ITS FUNCTIONS.

PARTS OTHER THAN THE TUBULE	THE TUBULES

- Afferent arterial entering the Bowman's capsule has wider lumen than that of efferent arterial leaving it, resulting into high hydrostatic pressure that causes ultrafiltration to occur.
- The glomerular capillaries are highly coiled to increase the surface area for ultrafiltration to occur.
- The structural arrangement of the three layers of glomerular capillary enables the diaphragms of slit pores formed by foot-like projections of podocytes to offer selective filtration while blood cells and the negatively charged large plasma protein are retained by endothelium and basement membrane respectively.
- The Bowman's capsule is funnel-shaped to direct the renal filtrate into the proximal convoluted tubule.

 The proximal convoluted tubule cells:

-Bear numerous microvilli at the free end to increase the surface area for reabsorption of substances like glucose, amino acids, vitamins, NaCl, water.

-Contain numerous mitochondria to form ATP that provide energy required in active transport of glucose, amino acids, Na^+, $H_2PO_4^-$ and

HCO_3^- into the blood capillaries

-The cell surface membrane is indented to form a large area of intercellular spaces bathed with fluid.

-Contain numerous pinocytic vesicles, which enable the digestion of small protein molecules from the renal filtrate.

-Form a thin thickness of one cell layer to ease reabsorption of substances.

 The loop of Henle is U-shaped with parallel, opposite flows of tubular fluid in its limbs to provide a multiplier effect that create a concentration gradient, which enables increased water reabsorption.

- The capillaries of vasa recta form loops that accompany the loops of Henle resulting into countercurrent exchange of solute and water between ascending and descending blood.
- The capillaries of vasa recta are in close proximity with tubules to increase the reabsorption of useful substances from the filtrate.
- The distal convoluted tubule is long and coiled to increase the surface area for reabsorption of water and mineral salts.
- The distal and proximal convoluted tubules are coiled to slow down the movement of renal filtrate to allow more time for efficient reabsorption of substances like water, mineral salts.