

HOMEOSTASIS

This is the process by which the body maintains a constant internal environment.

Internal environment is the immediate surrounding of cells i.e. tissue or intercellular fluid and blood. The composition of tissue fluid has to be maintained constant because body cells in animals can only function within a narrow range of conditions and the enzymes which control the metabolic reactions are affected by changes in composition of the medium in which they operate.

Since it is from the tissue fluid that cells obtain their nourishment and discharge their excretory materials, it is important that there is need for continued adjustment in the internal environment.

FACTORS OF THE INTERNAL ENVIRONMENT THAT MUST BE KEPT CONSTANT.

1. Chemical constituents / components. e.g. glucose, ions like Na^+ , K^+ , Ca^{2+} , Cl^- etc
2. Carbondioxide concentration
3. Osmotic pressure (water and solutes)
4. Temperature
5. PH (Acid – Base balance)

Certain chemical ingredients must be eliminated from the tissue fluid so as not to affect the activity of the cells. These include nitrogenous wastes from protein metabolism and other toxic substances.

The regulation of all the above factors is done by homeostatic organs which include the skin, liver, kidneys and lungs.

HOW HOMEOSTASIS MECHANISMS OPERATE / ESSENTIAL COMPONENTS OF A CONTROL SYSTEM

1. Receptors / detectors / monitors

These are parts of the body that constantly monitor and detect changes from the reference point / norm in the internal environment and then signal the deviations. eg Temperature receptors in the skin provide information on variation in temperature of external environment.

2. Control centre / Regulator / coordinator

This is where information from the receptors is sent for interpretation and later initiate corrective measures. This is usually the brain that coordinates the information received from the various receptors and sends out instructions which will correct this deviation. eg Variations in temperature of external environment are conveyed to the hypothalamus of the brain.

3. Effector / responding organs.

These are parts of the body that bring about the necessary changes needed to return the system to the reference point / norm. These receive instructions about corrective measures from the control centre. They carry out the corrective measures thus returning the internal environment to a steady state.

The hypothalamus initiates corrective responses in effectors like blood vessels and skin to restore the temperature back to the normal.

4. Reference point / norm

This is the set level at which the system operates.

5. Feedback loop

This is a system which informs the receptors that the norm or normal levels have been achieved due to the action of effectors and as a result, the corrective processes triggered by the control centre are switched off.

The homeostatic system involves the **principle of negative feedback** / restoration of a system to its original state after disturbance. This means that a slight change in the levels of a particular substance results into corrective processes which bring it back to normal. Therefore, an increase in the level of a substance above the normal (Norm) triggers responses that decrease it back to the normal levels and vice versa.

Types of feedback mechanisms

1. Negative feed back
2. Positive feed back

Negative feed back

This is where a slight change / deviation in the amounts of a particular parameter from the set point or normal level within a biological system such as internal environment sets into motion a series of corrective responses or processes which bring the level back to the normal.

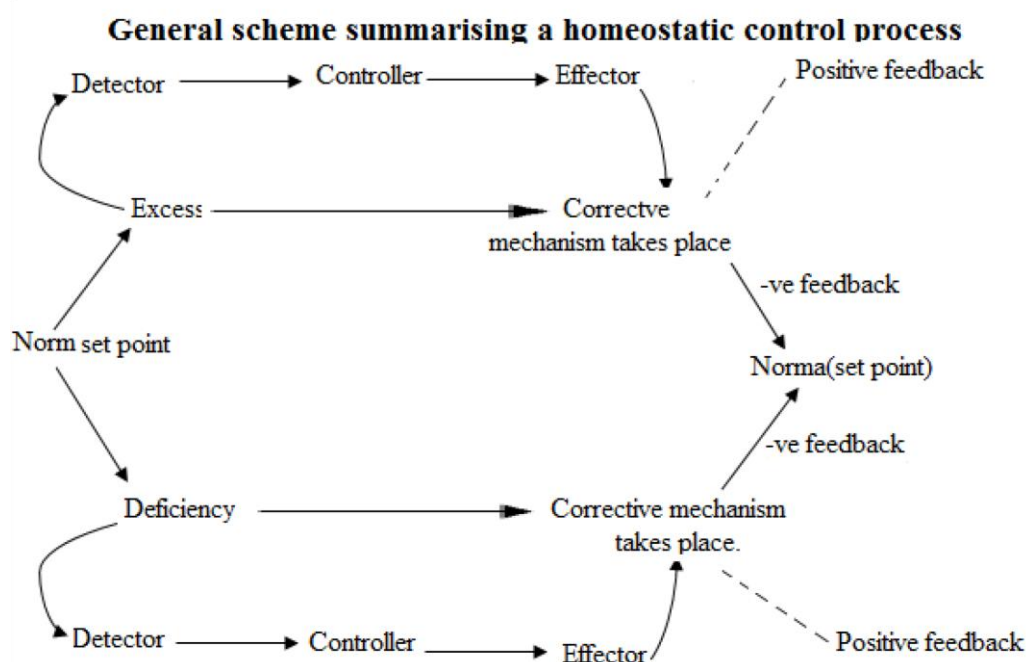
This implies that an increase in the level of a substance above the normal triggers corrective processes which will decrease it to normal levels and vice versa.

Positive feed back

This is where a deviation / change above the set point of any parameter in the substance in an open biological space like internal environment will set into motion a sequence of events which cause the level of a substance or that particular parameter to increase even further.

Positive feed backs are rare in biological systems since it leads to unstable situations and extreme states. However some that are important include;

1. In propagation of nerve impulses, depolarization of the membrane of the neuron increases the permeability of the membrane to Na^+ causing further influx or entry of Na^+ ions resulting into transmission of an impulse.
2. Production of oxytocin hormone during labour causes contraction of the smooth uterine muscles. This stimulates further secretion of more oxytocin hence increasing the strength of the contraction of the myometrium, labour pains intensify hence giving birth.
3. High environmental temperatures tend to increase the internal body temperature and any further increase in the environmental temperature causes metabolic rate to increase thus causing further increase in the internal body temperature to the extent that for any rise by the 1°C in the environmental temperature, the internal environmental temperatures doubles. However such a condition is lethal i.e. causes death of the individual.
4. During blood clotting, to stop bleeding in order to keep blood volume constant. One clotting factor activates another in a cascade that leads quickly to the formation of a clot. A cascade effect is the way in which a small amount of, say a hormone, can cause a target organ to produce a large amount of the product.



PROPERTIES / CHARACTERISTICS OF A HOMEOSTATIC SYSTEM

1. It is self-adjusting implying the homeostatic mechanism is triggered by the level of the very substance to be regulated.
2. It involves the principle of negative feedback i.e. restoration of the system to its original state after disturbance.
3. It works upon the fluctuations of the normal levels of the substance in the body called Norms or set points or reference points.
4. It relies on receptors to detect the changes (detectors), a control mechanism to initiate a corrective measure (regulator) and effectors to cause an appropriate response.

TISSUE FLUID / EXTRACELLULAR FLUID / INTERCELLULAR FLUID

This is the fluid found around tissue cells containing molecules that enter from or exit to the capillaries. The body's internal environment consists of tissue fluid and blood that bathe the cells.

Formation of tissue fluid

Tissue fluid is formed by ultrafiltration as blood passes within the capillaries. Capillary walls are permeable to small solute molecules and ions, but not to the red blood cells, platelets and plasma proteins. Tissue fluid is therefore a watery liquid which resembles plasma minus its proteins. It contains oxygen, glucose, amino acids, fatty acids, hormones, inorganic ions, antibodies and some white blood cells.

Its formation is controlled by two main processes ie **hydrostatic pressure** and **osmotic pressure**.

Hydrostatic pressure is caused by contraction of ventricles of the heart and resistance of blood flow due to the narrow capillaries. It forces water, ions and small molecules out of the capillaries while Osmotic pressure is due to presence of plasma proteins in blood and tends to pull water back to the capillaries.

At the **arteriole end** of the capillaries, hydrostatic pressure is greater than osmotic pressure hence water, ions, glucose, amino acids, oxygen and other small molecules are forced from the blood in capillaries in to the tissue space, forming **tissue fluid**. As a result, hydrostatic pressure along the capillaries falls.

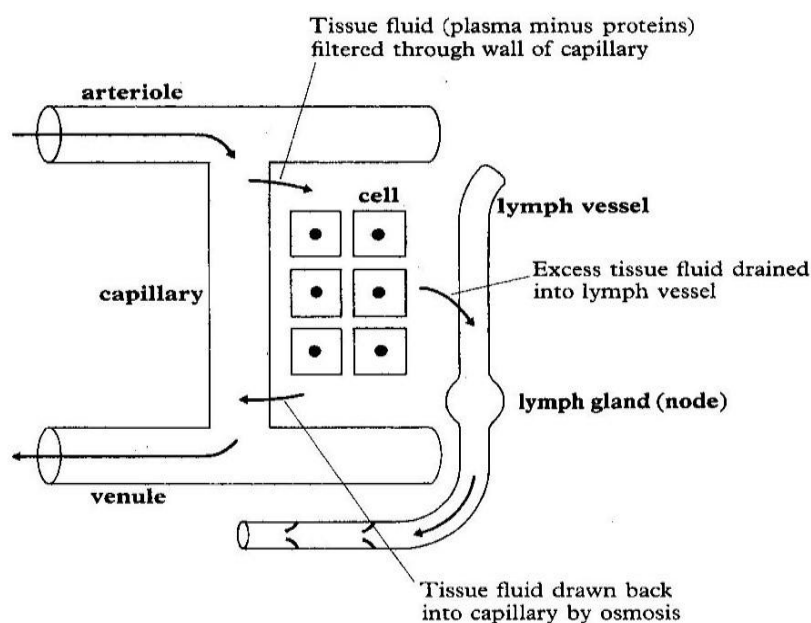
Midway along the capillary bed where the blood pressure is lower, the two forces of blood pressure and osmotic pressure essentially cancel each other and the substances diffuse according to their concentration gradients i.e. glucose, oxygen and other solutes diffuse out of the capillary while carbon dioxide and other wastes diffuse into the capillary. No net movement of water occurs

At the **venule end** of the capillaries, hydrostatic pressure is much lower than osmotic pressure. The high osmotic pressure is due to loss of water from blood at the arteriole end which concentrates the plasma proteins leading to an increased osmotic gradient. This causes water molecules to move from the tissue fluid back to the capillaries by osmosis. Hence some tissue fluid gets drained in to blood.

However, the total amount of fluid exiting capillaries at the arterial end exceeds that entering at the venule end. This is because the osmotic pressure causing entry of fluid at the venule end is lower than the blood pressure causing exit of fluid at the arterial end, resulting into failure of some fluid flowing into capillaries, forming what is called tissue fluid.

NB

Some tissue fluid is drained in to lymph vessels, forming **lymph**. It flows along the lymphatic system where phagocytes in the lymph nodes remove bacteria and other foreign particles from lymph and finally gets drained back in to blood in the subclavian veins just after they leave the arms and just before they reach the heart.

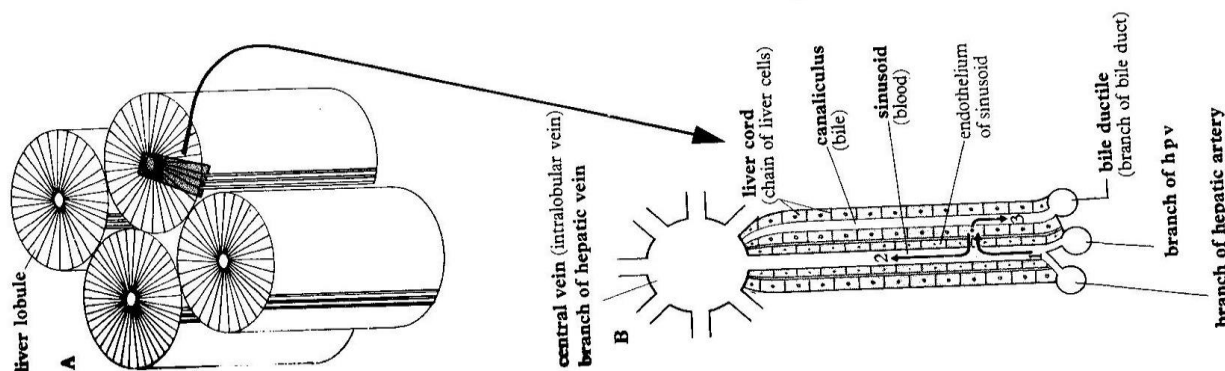


THE LIVER

It is the largest organ and main metabolic centre in the body.

- It is composed of numerous structural and functional units called **lobules**, which are cylindrically shaped.
- **Hepatocytes** (liver cells) closely pack in each lobule in various rows called **liver cords**, radiating outwards from the centre along the epithelium lining.
- Between the liver cords are wide **sinusoids** i.e. small blood capillaries and tiny bile canals called **bile canaliculi**
- Hepatocytes (liver cells) show no structural or functional differentiation. They have a prominent nucleus, golgi apparatus, numerous mitochondria, lysosomes, glycogen granules, fat droplets and peroxisomes. Peroxisomes contain catalase and other oxidative enzymes responsible for detoxification.
- Hepatocytes which are in contact with blood vessels bear microvilli
- Located between lobules are triads consisting of a branch of hepatic artery which brings oxygenated blood to the liver, a branch of hepatic portal vein which brings nutrients from the gut and bile duct that drains bile from the liver.
- A central vein (branch of hepatic vein) runs longitudinally midway through each lobule and is linked by sinusoids to the interlobular vessels (hepatic artery and hepatic portal vein).
- Blood reaches each of the lobules through the central vein and as it does so, the hepatocytes remove what they require i.e. oxygen and nutrients and release wastes into it e.g. urea and carbon dioxide but not bile.
- Bile released from the hepatocytes flows into the canaliculi where it is taken to the gall bladder for storage.
- Attached to the walls of sinusoids are phagocytic macrophages called **Kupffer cells** which destroy worn out red blood cells, bacteria and other foreign bodies as blood flows through the liver.

A simplified diagram of the liver lobule



Also see Biological science page 667

FUNCTIONS OF THE LIVER

1. Regulation of Glucose

The liver removes glucose from or adds glucose to the blood depending on the glucose concentration in blood. In the liver cells, glucose is either built up into glycogen for storage or broken down into carbondioxide and water releasing energy. If in much excess, glucose is converted into lipids.

2. Regulation of lipids and lipid metabolism

The hepatocytes remove certain lipids from the blood including cholesterol. Accumulation of cholesterol causes it to be deposited in the walls of arteries leading to obstruction of blood flow eventually causing intra vascular clotting. Liver cells therefore either break down these lipids or modify them and send them to fat deposits.

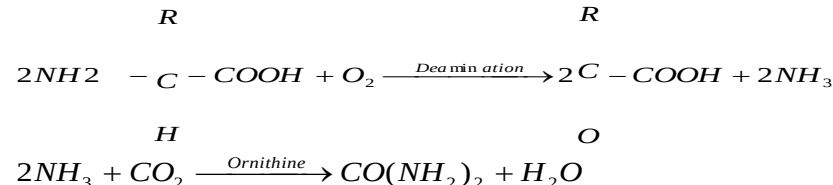
3. Regulation of Amino acids and proteins

The body is unable to store proteins or amino acids and any surplus is destroyed in the liver, a process called **deamination**. The amino group is removed from the amino acid leading to formation of ammonia.

The amino acid residue is then fed into carbohydrate metabolism and oxidized to release energy.

The ammonia under the influence of specific enzymes in the liver cells enters the ornithine cycle in which it reacts with carbon dioxide to form urea, a less toxic nitrogenous compound.

Urea is then shed from the liver cells into the blood stream and taken to the kidney i.e.



The liver also synthesizes non-essential amino acids, a process called **Transamination** e.g. Glutamic acid formed from the amino group transfer from amino acid alanine and it combines with Alpha keto glutaric acid. Transamination therefore is the synthesis of amino acids by the transfer of the amino group to an organic acid.

The liver also synthesizes plasma proteins eg fibrinogen for blood clotting, albumin and globulins involved in homeostasis.

4. Detoxification

It is the removal of toxins or poisons from blood. Liver cells detoxify many poisonous substances like drugs by absorbing them and changing of metabolism is rapidly split into water and oxygen by catalase enzyme. The toxic ammonia is also converted into less toxic urea. Foreign particles in the blood stream like bacteria and other pathogens are removed from blood in the sinusoids by the kupffer cells (phagocytic macrophages)

5. Inactivation of Hormones and elimination of sex hormones

This is done after hormones have achieved their effect on the target organs e.g. insulin, glucagon, thyroxin and many sex hormones are broken down immediately and sent to the kidney for renal excretion and others are expelled in bile.

6. Production of Bile

Bile is secreted by Hepatocytes and temporarily stored in the gall bladder attached to the liver and released into the duodenum through the bile duct under the influence of a hormone called cholecystokinin (CCK) also known as Pancreozymin.

7. Formation and break down of red blood cells (Erythrocytes)

In the foetus red blood cells are made in the liver while in adults, they are manufactured in the red bone marrow. The liver then destroys the old red blood cells (after 120 days) in adults. This is done by the kupffer cells in the liver sinusoids.

The haemoglobin in the process is broken down into **haem** and **globin**. Iron is removed from the haem and the remaining part of the molecule forms a pigment called **Biliverdin** that is converted to **Bilirubin** which is a component of bile. The iron combines with a plasma protein to form a complex called **transferrin**.

The Globin is the protein part and broken is broken down into its individual amino acids.

8. Storage of blood

The veins in the liver have great powers of expansion and contraction. This enables the liver to serve as a blood reservoir. Along with the spleen, it can regulate the amount of blood in the general circulation.

9. Storage of vitamins

The main vitamins stored in the liver are the fat soluble vitamins i.e. A, D, E and K. It also stores some water soluble vitamins especially vitamin B12.

10. Storage of minerals

It stores minerals like potassium, iron, copper, zinc, cobalt and molybdenum.

11. Production of heat

The liver has a high metabolic rate with a large size and excellent blood supply hence ideal for the steady production and distribution of heat to the different body parts thus important in temperature regulation in most endotherms.

How the structure of the liver is related to functions

- Kupffer cells ingest worn out red blood cells, bacteria and foreign particles from the blood flowing through the liver.
- Closeness of hepatocytes (liver cells) with sinusoids and canaliculi enables them to receive nutrients and expel waste substances.
- The excellent blood supply provides nutrients to the cells and enables wastes to be carried away.
- Hepatocytes bear numerous mitochondria for ATP production required in providing energy that facilitates some of the metabolic reactions.
- Hepatocytes, which are in contact with blood vessels, bear microvilli to increase the surface area for exchange of substances.
- The liver is large, providing large surface area for metabolic reactions to occur.
- Hepatocytes bear numerous peroxisomes containing catalase and other oxidative enzymes responsible for detoxification of poisonous substances in the liver.
- Its tissue is elastic, enabling expansion to store large volume of blood.
- Hepatocytes are similar in structure (undifferentiated) enabling them to perform various metabolic functions

Liver disorders

1. Hepatitis, which is an inflammation, caused by hepatitis viruses A, B, C, D and E.
2. Jaundice, which is characterised by a yellowish tint to the white of the eyes and a lightly pigmented skin
3. Cirrhosis, the liver becomes fatty, then fibrous and it is common in alcoholics
4. Liver cancer which is caused by exposure to chemicals like cigarette smoke, radiations e.g. X-rays, or genetic pathways

THE PANCREAS

In addition to its role in digestion as an exocrine gland due to secretion of enzymes, it also plays a role as an endocrine gland by secreting hormones.

Throughout the pancreas are a group of cells called **islets of Langerhans**. They are distinguished into;

- (i) The alpha cells which are larger and secrete glucagon hormone
- (ii) The beta cells which are smaller and secrete insulin hormone

Once secreted, these hormones are discharged into the blood where they are taken to the liver to bring about corrective responses in regulating glucose levels.

HOMEOSTATIC CONTROL OF BLOOD GLUCOSE LEVEL.

Glucose is a vital ingredient with a normal value of 90 mg/100cc of blood.

- For most tissues, glucose is the ideal food substance for respiration to produce energy (ATP) in the body.
- It is a preferred fuel molecule for both cardiac and skeletal muscles.
- It is the only metabolic fuel molecule absorbed by the brain because neurons are unable to respire lipids.
- Most cells are easily damaged by low glucose levels.

For the above reasons, glucose levels in blood have to be maintained at correct levels using two homeostatic organs i.e. liver and pancreas in presence of specific hormones mainly insulin and glucagon secreted by the pancreas. Other hormones involved include Adrenaline and glucocorticoids.

Question: Briefly explain why glucose levels should be kept constant in the body of an organism.

THE PROCESS OF GLUCOSE REGULATION

When the glucose level in blood increases beyond the normal (hyperglycemia), the beta cells of the islets of Langerhans of the pancreas secrete into blood **insulin hormone**.

On reaching the liver, insulin exerts the following effects

- It increases the oxidative break down of glucose to provide energy forming carbon dioxide and water.
- It causes the conversion of glucose to glycogen that is stored within the liver.

- It increases the conversion of glucose to fats in the Adipose tissue.
- It inhibits the formation of glucose from glycogen and non-carbohydrate foods (gluconeogenesis is prevented.)

This leads into glucose being removed from the blood resulting into a reduction of blood glucose level.

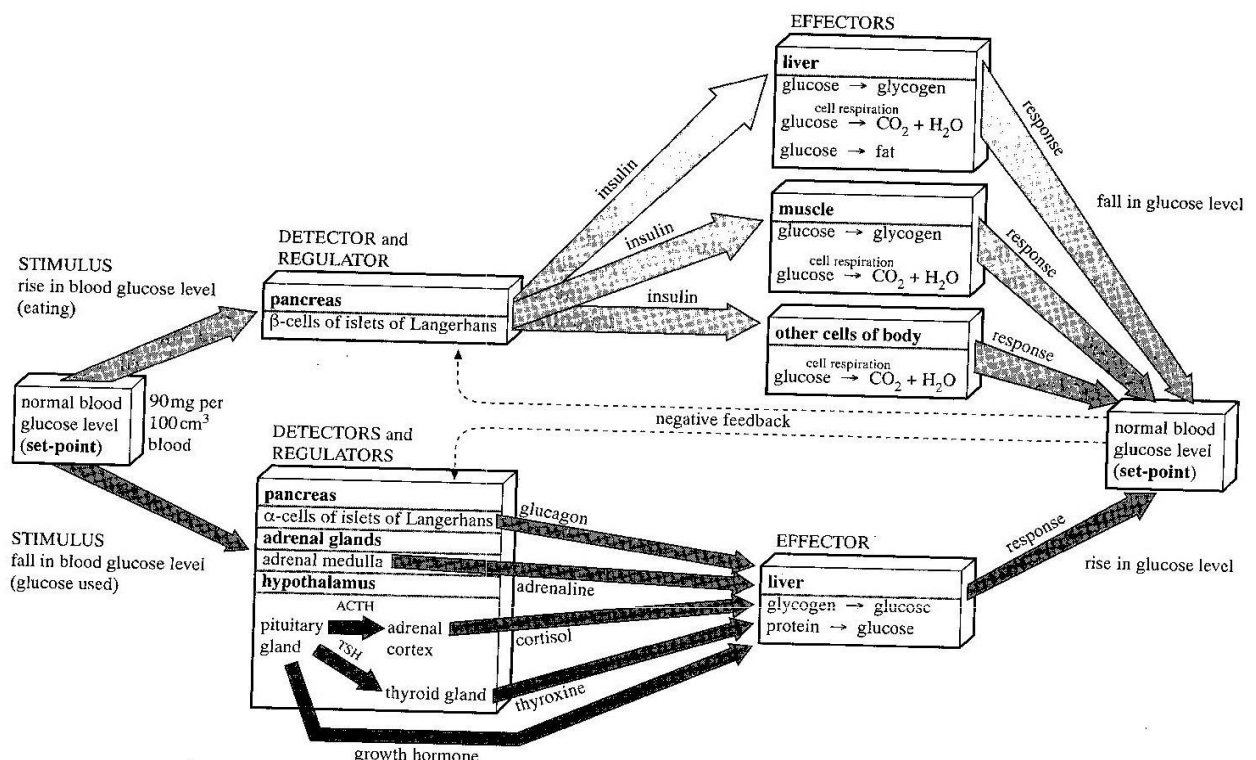
When the glucose levels in blood decrease below the norm (hypoglycemia), alpha cells of the islets of Langerhans of the pancreas secrete **glucagon hormone** into blood and taken to the liver where it stimulates the following:

- Increases the rate of breakdown of glycogen to glucose
- Increases the conversion of amino acids and glycerol to glucose, a process called gluconeogenesis
- Reduction in cellular metabolism / respiration within the hepatocytes.

In worse conditions, glucagon is assisted by glucocorticoids and adrenaline hormone, both secreted by adrenal gland. This occurs as a result of the hypothalamus detecting the very low glucose levels and induces the pituitary gland to secrete **Adrenal Corticotrophic hormone (ACTH)** that causes the adrenal glands to secrete **Adrenalin** and **glucocorticoids** which cause rapid conversion of amino acids and glycerol to glucose.

SUMMARY OF GLUCOSE REGULATION.

NB



Failure of one's pancreas to secrete the correct levels of insulin leads to the blood sugar level exceeding the norm, a condition called **hyperglycemia**. Should it reach critical levels, glucose starts to appear in urine, a condition called **glycosuria** that eventually leads to **Diabetes mellitus**. This type of diabetes is known as **Insulin diabetes / insulin dependent / type 1 diabetes**.

This condition can be regulated by injecting the victim with correct amounts of insulin.

Insulin cannot be taken by mouth since it is a protein and can be digested by pepsin enzyme within the stomach and trypsin enzyme in the duodenum.

Diabetes may also be brought about by the receptors in the membrane of the liver cells being insensitive to insulin. This results in less glucose being worked upon by the liver hence it accumulates in the blood and its level rises abnormally. This type of diabetes is known as **non-insulin diabetes / insulin independent / type 2 diabetes** and can be treated by careful regulation of the diet in which glucose is limited.

Symptoms of diabetes include;

- Hyperglycemia
- Glycosuria (glucose in urine)
- Frequent copious urine
- Visual disturbances
- Itching of genitals
- Fatigue
- Rapid weight loss
- Drowsiness
- Skin disorders e.g. boils
- General weakness

HOMEOSTATIC CONTROL OF IONS

Solutes responsible for determining the osmotic pressure of blood and body fluids contain various ions mainly sodium ions (Na^+), potassium ions (K^+), phosphate and chloride ions. Mammals control the quantity of all these ions at particular levels.

REGULATION OF CALCIUM AND PHOSPHATE IONS.

If there is too little calcium ions in blood relative to phosphate ions, the parathyroids in the thyroid gland are stimulated to secrete a hormone called Parathormone that exerts the following effects.

1. It increases the uptake of calcium ions by the gut.
2. It increases the re-absorption of calcium ions from the renal fluid back into the blood by the kidney.
3. It encourages release into the blood stream of calcium ions from bones.
4. It increases the elimination of phosphate ions by the kidneys to raise the concentration of calcium ions relative to phosphates.

If there is excess of calcium ions in blood relative to phosphate ions, secretion of parathormone is inhibited hence;

1. Reduced or no uptake of calcium ions by the gut
2. Reduced re-absorption of calcium ions from the renal fluid back into blood.
3. Reduced or no release of calcium ions from bones
4. No elimination of Ca^{2+} but increased re-absorption of phosphate ions by the kidney.

Secretion of the hormone parathormone is regulated by other hormones such as calcitonin which increases the secretion of Parathormone by the Parathyroids hence increasing calcium re-absorption.

Vitamin D, synthesized under the skin in presence of sunlight also increases absorption of calcium and phosphates by the gut and their uptake by bones.

REGULATION OF SODIUM IONS.

When the level of Na^+ is low, it is detected by the hypothalamus which stimulates the anterior pituitary gland to secrete **adrenal corticotrophic hormone**, which in turn stimulates the Adrenal cortex to secrete **Aldosterone**.

The low levels of sodium ions also bring about a decrease in blood volume which stimulates the **juxta glomerular cells** of the juxta glomerular complex of the kidney between the Distal convoluted tubule and the efferent arteriole to secrete an **enzyme rennin**.

Rennin catalyses the conversion of plasma protein, **Angiotensinogen** produced in the liver to an active plasma protein, **Angiotensin** which stimulates the Adrenal cortex to secrete **Aldosterone** hormone which stimulates the active uptake of sodium ions from the renal filtrate into the blood plasma.

This increases the levels of sodium to normal in blood and also increases the uptake of water into blood. Blood volume and levels of sodium then increase to normal.

High levels of sodium ions in blood do not stimulate the secretion of adrenal corticotrophic hormone. No renin is secreted, no angiotensin is produced and no aldosterone hormone is secreted. This leads to;

- No active re-absorption of sodium from the renal fluid
- Uptake of sodium from the gut reduces
- Sodium levels in blood are reduced back to normal

NB:

Aldosterone reduces the re-absorption of potassium ions into the blood and its levels fall below that of sodium ions.

OSMOREGULATION / REGULATION OF BLOOD WATER LEVELS / OSMOTIC PRESSURE IN MAMMALS

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 triggers the sensation of thirst, resulting into the drinking of water.

ADH increases the permeability of the distal convoluted tubule and the 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 into the medulla tissue fluid where it increases the osmotic pressure, leading to the 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 ducts become impermeable to water, less water is reabsorbed from the glomerular filtrate into blood and a large volume of dilute urine is passed out hence raising the osmotic pressure of blood.

Note:

- Diuresis is the production of copious dilute urine and antidiuresis is the opposite
- Insufficient production of ADH leads to a condition known as ***Diabetes insipidus*** characterised by frequent urination.
- Increase in blood osmotic pressure results from ingestion of little water, much sweating, ingestion of large amounts of salt while a decrease in blood osmotic pressure may be due to little sweating, ingestion of large volumes of water and little salt intake.

REGULATION OF BLOOD PH (ACID – BASE BALANCE)

The PH of blood is maintained at 7.4 and must be kept within a narrow limit so that enzymes and other proteins are not denatured resulting in metabolic failure that may cause death.

During respiration, the carbondioxide produced reacts with water forming carbonic acid, catalyzed by carbonic anhydrase enzyme. This lowers the pH of blood.

The rise in carbondioxide levels brings about reflex responses so that the breathing rate increases hence eliminating the much carbondioxide.

The carbonic acid formed dissociates into hydrogen carbonate ions and hydrogen ions. The hydrogen ions are then actively pumped across the cell surface membrane of the distal convoluted tubule into the lumen of the tubules. These are then exchanged for sodium ions which combine with hydrogen carbonate ions to form sodium hydrogen carbonate which is re-absorbed into the blood.

In the lumen of the distal convoluted tubule, hydrogen ions are buffered by phosphate salts mainly sodium hydrogen phosphate with which it combines to form sodium dihydrogen phosphate. The sodium ions are then retained and dihydrogen phosphate excreted in urine.

Some excess hydrogen ions combine with ammonia in the distal convoluted tubules to form ammonium ions that are also excreted in urine.

In case of increased acidity or alkalinity, Sodium hydrogen carbonate acts as pH buffer by mopping up the hydroxyl or hydrogen ions in an aqueous solution as appropriate.

In increased acidity / high concentrations of hydrogen ions / acidosis, hydrogen carbonate ions from dissociation of sodium hydrogen carbonate react with free hydrogen ions forming carbonic acid, lowering acidity.

In increased alkalinity / high concentrations of hydroxyl ions / alkalosis, hydrogen carbonate ions react with free hydroxyl ions forming carbonate ions and water thus lowering the alkalinity.

Qn: Explain the role of the kidney in regulation of pH of blood and tissue fluid.

Qn: Explain how sodium hydrogen carbonate acts a buffer.

THE ROLE OF BREATHING IN CIRCULATION

The respiratory and circulatory systems determine how much oxygen and carbondioxide are present in the body at a given time. If the amount of oxygen in blood is low and that of carbon dioxide is high, the body responds by increasing;

1. Rate and depth of breathing
2. The rate and force of heartbeat.

It is important to keep the respiratory gases at a constant level because of the effects that would follow when they fluctuate e.g.

- a) Deficiency of oxygen (**hypoxia**) deprives the tissues of the vital requirement for metabolism and the consequences include impairment of vision and brain activity. This results into irresponsible happy state of the mind leading to gross misjudgment of situations. The person becomes unaware that anything is wrong, unconsciousness occurs, suddenly followed by paralysis caused by damage to nerve cells and death.
- b) Breathing in excess oxygen at atmospheric pressure causes no problems. Breathing in pure oxygen does not increase the amount of oxygen delivered to the tissues. However if breathed in at pressures greater than the atmospheric pressure, the excess oxygen can cause the following problems:
 - Tissues metabolise rapidly.
 - Excess oxygen inhibits certain enzymes involved in the kreb's cycle thus interfering with cell respiration.
 - Oxygen poisoning occurs starting with muscular twitching followed by nausea, dizziness, impaired hearing and breathing difficulties.
 - Consequently there is lack of body coordination leading to convulsions and death.
- c) Accumulation of excess carbon dioxide within the body tissues interferes with respiration of cells. It also increases the acidity of blood and tissue fluids inhibiting enzymes and stopping essential metabolic processes and as a result, heart rate and breathing rate greatly lower. This is why it is dangerous to breath in and out a polythene bag.

TEMPERATURE REGULATION (THERMOREGULATION)

Most organisms maintain a narrow range of temperature. This is necessary to enable enzymatic reactions to occur so that the body's metabolic reactions can proceed.

Temperature indicates the amount of heat energy in the system and in living organisms.

Very low temperatures result into reduced metabolic rates due to inactivity of the enzymes while extremely high temperatures denature enzymes causing a great reduction in metabolic rate hence affecting the body's activities.

Since the environmental temperature keeps fluctuating, there is need for organisms to keep their body temperature fairly constant despite the heat gain or loss.

METHODS OF HEAT GAIN BY THE BODY

1. **Metabolism** i.e. Respiration of food to generate energy as heat.
2. **Conduction.** It is the transfer of heat from hotter objects to cooler objects in contact with each other.
3. **Convection.** It is the movement of air from a hot object to a cool object thereby transferring heat through air currents.
4. **Radiation.** It is the diffusion of heat from a warm body to a relatively colder object via air.

METHODS OF HEAT LOSS BY THE BODY

1. Evaporation of water e.g. during sweating
2. Conduction
3. Convection
4. Radiation

Heat gain and heat loss may depend on the following factors

1. Size of the organisms. Small organisms have a large surface area to volume ratio and tend to lose more heat than the large ones.
2. Temperature of the environment. In warm environment, heat gain is higher than heat loss and in cold environments heat loss is higher than heat gain.
3. Body's metabolic rate. It depends on the size of the organism and the higher the metabolic rate, the greater the heat gain
4. Environmental conditions e.g. Air movement enhances heat loss than heat gain.

ECOTHERMS / POIKILOTHERMS

These are organisms whose body temperature changes with that of the environment / organisms whose body temperature is regulated by behavior or by the surrounding. e.g. Amphibians, fish, reptiles and most invertebrates.

These organisms have a limited ability to regulate their own temperature therefore they obtain heat from sources outside their body.

Their body temperature increases with increase in environmental temperature.

Temperature regulation in ectotherms

It depends on behavioral means during cold or hot conditions.

During hot conditions, they carry out activities that promote heat loss ie

1. Thermo gapping in large reptiles e.g. crocodiles. It is the opening of the mouth to lose water by evaporation, resulting into cooling
2. Salivation over the legs and neck e.g. the tortoise. It increases heat loss by evaporation of water from the wetted surfaces.
3. They rest on cold rocks to lose heat by conduction.
4. They move and rest in shades. Aquatic ectotherms e.g. crocodiles move into the water.
5. They burrow in cracks and caves where they lose heat by radiation
6. Thermal dancing ie lifting of opposite pairs of feet alternately so that they can cool in air e.g. shovel-snout lizards.
7. Salivation over the neck and legs in tortoises to increase loss of heat as a result of water evaporating from such surfaces.

During cold conditions, they gain heat by the following;

1. Basking under the sun to gain heat by radiation from the sun and by conduction from the warm surface.
2. Resting on hot rocks to gain heat by conduction.
3. They burrow in hot sand to gain heat by conduction.
4. Burrowing in crevices e.g lizards. This allows them to warm up the air around them so as to keep their body temperature slightly higher than the environmental temperature.

Advantages of ectotherms

1. Temperature regulation is by behavioral means alone with demands less energy than physiological or metabolic reactions.
2. The ectotherms require less food compared to endotherms of the same size because ectotherms do not generate heat internally by respiration which requires a lot of food.

Disadvantages of ectotherms

1. Their metabolic rate is normally kept low hence cannot exploit a wide variety of habitats having extreme cold or hot weather conditions.
2. Due to the low metabolic rate, ectotherms have a slow response to stimuli.

ENDOTHERMS / HOMEOTHERMIC ORGANISMS

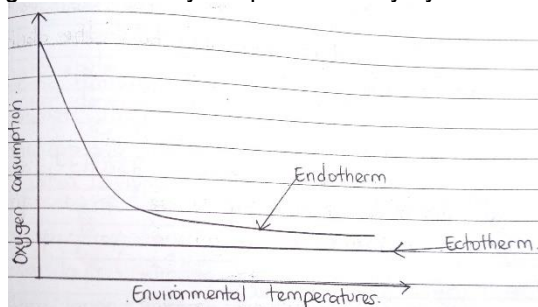
These are organisms whose body temperature remains constant irrespective of environmental temperatures. They generate heat within their body hence their body temperature is independent of the environmental temperature e.g. Mammals and birds.

Endothermy is the ability of animals to maintain a constant internal body temperature.

In cold weather endotherms need a lot of energy to keep their bodies warm and to maintain a constant body temperature therefore in cold, endotherms use a lot of oxygen to maintain a high metabolic rate to generate much heat to maintain a constant body temperature.

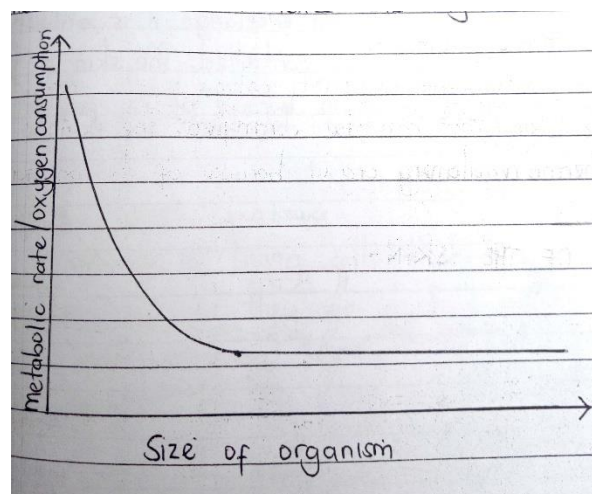
As the environmental temperature increases, the oxygen consumption decreases rapidly and then gradually because the metabolic rate lowers, generating less heat needed to maintain a constant body temperature. Further increase in environmental temperature, the oxygen consumption remains constant to generate some energy from metabolism needed for other body activities besides temperature regulation.

For ectotherms their oxygen consumption remains constant with increase in environmental temperature because they regulate their body temperature only by behavioral but not physiological means or metabolism.

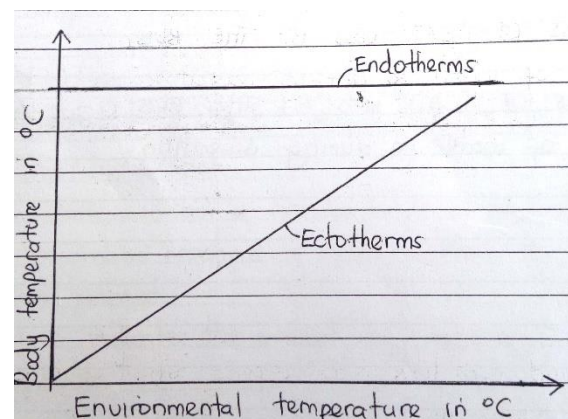


Size and metabolic rate also affect temperature regulation in endotherms. The larger the organism, the smaller the surface area to volume ratio, the less the heat lost from the body, the lower the metabolic rate and hence the lower the oxygen consumption.

The smaller the organism, the larger the surface area to volume ratio, the more the heat lost from the body, the higher the metabolic rate and hence the higher the oxygen consumption.



A graph showing changes in body temperature with that of the environment in ectotherms and endotherms



In terms of heat exchange, a bulky or large animal has a large volume of tissue in which heat is released but has a relatively smaller surface through which heat is lost to the environment. This explains why large organisms lose less heat to the surrounding.

Advantages of endotherms

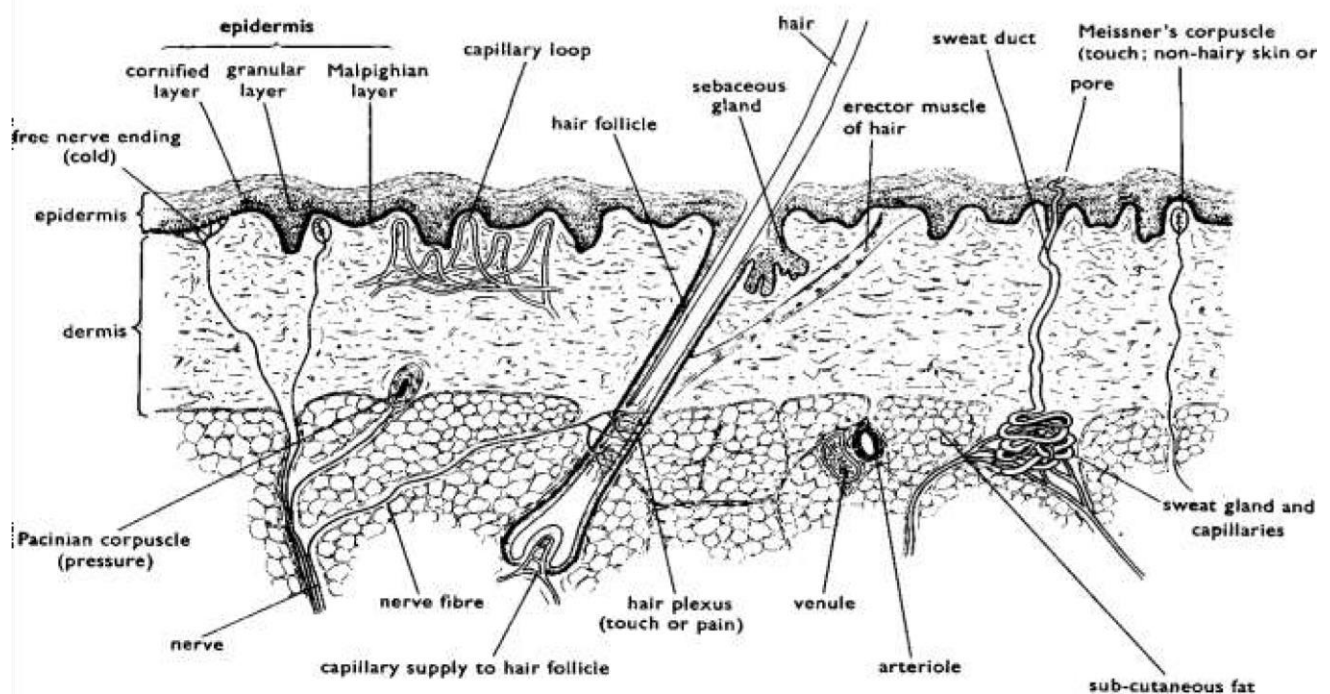
1. They can live in a wide range of environments irrespective of the prevailing temperatures since they have the ability to generate heat within their bodies.
2. The enzyme controlled activities of endotherms proceed efficiently most of the times since an optimum body temperature is always maintained. This makes them more active, speedy and quick to respond to stimuli hence have high survival rates than the ectotherms.
3. Since high metabolic rates are maintained all the time, plenty of energy is available to support body processes.

Disadvantages of endotherms

1. Most of the heat used to maintain a constant body temperature is generated through metabolic means. This requires a high food intake and in the process creates a problem of finding adequate food supply.
2. Maintaining a constant body temperature requires much energy.
3. It requires efficient cooling mechanisms during hot temperatures to avoid overheating of the body, and efficient insulation when the external temperature is too low.

Mammals gain or lose heat through any surface which comes into contact with their environment. In relation to other areas of heat exchange, it is only heat exchange through the skin that can be controlled. The skin is therefore an important thermoregulatory organ because of its position and structure.

STRUCTURE OF THE SKIN



The skin consists of two layers ie the outer epidermis and the inner dermis

THE EPIDERMIS

It comprises of three layers ie

- The malpighian layer (Germinative layer)
- Granular layer (*Stratum granulosum*)
- Cornified layer (*Stratum conersum*)

The malpighian layer

It is the inner most layer of the epidermis made of actively dividing cells.

A pigment melanin which determines the skin colour is produced in this layer.

It has numerous infoldings that extend deep into the dermis giving rise to the sweat glands, sebaceous glands and hair follicles.

It has no blood vessels and obtains food and oxygen by diffusion and active transport from the capillaries of the dermis.

Granular layer

It is made up of living cells that have been produced by the malpighian layer as they are pushed towards the skin surface by new cells produced beneath or below. They accumulate fibrous proteins, keratin and later lose their nuclei and die.

Cornified layer

It is the surface layer of the skin made of flattened dead cells and lack a nucleus.

The cells are impregnated with keratin

It forms a tough resistant water proof layer which is constantly replaced as it gets worn out.

The thickness of this layer increases in parts where there is considerable friction e.g. on the palm of the hand and soles of the feet.

This layer is pierced by pores which open to the sebaceous gland, sweat gland and hairs.

It protects the cells underneath against entry of germs.

THE DERMIS

It is largely made up of connective tissue consisting of collagen and elastic fibres. It comprises of;

- **Blood capillaries**

These supply the epidermis and dermis with food and oxygen.

They play a role in thermo regulation. Since heat is taken to the dermis by blood in numerous arterioles and capillaries.

When the volume of blood flowing through the dermis is high, much heat is lost and this happens when the arterioles of the skin dilate a process called Vasodilation.

Blood flowing through the skin is reduced by vasoconstriction hence reducing heat loss to the environment.

- **Hair follicles**

These are formed by in pushing of the malpighian layer. Cells are the base multiply forming long cylindrical hair cells that become impregnated with keratin and melanin.

Attached to the hair follicles is a small bundle of smooth muscles called erector pili muscles which contract and make the hairs to erect or to rise up.

- **Sebaceous glands**

These secrete an oily substance called Sebum on the hair making it water proof. The sebum also keeps the epidermis supple preventing entry of bacteria.

- **Sweat glands**

These are coiled tubes made up of cells which absorb fluids from the surrounding capillaries and secrete it into the tube from where it passes to the skin surface via sweat ducts.

Sweat consists of mainly water, mineral salts and urea. Evaporation of sweat from the skin surface cools the body.

- **Sub cutaneous fat**

It is a layer of fat tissue (adipose) beneath the dermis. It is a long term food reserve and an insulating layer.

- **Sensory nerve endings**

Different sensory cells provide information on the external environment. These include;

- (a) Touch receptors (meissner's corpuscles), sensitive to touch
- (b) Pressure receptors (Pacinian corpuscles), sensitive to pressure
- (c) Pain receptors (the free nerve endings), sensitive to pain.
- (d) Temperature receptors i.e. ruttin's endings sensitive to heat or warm temperatures and Kranse's endings sensitive to cold.

FUNCTIONS OF THE SKIN

1. Protects the body from water loss, injury and infection
2. It contains numerous sensory cells hence important in reception of stimuli
3. It is important in temperature regulation
4. For formation of vitamin D an exposure to sunlight.
5. It is an excretory organ of urea, salt and excess water.

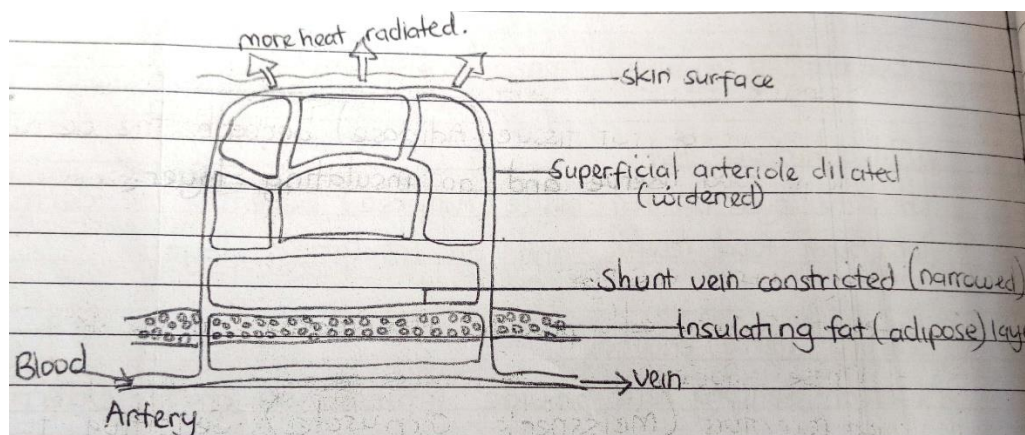
RESPONSE OF ENDOTHERMS TO VARIATION IN THE EXTERNAL TEMPERATURE. RESPONSE TO HOT CONDITIONS

It involves physiological and behavioral mechanisms to promote heat loss and avoid overheating.

Physiological mechanisms

1. **Vasolidation.** The superficial blood vessels in the skin are dilated so that much blood flows to the skin surface where it loses much heat to the surrounding by radiation.

However during hot conditions, the shunt vessels close so as to make blood pass near the skin surface in order to release more heat to the outside environment.



2. **Sweating.** It involves secretion of a watery fluid from the sweat glands of the skin. As the sweat evaporates it takes with it a large amount of heat and eventually cools the body.

3. The erector pilli muscles of the skin relax. This causes the hairs to lie flat on the skin trapping no layer of air but promoting heat loss from the skin surface hence cooling the body.
4. The metabolic rate decreases. This ensures that less heat is generated by the body. This is the reason why animals are generally less active during hot conditions than cold conditions.
5. Panting. Animals with few or no sweat glands e.g. dogs and birds cool their bodies by panting. They open their mouth and expose their tongue as they breath out continuously through the mouth. This speeds up evaporation of water from the mouth and lungs losing heat hence cooling the body. Some organisms like the Kangaroo rats lick their bodies to cause cooling.

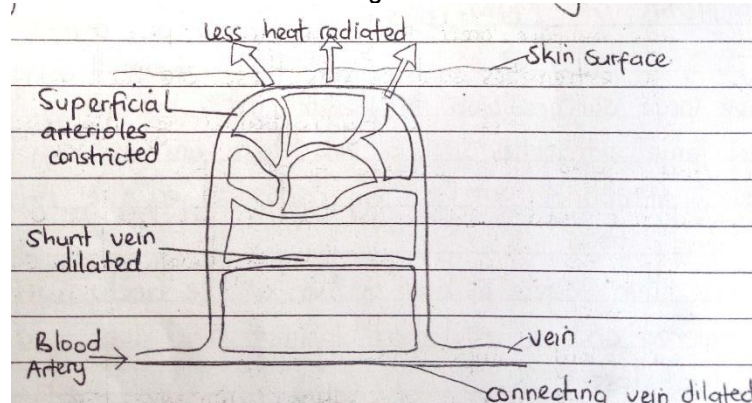
Behavioral mechanisms

1. Taking cold drinks
2. Bathing
3. Swimming
4. Putting on or wearing light clothes
5. Moving close to a fan or fanning
6. Moving to shady places

RESPONSE TO COLD BY ENDOTHERMS

Physiological mechanisms

1. **Vasoconstriction.** The superficial blood vessels in the skin constricts hence the amount of blood reaching the skin surface reduces since blood is diverted blood vessels deeper in the skin, this reduces heat loss to the surrounding and conserves heat with the body.



2. **Involuntary muscle contraction.** The skeletal muscles of the body undergo involuntary rhythmic contraction (shivering) which provides metabolic heat that raises the body temperature. Shivering also causes contraction of smooth muscles of the skin forming goose pimples.
3. The body hairs are raised due to contraction of the erector- pilli muscles. This traps a layer of air over the skin surface thereby insulating the organism against heat loss.
4. Increase in metabolic rate. This occurs especially in the liver induced by hormones such as thyroxine and adrenaline. Heat is then generated that maintains the body temperature. For this to occur, a high consumption of food is required and this is the reason why mammals living in cold environments consume more food per gram of their body weight than mammals in the tropics where temperatures are higher.

Behavioral means

1. Humans put on thick clothes
2. Humans take hot drinks
3. Organisms sit near hot objects or bodies
4. Humans carry out physical exercises
5. Some organisms cuddle in groups to reduce heat loss.

ADAPTATIONS TO EXTREME CLIMATES

a) Adaptations of life to low temperature

Structural adaptations

1. Possession of thick fur for trapping a layer of air that is warmed and remains insulating the body against heat loss e.g. polar bears
2. Possession of a thick layer of subcutaneous fat for insulating against heat loss e.g. polar bears
3. Development of a large body size as compared to their counterparts in warmer climates to reduce the surface area to volume ratio in order to reduce heat loss e.g. whales and polar bears
4. Extremities such as ear lobes are of reduced size than those of related species in warmer climates to reduce surface area for heat loss.

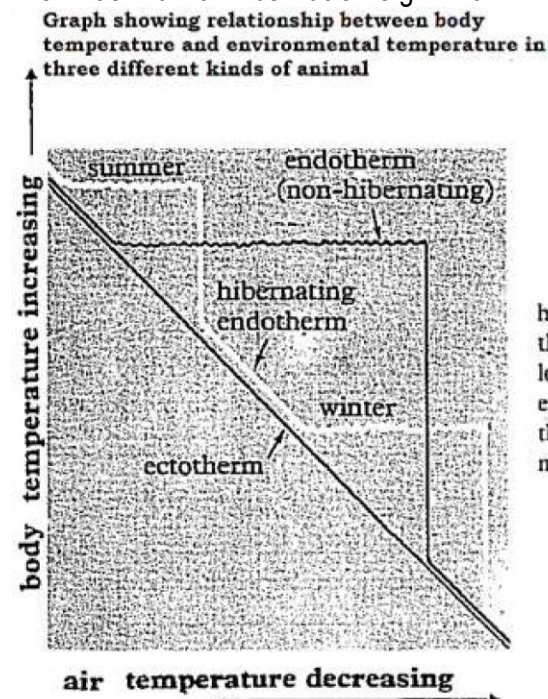
Behavioral adaptations

1. Some animals migrate to warmer places e.g. birds like swallows
2. Cuddling in groups to reduce heat loss from their bodies
3. They are active during the day (diurnal) and less active at night when the environmental temperatures are too low.
4. Small sized animals hibernate e.g. bats, hamsters, hedgehogs and rodents like mice. **Hibernation** is a seasonal response by animals to cold temperatures during which they become dormant, body temperature and metabolic rate fall to the minimum required for maintaining the vital activities of the body. The animals are said to be in a 'deep sleep' to reduce energy needs to survive the winter when food is scarce. This form of hibernation used by endotherms to maintain the core body temperature is called true hibernation.

Brown fat is conserved and used up rapidly at the end of hibernation to quickly raise the metabolic heat. Brown fat owes its colour to the numerous mitochondria it contains. The mitochondria generate heat and not ATP. Animals moving out of hibernation break it down and it generates heat more quickly than ordinary fat since it has good blood and nerve supply

NOTE: Other species may show a form of hibernation which may be in a state of sleep and the organisms wake up if the environmental temperature rises, this is called sleep / pseudo hibernation e.g. Snakes, lizards, tortoises, toads, newts and frogs.

Some small birds and mammals with large surface area to volume ratios have extremely high metabolic rates and in order to survive, they lower their body temperature at night when they are unable to feed. This is known as **Diurnal hibernation** e.g. in humming birds and small insectivorous bats.

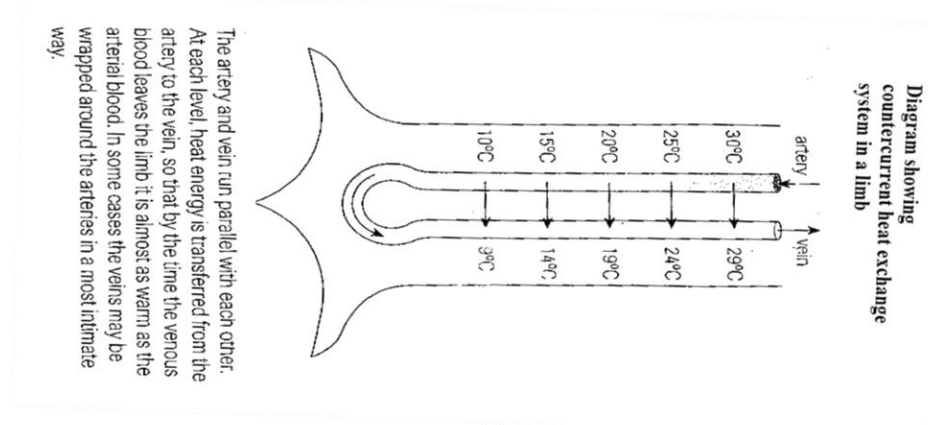


Note that in winter the hibernator's homeostatic set-point is lowered so that it maintains a constant body temperature at a lower level than in summer. The non-hibernating endotherm maintains the same body temperature throughout the year. The ectotherm is unable to maintain a constant temperature.

Other adaptations

1. Development of a counter current heat exchange system in limbs to enable heat conservation by minimizing its loss to the environment e.g. in ducks legs and dolphin flippers. The extremities of animals in cold regions are maintained at lower temperatures than the core body temperature. This reduces the temperature gradient between the extremities and the environment hence reducing heat loss e.g. from the feet which are in contact with the cold ground; this is achieved by the counter current heat exchange system.

In the counter current heat exchange system above, arterial blood flowing towards the end of the limbs gets gradually cooler while the venous blood gets warmer as it moves towards the body. This is because arteriole heat is constantly transferred to the venous blood so that by the time blood gets to the feet, it has the same temperature as the cold environment hence no heat loss to the environment. This system warms the venous blood as it gets back to the main body.



b) Adaptations of endotherms to survive in hot conditions

Structural adaptations

1. Their bodies are thinly insulated with fat to promote heat loss.
2. Having tissues that are tolerant to large temperature fluctuations between day and night e.g. the camel
3. Development of smaller body size than their counterparts in colder climates to increase surface area to volume ratio in order to increase heat loss.
4. They have large thin extremities such as ear lobes that are well supplied with blood capillaries promoting heat loss by radiation e.g. the elephants, African foxes and arctic foxes.
5. They have thin layers of hair or fur on the body surface hence less air is trapped and no insulation against heat loss occurs thus promoting heat loss.

Behavioral mechanisms

1. Many desert animals are nocturnal so as to avoid the period of greatest heat stress during the day.
2. Sheltering under rocks / burrowing beneath the surface.
3. Aestivation. It is a seasonal response of animals to drought or excessive heat during which they become dormant and metabolic rate decreases followed by a decrease in body temperature to a minimum required to maintain the vital activities of the body eg the African lung fish burrows in to mud until the dry season ends. Amphibians, earthworms and garden snails also aestivate.

Other adaptations

1. Variation in body temperatures. Some desert animals like camels allow their body temperature to rise during the day. This reduces the temperature gradient between the body and the environment hence reducing heat gain. These animals also delay the onset of sweating hence conserving water within their bodies.

Adaptations to extreme heat by the camel.

1. It faces the sun, therefore exposing a small surface area to the sun's radiations.
2. Its body is insulated by fat on top, which minimizes heat gain by radiation
3. The underpart of its body, which has much less insulation, radiates heat out to the ground cooled by the animals' shadow
4. Flattened nostrils which retard water loss
5. It excretes very concentrated urine
6. It can tolerate the loss of more than 25 percent of its body weight in water.
7. It can go without drinking for as long as an entire week in the summer and three weeks in winter.
8. The hump acts as an insulator since it has fats.
8. It can tolerate a fluctuation in internal body temperature of 5 to 6°C ie. it stores heat during day by letting its temperature rise up and then release it during the night.

THE BRAIN AND TEMPERATURE REGULATION (HOMEOSTATIC CONTROL OF BODY TEMPERATURE)

In the brain, the hypothalamus detects temperature fluctuations within the body from the blood that flows through it. It particularly has the thermoregulatory centre made up of the heat gain centre and heat loss centre. The skin also contains thermal receptors which monitor temperature changes of the skin as a result of environmental temperature changes.

When the environmental temperature **increases**, the skin hot receptors are stimulated and they generate impulses that are carried by the sensory neurons / nerves to the heat loss centre.

This responds by sending impulses through the motor neurons or nerves to the effectors which cause;

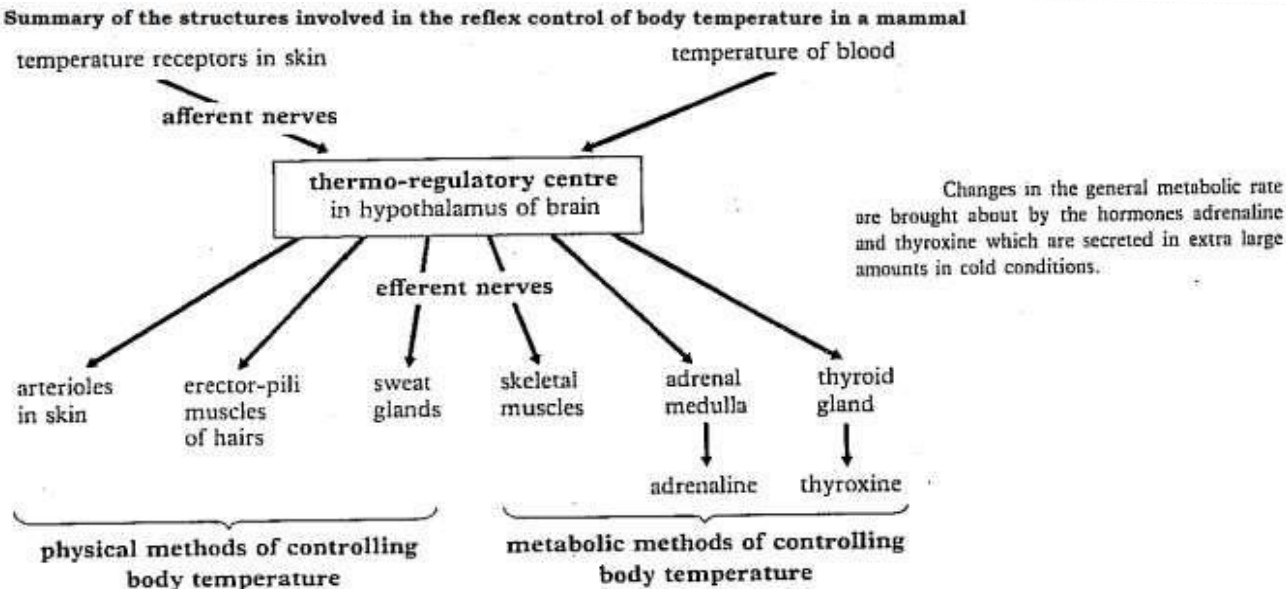
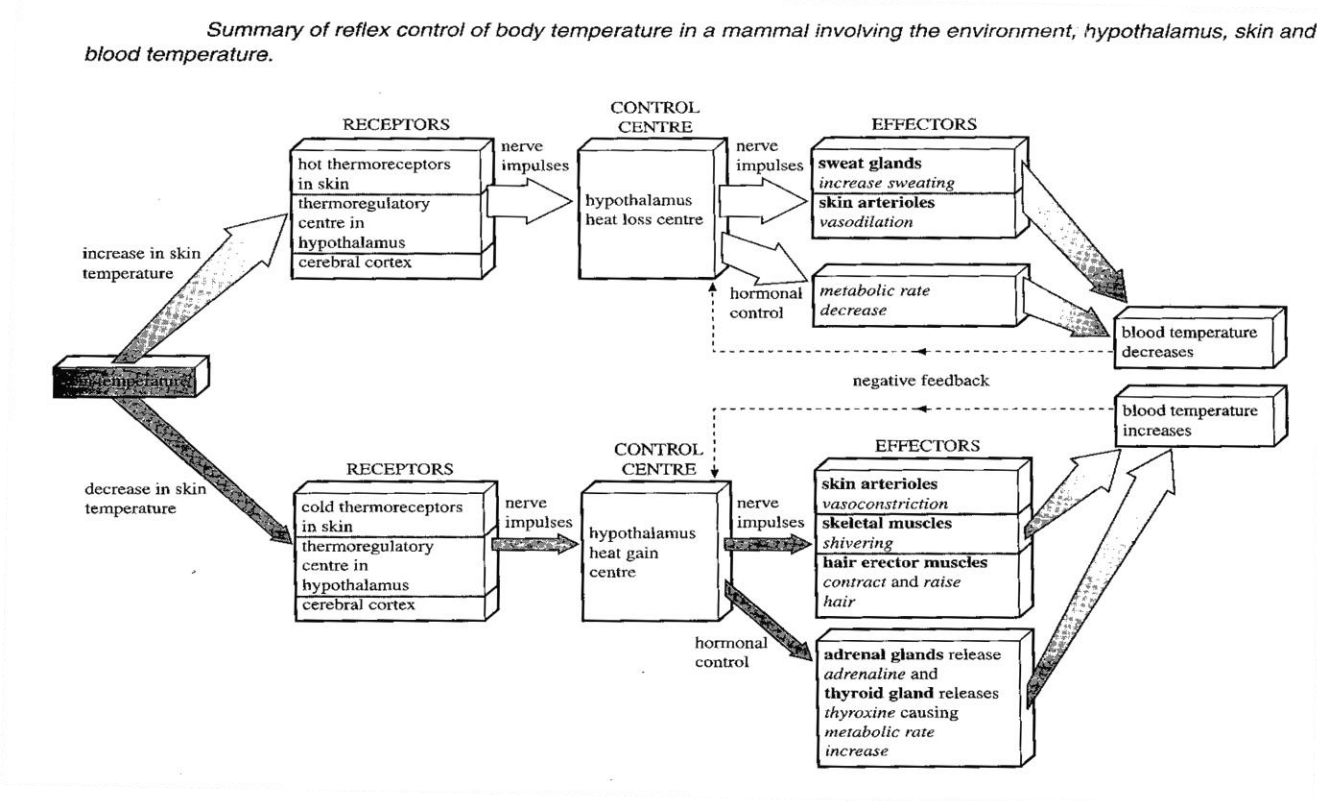
- Increased vasodilation thereby increasing heat loss from the skin by radiation, convection and conduction.
- Increase in sweating and panting.
- Decrease in metabolic activity.
- Relaxation of the erector pilli muscles hence hairs lie flat on the skin and no layer of air is trapped increasing heat loss.

When the environmental temperatures **decreases**, the skin cold receptors are stimulated to generate impulses that are carried along the sensory neurons to the heat gain centre of the hypothalamus.

This responds by sending impulses along the motor neurons to the effectors causing;

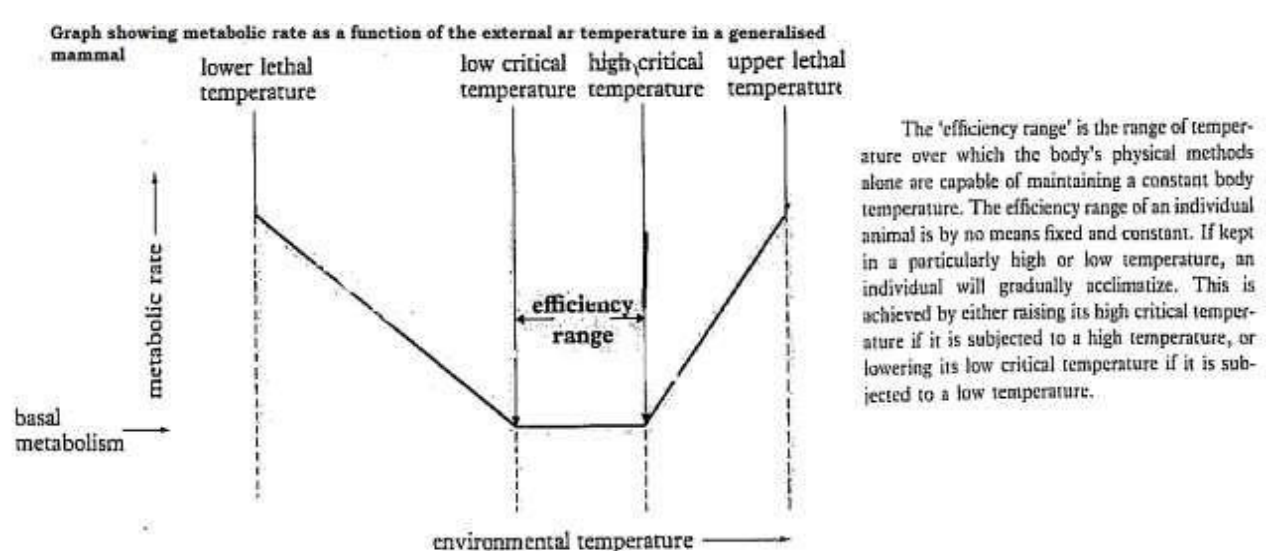
- Increased vasoconstriction thereby decreasing heat loss from the skin by radiation, convection and conduction.
- Inhibits sweating and panting
- Increased metabolic activity to generate more heat.
- The thyroid gland is stimulated to secrete thyroxine and the adrenal gland stimulated to secrete adrenaline both of which increase the metabolic rate to generate more heat.
- Shivering (contraction of muscles) to generate heat.
- Contraction of the erector pilli muscles making the hairs to stand upright on the skin trapping a thick

layer of air reducing heat loss.
 After the body temperature is restored to normal, the hypothalamus ceases to send impulses therefore all those mechanisms above stop hence a negative feedback mechanism.



EFFECTS OF RAISING AND LOWERING ENVIRONMENTAL TEMPERATURE AND BODY TEMPERATURE

The ability of an organism to adopt to extreme temperatures varies from one organism to another. Body temperature regulation combines physical and chemical (metabolic mechanisms) There is a relative extent to which the mechanisms above can work when the environmental temperature is lowered or raised as shown in the graph below.



When the environmental temperature **lowers**, the organism will first rely on physical mechanisms to maintain a constant body temperature.

- The metabolic rate remains unchanged / constant at basal metabolism.
- However at a certain environmental temperature, physical mechanisms alone will not be able to keep the body temperature constant. At this point, the metabolic rate starts to increase in order to maintain a constant body temperature i.e. the lower critical temperature therefore **lower critical temperature** is the lowest environmental temperature at which physical mechanisms alone like vasoconstrictions and erection of hair can no longer regulate the body temperature.
- As the environmental temperature is further lowered, the metabolic rate continues to increase until eventually the metabolic mechanisms can no longer regulate the body temperature. This environmental temperature at which increased metabolic rate fails to generate enough heat to maintain body temperature constant, resulting into death of the organism is called the **lower lethal temperature**. The organism then dies due to **hypothermia** (over cooling)

Hypothermia, is a condition that results when heat loss greatly exceeds heat gain from metabolism due to prolonged exposure to cold, resulting into great reduction in core body temperature of the organism

When the environmental temperature **increases**, the animal reaches its upper / high critical temperature when the environmental temperature rise exceeds the body temperature.

- The **upper critical temperature** therefore is a high environmental temperature at which physical mechanisms like sweating and vasodilation fail to maintain temperature constant, triggering a rise in metabolic rate and body temperature as environmental temperature rises.
- The metabolic rate and body temperature start to increase with the temperature of the environment.
- Animals living in hot weather conditions have a higher upper critical temperature compared to the ones living in water conditions.
- When the environmental temperature rise exceeds the upper critical temperature, the metabolic rate increases even more quickly causing a further rise in body temperature. The body temperature therefore increases indefinitely causing enzyme denaturation and permanent tissue damage leading to death due to heat stroke or hyperthermia, a temperature called the upper lethal temperature. This is an example of positive feedback.
- **Upper lethal temperature** is an extremely high environmental temperature at which increased metabolic rate generates excessive heat which denatures enzymes and other structures, resulting into death of the organism.
- The temperature between the lower critical point and the upper critical point is called the **efficiency range or the range of thermal neutrality**. In the efficiency range, the body's physical mechanisms alone can regulate the body temperature. Therefore efficiency range (range of temperature neutrality) this is the external temperature range at which the body's physical mechanisms are capable of maintaining the temperature constant.

TEMPERATURE CONTROL IN PLANTS

Plants lose and gain heat by the same physical processes as animals i.e. radiation, convection, conduction and evaporation

Plant tissues can tolerate wide fluctuations in temperature and are adapted to live in a variety of habitats, but still they must regulate the temperature to avoid overheating which would denature enzymes, and freezing of tissues which would slow down the metabolic processes.

Plants prevent overheating by;

- Transpiration, as water evaporate into the atmosphere it cools down the body of the plant
- Wilting, parenchyma cells lose turgidity to reduce the surface area of leaves and stems exposed to the sun, hence avoiding much heat gain
- Possession of a shiny cuticle on leaves to reflect heat (sun's radiation) and avoid overheating
- Possession of small needle-like leaves in some plants also reduces excessive heat gain from the sun's rays
- Wilting due to more water being lost in transpiration than that being absorbed causing cells to lose their turgidity hence leaves drop off the plant reducing the surface area for the heat absorption.

Plants prevent freezing by;

- Producing spores or seeds which are very temperature resistant
- Losing the easily damaged leaves when external temperature is low e.g. during winter in temperate plants
- Orienting leaves to take maximum advantage of light at any one time so that they do not shade each other.

EXCRETION AND OSMOREGULATION

Excretion is the removal of metabolic waste products from the body which if left to accumulate become harmful and prevent the maintenance of a constant internal environment.

Excretion is different from secretion in a way that **secretion** is the discharge of materials that have been formed by specialized cells of an organism for use by the body for example release of hormones and digestive juices.

Importance of excretion

- It removes metabolic waste substances which are often by products of major biological reactions.
- It leads to the removal of toxic substances which if allowed to accumulate would harm body cells and some of them are inhibitors of enzymes.
- Organisms sometimes take in nutrients above the required quantity. This excess is therefore removed to avoid interference of the body's functioning.
- Organisms also take in unwanted substances along with nutrients which therefore have to be removed from the body.

Osmoregulation is the regulation of the relative amounts of salts (solutes) and water (solvents) in the body at a steady state. It involves maintaining the solute potential of body fluids constant.

Importance of osmoregulation

- It maintains a constant balance of salts and water in the body so as to provide a normal working concentration.
- It allows elimination of unwanted salts which would alter the concentration of blood.
- It enables the regulation of water content in body fluids hence maintaining a constant osmotic pressure.
- It regulates the hydrogen ion concentration (pH) of the body fluids for efficient enzyme activity.

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

1. Osmotic conformers (Osmo conformers)

Animals whose osmotic concentration of body fluids fluctuates according to that of the environment. eg fresh water lower animals.

2. Osmotic regulators (Osmo regulators)

Animals that maintain or regulate the osmotic concentration of body fluids within narrow limits despite environmental changes eg. most marine vertebrates, higher fresh water animals

EXCRETION IN ANIMALS

Different animals use different organs to carry out excretion as shown below.

Animals	Excretory and osmoregulatory structures
Unicellular organisms	Cell surface membrane
Platyhelminthes	Flame cells
Crustaceans	Antennal glands
Annelids	Nephridia
Arachnids	Book lungs
Insects	Malpighian tubules, trachea
Fish	Gills and kidneys
Amphibians	Lungs, kidneys, liver, gills and skin
Birds and reptiles	Lungs, kidneys and liver
Mammals	Lungs, kidneys, liver and skin

EXCRETORY PRODUCTS

a) Non nitrogenous excretory products

These are the ones that do not contain any nitrogen in them e.g.

1. Carbondioxide from cellular respiration.
2. Water as a result of excess intake or as a by product of respiration excreted in sweat, urine or vapour in the air breathed out.
3. Inorganic ions resulting from excess intake removed by the kidneys in urine or removed as sweat e.g. K^+ , Mg^{2+} , etc
4. Detoxification products resulting from the breakdown of drugs and poisons.

b) Nitrogenous products

These contain nitrogen and they include;

1. Ammonia
2. Urea

3. Uric acid
4. Trimethylamine oxide excreted by marine fishes
5. Creatine and creatinine
6. Hippuric acid excreted by horses

The nitrogenous products are formed as;

1. Products of deamination resulting from the breakdown of excess amino acids in the liver and other parts in different organisms.
2. Products of metabolism e.g. from the metabolism of phosphagens in muscles forming creatine and creatinine. Bile pigments also result from metabolism of worn out red blood cells.
3. Products of breakdown of the nitrogenous bases in nucleic acids.

AMMONIA

Aquatic animals excrete mainly ammonia and therefore called **Ammonioteric** organisms.

Ammonia is extremely soluble in water.

It is highly toxic hence requires dilution by large amounts of water.

Because of the abundant water supply, aquatic animals continuously take in water hence able to excrete ammonia in a dilute solution without dehydration.

Examples of organisms in this category include

- Aquatic invertebrates e.g. water fleas
- Protozoans
- Echinoderms
- Fresh water bony fish
- Larval amphibians

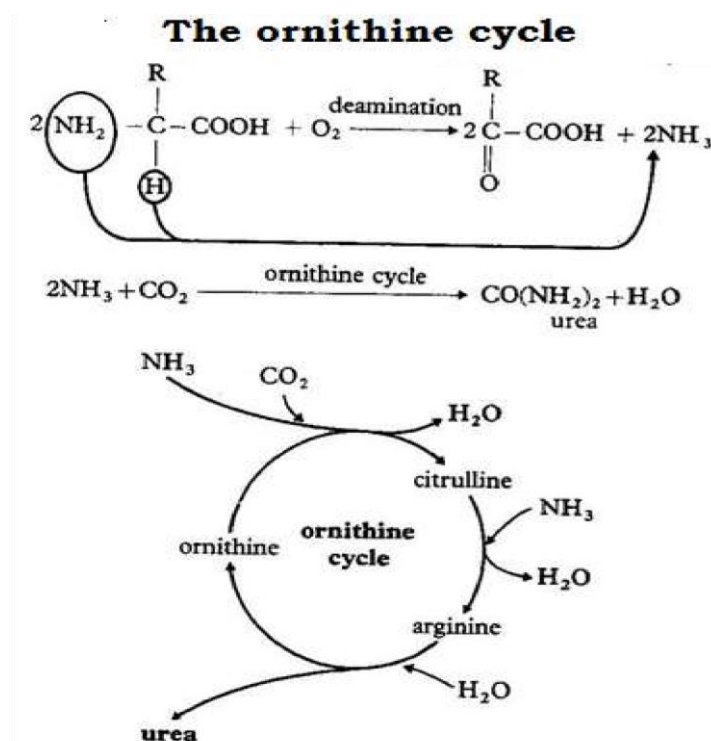
UREA

Animals that eliminate urea are called ureateric organisms.

Urea is less soluble in water than ammonia.

It is less toxic therefore little water is needed for its elimination from the body compared to ammonia.

It is formed from ammonia resulting from deamination in a cyclic reaction called ornithine cycle.



- The amino group (NH_2) of an amino acid is removed and reacts with hydrogen to form ammonia
- Ammonia reacts with carbondioxide to form carbamoyl phosphate, using energy from ATP.
- The carbamoyl phosphate reacts with ornithine to form Citrulline. (Reactions (ii) and (iii) occur in the mitochondrial matrix).
- Citrulline diffuses into the cytoplasm of liver cells and reacts with aspartate to form argininosuccinate.
- Argininosuccinate splits into arginine and fumarate. Fumarate can enter the kreb's cycle.
- Arginine is hydrolysed to form urea and ornithine.
- Urea formed is carried by the blood stream to the kidneys for excretion in urine

Examples of organisms that excrete urea include;

- Mammals
- Marine bony fish
- Cartilaginous fish
- Adult amphibians

URIC ACID

It is insoluble in water, non-toxic and requires very little water for its elimination. It is suitable for animals living in dry conditions since it can even be stored in the cells without toxic effects.

It is excreted in organisms called uricotelic organisms e.g. reptiles like snakes and lizards, insects and birds.

NB:

Trimethylamine oxide is soluble and non-toxic. It is excreted mainly in fish and gives fish its characteristic odour / smell when dead.

THE MAMMALIAN KIDNEY

Functions of the kidney

1. Removal of metabolic waste products.
 2. Regulation of the water content of body fluids and volume of body fluids.
 3. Regulation of the pH of body fluids.
- The kidney has a rich blood supply ie it receives blood from the aorta via the renal arteries and the renal veins return blood to the inferior venacava.
 - There is a pair of kidneys in humans at the base of the abdominal cavity on either side of the vertebral column.
 - Urine formed in the kidneys passes through the ureter to the urinary bladder where it is stored until it is released via the urethra.

Structure of the mammalian kidney

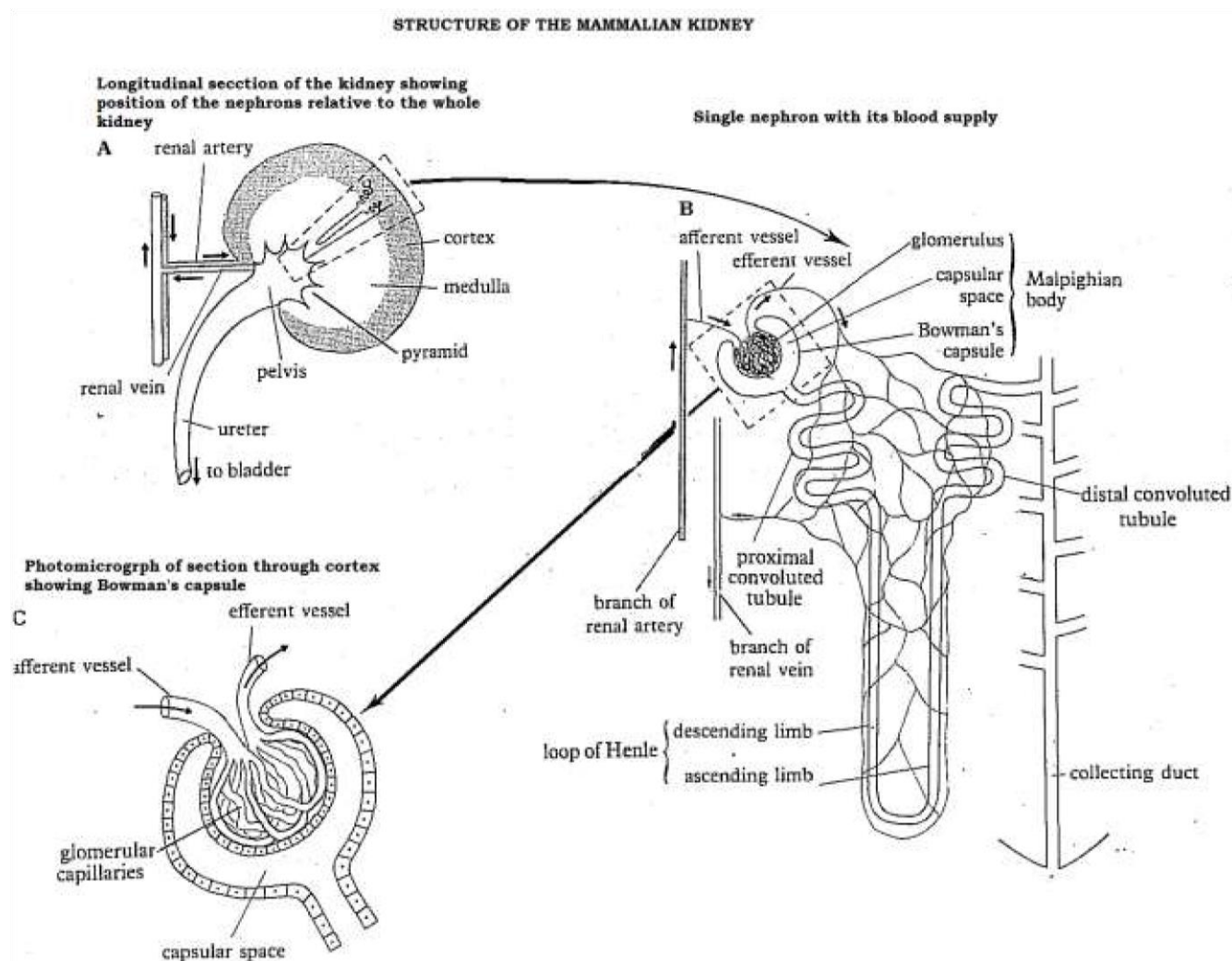
The kidney has two distinct regions, an outer region called the cortex and the inner one called the medulla. The cortex contains the bowman's capsule, proximal convoluted tubule and the distal convoluted tubule of the nephron. It also contains several glomeruli within the bowman's capsule.

The cortex is covered by a fibrous capsule or coat.

The inner region, the medulla contains the loop of Henle and the collecting ducts.

At the centre of the kidney is a pelvis which is an expanded / extended cavity behind the medulla. It is connected to the ureter that carries urine to the urinary bladder.

Each human kidney contains about one million nephrons



THE NEPHRON

Types of nephrons

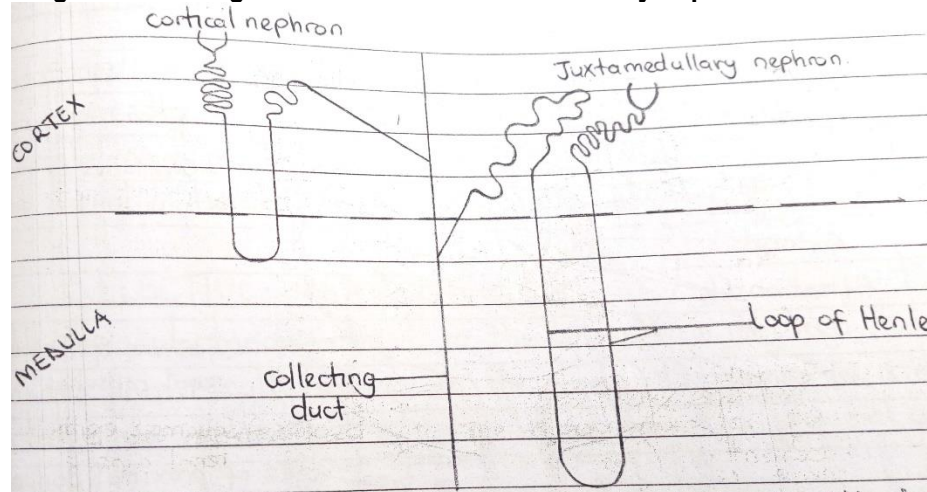
1. Cortical nephrons

These are found in the cortex with relatively short loops of Henle which just extend into the medulla. These nephrons are used under normal water availability.

2. The Juxta medullary nephrons

They have their renal corpuscle close to the junction of the cortex and the medulla. They have long loops of Henle which extend deep into the medulla. These nephrons are used when the amount of water available is low hence retain much of the water in blood.

Diagrams showing the cortical and Juxta medullary nephrons



Structure of a nephron

- Each nephron consists of a cup shaped **Bowman's capsule** which encloses a dense network of capillaries called the **glomeruli**.
- The bowman's capsule and the glomerulus form the **malpighian body / corpuscle**.
- Between the inner and outer lining of the bowman's capsule is the **capsular space**.
- Each glomerulus is supplied by an **afferent arteriole** arising as a branch of the renal artery.
- Emerging from the glomerulus is the **efferent arteriole** which leads to a capillary network surrounding the tubules.
- Leading from the bowman's capsule is a coiled tubule called **proximal convoluted tubule** (located in the cortex)
- The proximal convoluted tubule leads to a U shaped **loop of Henle** with the descending and ascending limbs located in the medulla.
- The loop of Henle leads to another coiled tubule i.e. the **Distal convoluted tubule** located in the cortex, which opens into the collecting ducts along with other nephrons.
- Ducts converge at the pelvis and shed their contents into the ureter which conveys urine to the urinary bladder for temporary storage.

The kidney purifies blood mainly by ultrafiltration and selective re-absorption of materials finally leading to formation of urine.

HOW THE NEPHRON WORKS

ULTRA FILTRATION IN THE BOWMAN'S CAPSULE

This is the removal from blood of all blood components except blood cells and proteins under pressure. Ultra filtration is facilitated by;

1. High blood pressure in the glomerulus which causes many components of the blood including water and nitrogenous wastes excluding plasma proteins and blood cells to pass into the capsular space. The high pressure in the glomerulus is maintained by:
 - Pumping action of the heart.
 - Diameter of the afferent arteriole being greater than that of the efferent arteriole.
2. The pores in the capillary endothelium and the spaces in the epithelial cells of the bowman's capsule which allow passage of blood plasma. The pores are large enough to allow small substances to pass through but small enough to prevent large molecules from passing through hence the basement membrane between the capsule and the capillaries prevents blood cells and proteins from passing out of the glomerulus.

Diagram of the renal corpuscle showing typical cells of the renal / bowman's capsule

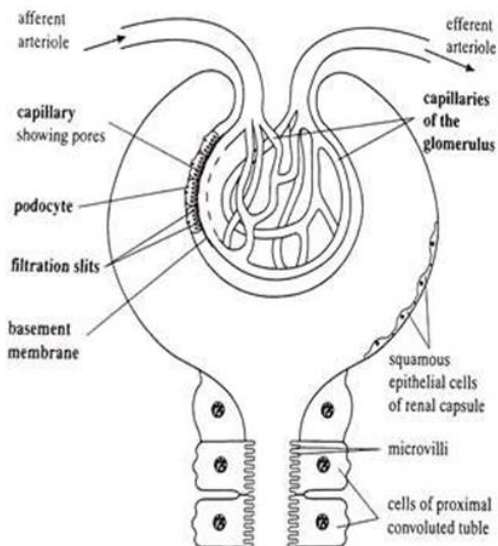
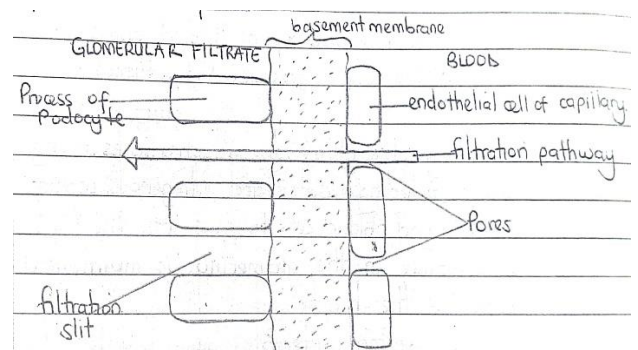


Diagram showing the path taken by the fluid (glomerular filtrate) as it passes from the plasma in the glomerular cavity to the lumen of the renal / bowman's capsule.



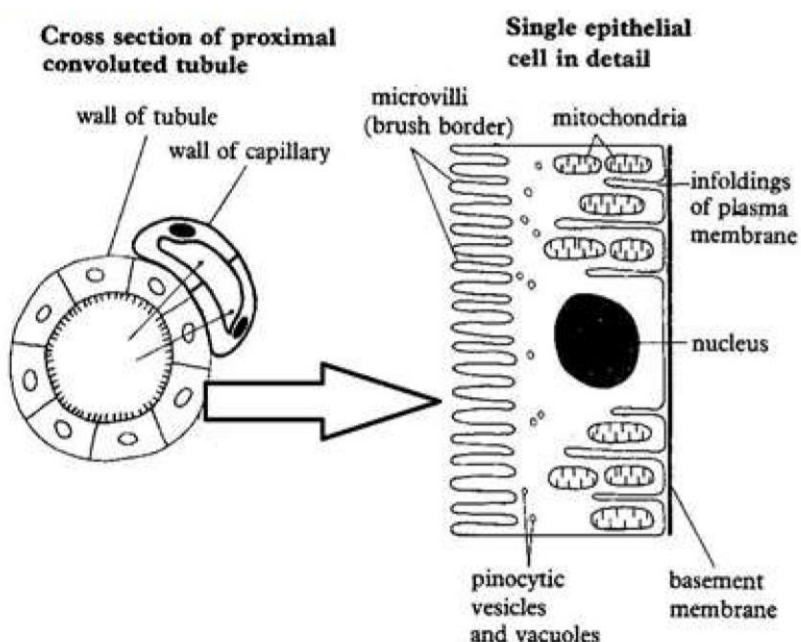
Ultra filtration takes place through three layers i.e.

1. The endothelium of the blood capillary which is perforated with pores.
 2. The basement membrane of the blood capillary that supports the epithelium. In this membrane, water and small solute molecules pass through but blood cells and protein molecules cannot pass through.
 3. The epithelium of the renal / bowman's capsule made of **podocytes** with slit pores called **filtration slits**.
- The molecules filtered include glucose, vitamins, amino acids, some hormones, ions, urea etc. From the renal / bowman's capsule, these molecules in the glomerular filtrate move to the proximal convoluted tubule where most of the useful materials are reabsorbed back into the blood.

SELECTIVE REABSORPTION

All substances useful to the body that are required to maintain the water salt balance in the body fluids at a steady state, are reabsorbed into the blood from the proximal convoluted tubule.

Structure of the Proximal convoluted tubule



- The cells of the **PCT** are tightly arranged but with some intercellular spaces behind them.
- At the base of the cells is a capillary network derived from the efferent arteriole.
- Glucose and amino acids first diffuse into the cells of the **PCT** from the glomerular filtrate. They are then actively transported into the fluid of the intercellular spaces and basal channels by carrier molecules into the plasma membrane from where the substances diffuse into the blood in the capillary network.
- Vitamins and hormones simply diffuse from the filtrate into the blood.
- Sodium ions are actively pumped from the filtrate into the PCT cells and transported into the blood via the intercellular spaces.
- This movement of dissolved substances from the filtrate into the blood capillary network brings about osmotic movement of water in the same direction hence 70% of water is reabsorbed into the blood from the glomerular filtrate.

- Some urea in the filtrate diffuses back into the blood because of the concentration difference generated by water reabsorption.
- The cells of the blood capillaries next to the PCT actively excrete poisonous substances from the blood into the filtrate along with some nitrogenous wastes e.g. creatinine.
- Any blood proteins that may have been forced into the glomerular filtrate by any extra high pressure in the glomerulus are taken out of the filtrate by pinocytosis.
- As the result of the above processes a much reduced volume of the glomerular filtrate which is isotonic with the body fluid is then passed into the loop of Henle.

Adaptations of PCT cells for reabsorption

- They have microvilli and basal channels increasing the surface area for reabsorption.
- They have numerous mitochondria which provide ATP for the carrier molecules involved in active transport of sodium ions, glucose and amino acids.
- Blood capillaries are so close to these cells for onward transport of materials that have been selectively reabsorbed.

THE LOOP OF HENLE

Its main function is to conserve water and to concentrate sodium chloride in the medulla.

It's found in birds and mammals only hence an adaptation for life on land.

The drier the natural habitat of the organism, the longer its loop of henle eg. A desert Kangaroo rat has a very long loop of henle while a beaver which is a semi aquatic mammal has a very short loop of henle.

The longer the loop of henle, the more concentrated the urine.

Structure of the loop of Henle

It is made up of 3 parts.

1. The descending limb made up of thin epithelial cells. It is very permeable to water molecules and impermeable to ions.
2. The thin ascending limb i.e. the lower part of the ascending limb
3. The thick ascending limb i.e. the upper part of the ascending limb impermeable to water but permeable to sodium, potassium and chloride ions.

Criss crossing the loop of henle is a blood capillary network called **Vasa recta**.

The greater part of these structures lie in the medulla region of the kidney along with the collecting ducts.

Role of the loop henle (Hair pin countercurrent multiplier)

The high concentration of sodium chloride in the medulla of the kidney results into osmotic flow of water from the glomerular filtrate in the descending loop of henle into the interstitial tissues of the medulla, this causes the concentration of the filtrate to increase downwards towards the apex of the loop of henle due to a high salt concentration.

As the renal fluid flows up the ascending loop of henle, Na^+ , K^+ and Cl^- are actively transported out of the renal fluid into the surrounding tissues of the medulla. This forms a region of high salt concentration in the deeper parts of the medulla where the collecting ducts pass before opening into the pelvis.

Some ions like sodium ions diffuse back into the descending loop of henle.

The constant out flow of water from the descending loop by osmosis increases the salt concentration of the renal fluid down the descending loop while its movement up the ascending loop makes the renal fluid dilute due to Na^+ and Cl^- being actively pumped out into the medulla. This phenomenon is called the **unit effect**.

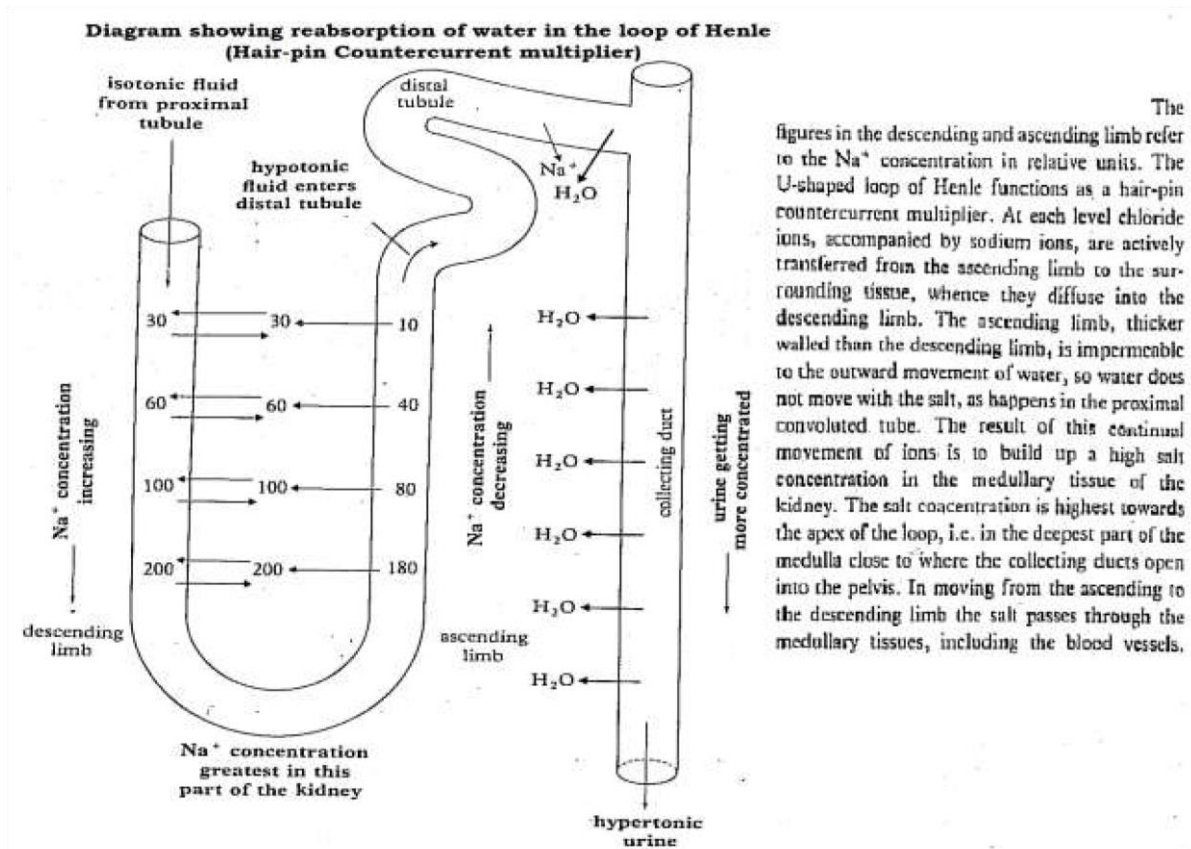
The effect of this at one level of the loop of henle is slight but the overall result is multiplied by the length of the loop of henle / hair pin hence the **Hair pin countercurrent multiplier**.

Therefore, the Hair pin countercurrent multiplier describes the exchange of salts between the renal fluids in the loop of henle where the fluids flow in opposite direction resulting into an increase in concentration of the renal fluid flowing down the descending loop of henle and the decrease in concentration of the renal fluid flowing up the ascending loop of henle.

Adaptations of the loop of henle to operate as a counter current multiplier system.

- The descending limb of the L.O.H is permeable to water but impermeable to salts and solutes so water can be drawn out along the length of the limb.
- The ascending limb of the L.O.H is permeable to salts ie Na^+ , K^+ , Cl^- but impermeable to water therefore salts are actively pumped out of the renal fluid flowing up the ascending limb into the surrounding tissue of the medulla of the kidney.
- The L.O.H is surrounded by the fine network of blood capillaries called the vasa recta which transport away the reabsorbed salts thus promoting the counter current exchange system.
- The hair pin bend of the loop brings into close proximity of the ascending and descending limbs of L.O.H with renal fluids in them flowing in opposite directions resulting into quick exchange of materials between the descending and ascending limbs.

- The blood flowing in the vasa recta is very sluggish hence a high concentration in the medulla is not lowered by quick removal by the blood in the capillaries.
- The walls of the loop of henle contain numerous mitochondria which provide energy for active pumping of salts out of the renal fluid in the ascending loop of henle.



THE DISTAL CONVOLUTED TUBULE

It is the second coil after the loop of henle. Its cells have microvilli and mitochondria enabling active transport of ions and increasing the surface area for reabsorption.

In the DCT, ions and water are reabsorbed from the renal fluid.

COLLECTING DUCTS

These are tubules that run from the cortex down to the medulla where they join with several ducts to form large ducts known as **Ducts of Bellin**.

As the collecting ducts pass into the concentrated medulla, the filtrate in them lose water by osmosis to the medulla region resulting into the formation of highly concentrated urine.

The permeability of the walls of the collecting ducts to water is controlled by Antidiuretic hormone (ADH) which indirectly regulates water re-absorption in this region.

THE PROCESS OF URINE FORMATION

The afferent vessel or arteriole brings blood to the glomerulus in the bowman's capsule / renal capsule and a high pressure builds up within the glomerulus.

This forces the components of blood with small molecules such as glucose, amino acids, hormones, urea, vitamins and salts and water to pass into the capsular space but plasma proteins and blood cells with large molecules are prevented leading to formation of glomerular filtrate, a process called Ultra filtration.

The glomerular filtrate is passed to the proximal convoluted tubules where substances like glucose, amino acids, vitamins and hormones are reabsorbed into the blood stream by active transport and diffusion, salts re-absorbed by active transport and water reabsorbed by osmosis.

The renal fluid passes down the descending limb of the loop of henle where water is passed out of the fluid into the medulla by osmosis, increasing the concentration of the renal fluid down the descending limb of the loop of Henle.

In the ascending limb, Na^+ , K^+ and Cl^- are passed out of the renal fluid into the medulla by active transport. This decreases the concentration of the renal fluid as it flows up the ascending limb of the L.O.H

The renal fluid flows to the distal convoluted tubule where salts are actively reabsorbed and water reabsorbed by osmosis, increasing the concentration of the renal fluid down the descending limb of the loop of Henle.

In the ascending limb, Na^+ , K^+ and Cl^- are passed out of the renal fluid into the fluid into the medulla by active transport. The decreases the concentration of the renal fluid as it flows up the ascending limb of the L.O.H

The renal fluid flows to the distal convoluted tubule where salts are actively reabsorbed and water reabsorbed by osmosis.

The fluid flows to the collecting ducts where more water is reabsorbed by osmosis forming urine which is passed to the bladder for temporary storage before being passed out through the urethra.

Question

Account for the kidney as an excellent organ for excretion and osmoregulation in mammals.

(Adaptations of the kidney)

- It has numerous nephrons that increase the efficiency of ultra-filtration and selective re-absorption.
- Each nephron has coiled tubules which increase the surface area for reabsorption.
- The afferent arteriole has a wider lumen than the efferent arteriole creating a high pressure in the glomerulus that promotes ultra-filtration.
- The bowman's capsule has a thin epithelial layer and filtration slits in the basement membrane allowing easy passage of substances of smaller molecules from the glomerulus to the capsular space promoting ultra-filtration.
- The thin wall of the glomerulus capillaries allows easy passage of blood constituents with small molecular sizes out of the glomerulus during ultra-filtration.
- The highly coiled glomerulus increases the surface area over which ultra-filtration occurs.
- The bowman's capsule has special cells called podocytes that enhance movement of fluids with dissolved substances from the glomerulus into the capsular space.
- Close proximity of the blood capillaries in the Vasa recta with the descending and ascending limbs of the L.O.H make it easy for re-absorption of essential substances into the blood stream.
- The high concentration of salts in the interstitial tissues of the medulla through which the collecting ducts pass maximizes reabsorption of water into the blood hence its conservation.
- The renal / bowman's capsule has a cup shaped cavity or space where glomerular filtrate easily collects.
- The epithelial cells of the proximal convoluted tubule contain numerous mitochondria for provision of energy to enable active transport of substances e.g. glucose, amino acids etc from the kidney tubules.
- Sensitivity of the walls of the collecting ducts to Anti diuretic hormone promotes maximum reabsorption of water forming hypertonic / concentrated urine hence water conservation.

Why does urine production almost stop 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 brain to maintain life. Therefore the volume of blood flowing through the kidneys reduces greatly to the extent that less ultra-filtration occurs leading to formation of less urine.

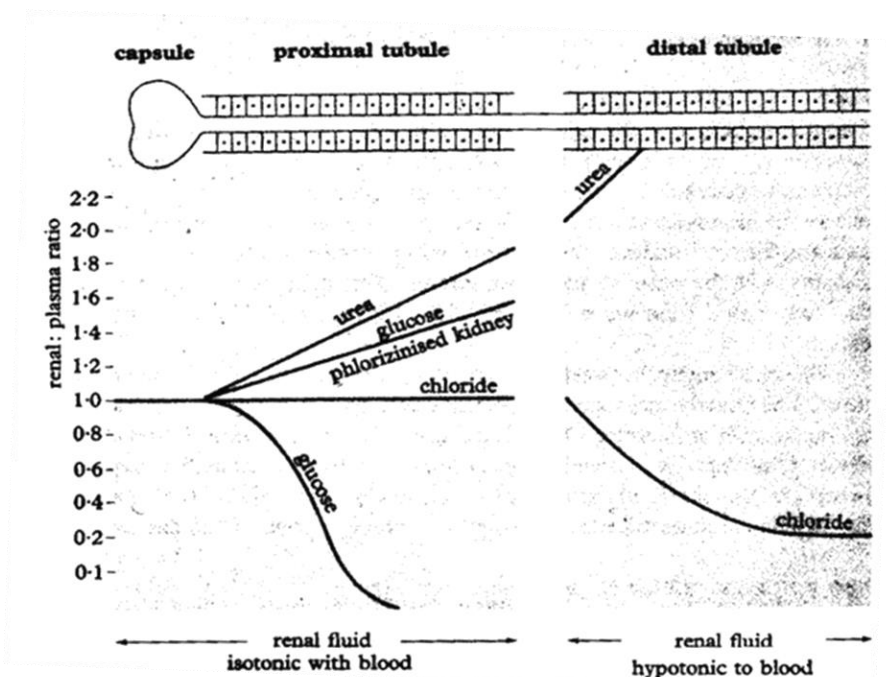
COMPOSITION OF RENAL FLUID

The composition of renal fluid is expressed in terms of **Renal Plasma Ratio (RPR)**

Renal plasma ratio is the ratio of concentration of a particular constituent in the renal fluid to the concentration of the same constituent in the blood plasma. i.e.

$$\text{RPR} = \frac{\text{Concentration of a constituent in renal fluid}}{\text{Concentration of the constituent in blood plasma.}}$$

Graph showing the Renal Plasma Ratios for glucose, chloride ions and urea at different points along the kidney nephrons.



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.
ii) Chloride concentration remains almost constant in the renal fluid and the blood plasma at the capsular space up to the end of the proximal tubule	Reabsorption of chloride ions has not yet occurred.
iii) 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 - large volume of water is reabsorbed into capillaries - 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.
iv) 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 sodium ions.

Percentage concentrations of some substances in the glomerular filtrate and urine of the mammal.

Substance	Glomerular filtrate	Urine
Water	90	95
Protein	0	0
Na^+	0.3	0.35
Cl^-	0.37	0.6
Glucose	0.1	0
Urea	0.03	2.0

EXCRETION AND OSMOREGULATION IN OTHER ORGANISMS.

1. PROTOZOANS

They live in fresh and marine water habitats. Their cell membrane is selectively permeable therefore excretion of carbondioxide and ammonia occurs by diffusion over the entire surface of the cell.

Amoeba is a small organism with a large surface area to volume ratio for easy diffusion.

The internal osmotic pressure (O_{pi}) is greater than the osmotic pressure of the surrounding environment (O_{pe}). As a result, water enters the cell by osmosis. The large influx of water is counteracted by action of the contractile vacuoles in the cytoplasm.

It removes the water and regulates the volume of the cell preventing it from increasing in size and bursting. The water in the cytoplasm collects into small temporary vacuoles that eventually fuse with each other and empty the water into the contractile vacuole that eventually discharges its contents to the exterior through small pores in the cell membrane.

The contractile vacuole is surrounded by numerous mitochondria that provide energy for the filling of the contractile vacuole with water.

In fresh water, some amoeba and other protists osmoregulate by any of the following methods:

1. Actively secreting salts out of the body. This enables the internal osmotic pressure (O_{pi}) to become relatively lower than the external osmotic pressure (O_{pe}) hence water is instead lost by osmosis to the surrounding environment. The activity of the contractile vacuole is consequently lowered and cell bursting that would be due to large influx of water is prevented.

- Altering the permeability of the cell membrane to water such that water is only allowed to move out and its entry into the cell is limited.

N.B

Presence of numerous mitochondria was proved right when amoeba was treated with a metabolic poison such as cyanide, dinitrophenyl, phlorizin and the contractile vacuoles became functionless and water then rapidly filled the cell and the organism died.

Question:

- Explain what happens when amoeba living in marine water is transferred to fresh water.
- Explain what happens when amoeba in fresh water is transferred to marine water.
- 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, 2nd edition, page 527)**

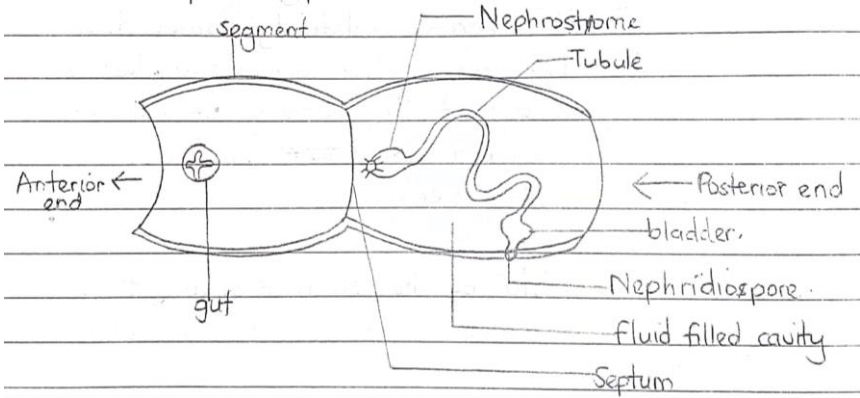
Sea water concentration in % (normal sea water = 100%)	Number of vacuolar contractions per hour	
	Species A	Species B
5	82	20
10	74	63
15	65	64
20	58	56
30	34	31
40	14	13
50	0	6
60	0	0

- Plot the results of the experiment as a graph
- Describe the functioning of the contractile vacuole.
- 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.
- What information may be deduced about the natural habitats of the two species from the rates of vacuolar contractions?

2. ANNELIDS eg earthworms, lug worms and leeches.

In earthworms, the excretory and osmoregulatory structures are known as **Nephridia**. Each segment of the earthworm has a nephridium except the first and last segments. A nephridium is made up of a ciliated funnel shaped structure called the **nephrostome**. The nephrostome rests on the septum. It leads to the next posterior segment as a long coiled tubule. The far end of the tubule enlarges to form a temporary storage chamber called the **bladder** which opens to the outside through a pore called the **nephridiopore**.

Structure of the nephridium in an earthworm.



HOW THE NEPHRIDIUM FUNCTIONS.

The nephrostome lies in the fluid filled cavity containing haemolymph. Haemolymph contains glucose, amino acids, salts, urea and ammonia. Muscular contractions and movements of the cilia lying in the cavity permit fluids to enter the nephrostome and pass down to the tubules. As the fluid moves along the tubules, useful materials like salts, glucose, amino acids, and water are reabsorbed by the cells lining in the tubules. The tubules are well supplied by a network of blood capillaries hence useful materials are returned to the bloodstream.

The nitrogenous wastes continue into the bladder where they are temporarily stored before being excreted out of the body of the earthworm through the nephridiopore.

The waste fluid containing urea and ammonia is called **Urine**.

3. AMPHIBIANS

Amphibians being the first terrestrial vertebrates, they use the kidneys for excretion

- Body fluids of amphibians 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
- During aestivation, amphibians instead of the usual ammonia form urea, which is less toxic and therefore can be retained until water is available for excretion
- Amphibia never drink water hence water gain is osmotic via the skin or in food consumed.

The kidney is more concerned with elimination of excess water other than waste products of metabolism. This is because amphibians are both terrestrial and aquatic hence have to adjust to varying water contents in the surrounding.

They achieve this by altering the rate of filtration. The rate of filtration is high while in water and low while on land.

In addition, certain amphibians e.g. frogs use their urinary bladder for water conservation. In such frogs, the bladder quickly fills with water when the frog is in water. When on land, water from the urinary bladder is reabsorbed to replace water lost by evaporation through the skin surface.

This absorption mechanism is under the control of a hormone similar to antidiuretic hormone in mammals.

4. REPTILES

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 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.
- Terrestrial reptiles reabsorb much of the salt and water in the nephron tubules of kidneys, enabling them to conserve blood volumes in dry environments. Like amphibians and fishes, though, reptiles cannot produce urine that is more concentrated than the blood plasma.

Reptiles minimize water loss by

- (i) Laying cleidoic eggs with waterproof embryonic membranes and supporting shell
- (ii) Possession of waterproof keratinized skin and scales
- (iii) Possession of kidneys with reduced glomeruli hence low rate of glomerular filtration
- (iv) Production of insoluble uric acid which is almost non-toxic and therefore requires little water for elimination
- (v) Absorption of water by the cloaca from faeces and nitrogenous wastes.

5. TERRESTRIAL ARTHROPODS.

Arthropods on land have a challenge of water loss from their bodies. However, they have developed the following mechanisms to prevent water loss.

1. They have hard water proof cuticles with wax covering their body to reduce water loss from the body surface.
2. Possession of valve-like structures and hair in the spiracles to reduce on water loss
3. The rate of evaporation of water in an insect is kept at a low rate.
4. The temperature at which the rate of evaporation from the body of insects most rapid takes long to be reached.
5. Laying cleidoic eggs such that water loss is prevented during embryo development by a relatively impermeable shell.
6. Reabsorption of water by malpighian tubules and rectal glands, resulting in very concentrated uric acid that requires less water for its excretion because it is less toxic and very insoluble in water.

Malpighian tubules and excretion of Uric acid.

They lie in the intercellular space of the abdomen and are bathed by haemolymph. The tubule has two distinct regions ie the upper segment (distal to the gut) and the lower segment (proximal to the gut).

The tubules open into the gut at one end while their free ends float in the haemolymph in the body cavity.

The tissues of insects produce nitrogenous wastes in form of soluble **potassium urate** which is discharged into the haemolymph and taken up by cells lining the malpighian tubules at the distal end.

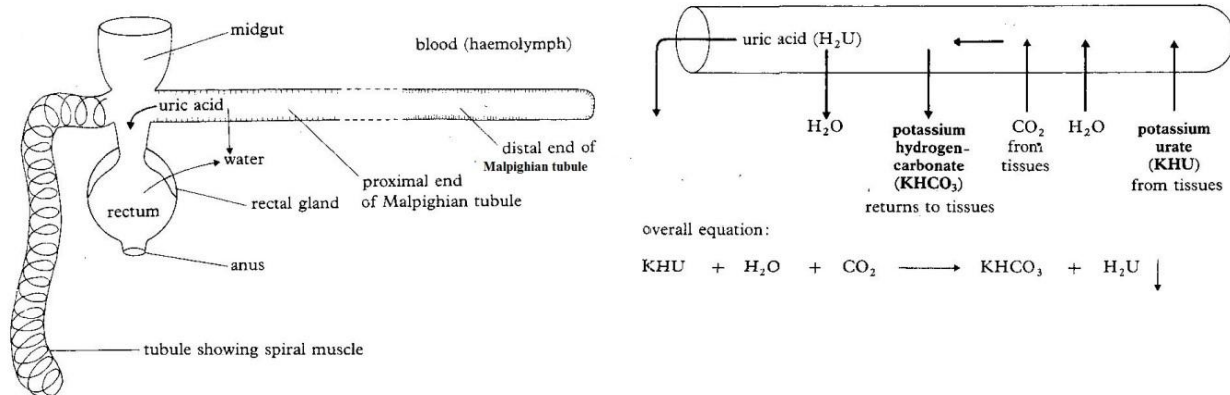
In the cells of the tubule at the distal end, potassium urate reacts with water and carbon dioxide to form **potassium hydrogen carbonate** and **uric acid**.

Potassium urate + Water + Carbondioxide $\longrightarrow$ Potassium hydrogen carbonate + Uric acid
 The potassium hydrogen carbonate is reabsorbed into the haemolymph and uric acid is deposited in the lumen of the tubule.

The reabsorption of potassium hydrogen carbonate back into the haemolymph increases the osmotic pressure in the haemolymph hence water is reabsorbed into the haemolymph.

The proximal end becomes filled with solid crystals of uric acid, water is further reabsorbed by the folded walls of the rectal glands making uric acid more concentrated.

Structure of the Malpighian tubule.



6. AQUATIC ARTHROPODS.

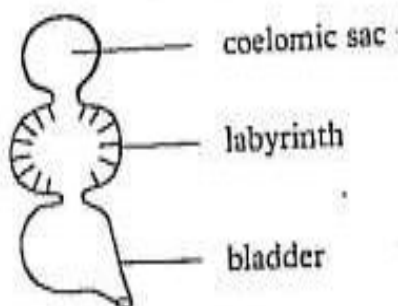
In aquatic crustaceans like the **shore crab, carcinus**, water is eliminated by a pair of **antennal glands** which lie in the haemocoel just in front of the mouth region and open to the exterior by a small pore underneath the base of the antenna.

Each antennal gland consists of a small end sac called **coelomic sac** connected to a large sponge like cavity called the **labyrinth**. This in turn connects to the **bladder** which opens to the exterior by a small pore at the base of the antenna.

The antennal glands excrete nitrogenous waste products. Fluids which are rich in the nitrogenous wastes are filtered into the coelomic sac and into the labyrinth from the surrounding blood and body tissues.

The urine passed out is isotonic with the blood. This is compensated by the gills that absorb salts from the surrounding medium and secrete them into the blood against a concentration gradient. This maintains the internal osmotic pressure (O_{Pi}) relatively higher than that of the external environment (O_{Pe})

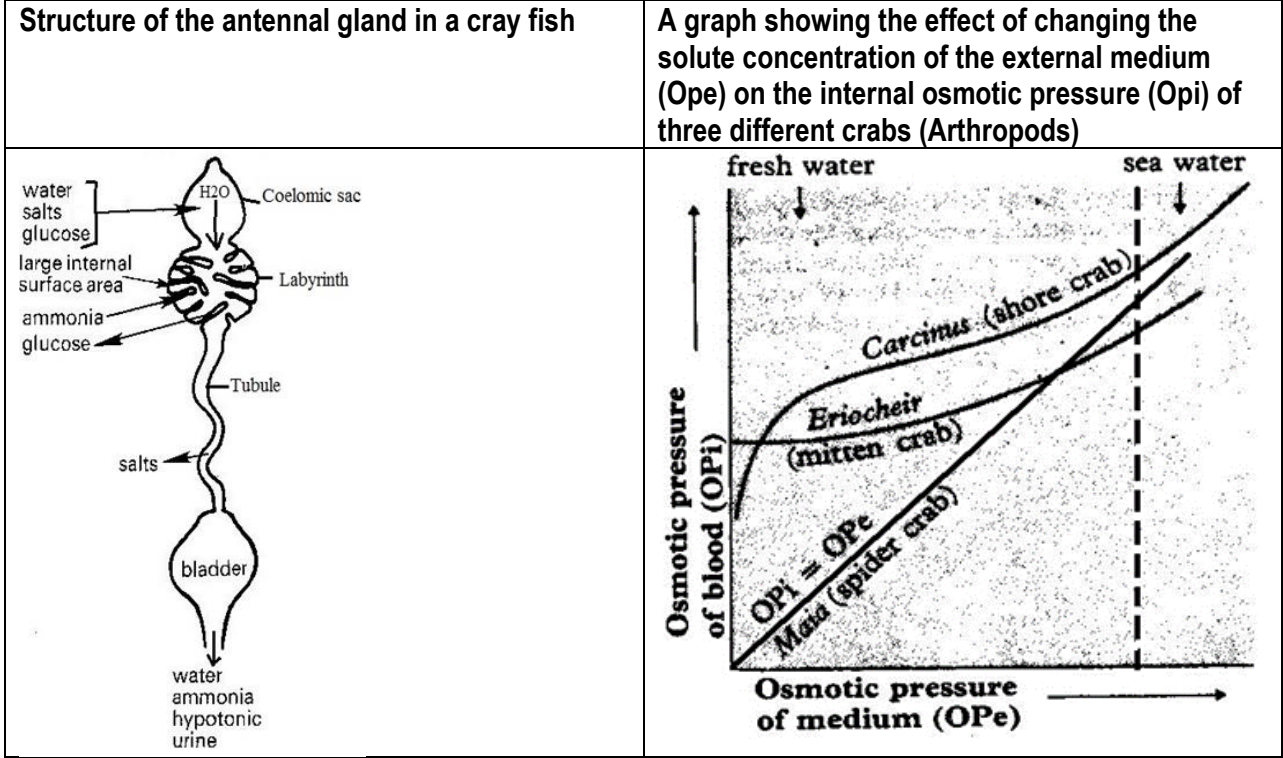
Structure of the antennal gland of the shore crab.



Like in the carcinus (shore crab), **cray fish** has a pair of antennal glands but its antennal gland mainly reabsorbs salts hence capable of forming hypotonic urine.

Salt reabsorption occurs in a coiled tubule linking the labyrinth to the bladder.

The contents of the coelomic sac / end sac and those of the labyrinth are isotonic with the blood but as the urine flows along the coiled tubule, salts are reabsorbed from it hence excess water is eliminated and salts are instead held back thus the internal osmotic pressure (O_{Pi}) is relatively higher than the external osmotic pressure (O_{Pe})



a) Carcinus / shore crab

It can only osmoregulate quite well in fresh water but not efficiently in sea water

Variation

Opi of carcinus is low in fresh water, increases rapidly with slight increase in Ope, then increases slowly thereafter with increase in Ope. Osmoregulation breaks down and Opi increases rapidly with transition into highly concentrated external medium / sea water.

Explanation:

Marine crustaceans experiencing reduced salinities are subjected to osmotic influx of water from the surrounding medium. In Carcinus 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.

b) Eriocheir / mitten crab:

It can osmoregulate in both fresh water and sea water

Variation

Opi of Eriocheir is remains almost constant in fresh water, and increases gradually in sea water.

Explanation:

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

c) Maia / spider crab

It cannot osmoregulate at all.

Variation

Its Opi rapidly increases with increase in Ope.

7. FISH.

Excretory and osmoregulatory organs in fish are gills and kidneys. They have a large surface area to facilitate exchange of materials. They are also permeable to water, nitrogenous wastes and ions.

a) FRESH WATER FISH.

These include;

- i) Fresh water bonny fish (fresh water teleosts) e.g. tilapia
- ii) Fresh water cartilaginous fish (fresh water elasmobranches)

The concentration of the internal fluid of fresh water fish (Opi) is greater than that of the surrounding environment (Ope).

Fresh water fish are therefore faced with the following problems;

- Osmotic influx of much water into their bodies across the gills, lining of the buccal cavity and pharynx. This may / would result into cell bursting.
- Excessive loss of salts from the body due to frequent passage of large volumes of very dilute urine.

The fresh water fish overcome the above problems in the following ways.

- The rate at which glomerular filtrate is formed in the kidney is very high. This is achieved by the kidney possessing numerous large glomeruli hence greater ultrafiltration. This permits fresh water fish to continuously lose a large volume of water and form very dilute urine which contains a considerable quantity of salts and some ammonia.
- As the renal fluid flows along the kidney tubules, salts are extensively reabsorbed into the blood stream forming hypotonic urine to the blood
- The small amount of salt lost in urine is replaced by active uptake of salts by special chloride secretory cells in the gills. These take up salts from the external medium against a concentration gradient and move them to the blood stream so that the salt concentration in the blood stream is relatively greater than that of the surrounding environment.
- By excretion of nitrogenous wastes in form of ammonia which is soluble and toxic and requires a lot of water for its excretion.

b) MARINE FISH.

These include;

- i) Marine bony fish (marine teleosts)
- ii) Marine cartilaginous fish (marine elasmobranches)

Marine fish have body fluids which are hypotonic to the surrounding i.e. their body fluids have a lower Opi than Ope.

Marine fish are therefore faced with the following problems;

- Osmotic movement of water from the body tissues to the environment leading to dehydration of the tissues.
- Too much salts accumulating in their body tissues due to swallowing of large volumes of sea water.

Marine fish overcome the above problems in the following ways.

- The rate at which glomerular filtrate is formed in the kidney is low. This is achieved by the kidney having few glomeruli. This conserves much water in the blood
- By actively excreting out salts by means of chloride secretory cells in the gills. This moves salts against a concentration gradient from the blood to the surrounding sea water.
- By eliminating nitrogenous wastes in form of a compound which is soluble but not toxic i.e. Trimethylamine which requires comparatively little water for its removal.

Marine elasmobranches (marine cartilaginous fish)

These include sharks, rays, dog fish etc.

They have similar salt concentration with marine fish. They would both be expected to have the internal osmotic pressure (Opi) lower than that of the external environment (Ope). However, the Opi of the marine elasmobranches is slightly higher (hypertonic) than that of the environment hence the blood is hypertonic to the sea water. This is achieved by retaining the nitrogenous waste products like urea so that the osmotic pressure of the body fluids is raised relatively to that of the surrounding sea water. This results in slight entry of water into the body of fish.

The retention of urea prevents swallowing of sea water and prevents excess salt accumulation in the body.

This urea retention is made possible by its reabsorption in the kidney tubules and impermeability of gills to it.

Urea can denature proteins but the proteins of elasmobranches are immune to this effect.

c) MIGRATORY FISH (Euryhaline fish)

These are adapted to survive in both fresh and marine water e.g. salmon fish, eel etc

In the course of evolutionary history, certain fish return from fresh water to sea water e.g. the cod whiting.

Salmon spends its first year in fresh water and then moves to the sea. It returns to fresh water to breed after which it goes back to the sea.

The eels on the other hand breed in sea water and their young ones (elvers) then swim to fresh water to complete their growth. When mature, the adults migrate to the sea again.

Migratory fish are adapted to live in both fresh and sea water in a way that when they are in fresh water, their gills pump salts into the body and maintain a constant osmotic pressure, while in sea water the euryhaline chloride secretory cells in the gills actively pump salts out of the body hence maintaining a constant osmotic pressure of their body fluids in both environments thus survival in both environments.

NB.

Gills of other fish can pump salts in only one direction enabling the organisms to survive in either fresh or marine water alone. Because the euryhaline gills can actively pump salts in and out of their bodies, it enables them to;

- Survive in both marine and fresh water.
- Exploit resources maximally in their environment
- Reduce overcrowding and competition.

OSMOREGULATION IN TERRESTRIAL ANIMALS

They lose water through evaporation from the permeable surface exposed to the atmosphere. They exhibit different physiological, morphological and behavioral adaptations so as to minimise water loss / conserve water.

Morphological adaptations.

1. Possession of water proof integuments. This has been developed by insects, reptiles, birds and some mammals e.g. keratinized scales of reptiles, cornified skins in mammals and layers of chitin in the exoskeleton of insects. These all provide protection and reduce excessive water loss from the body surfaces of organisms by evaporation.
2. Sweat pores are more concentrated under armpits to prevent direct exposure to heat from the environment preventing evaporation and loss of water in other areas where the sweat pores are not concentrated. In organisms like dogs, sweat glands are in specific regions of the body that do not encourage excessive water loss.
3. Some animals like the tortoises and snails have shells to control and prevent water loss.
4. Some animals especially desert animals have long loops of henle to increase the surface area for reabsorption of water in the body.
5. Some animals have much hair or fur on their bodies to reduce much exposure of the skin to the environment thereby reducing on the evaporation of water from their bodies.

Physiological / metabolic adaptations.

1. Reduction in the rate of ultrafiltration e.g. in desert frogs which have fewer and smaller glomeruli hence conserving more water.
2. High water reabsorption capacity by the kidney hence much water is reabsorbed from the glomerular filtrate and renal fluid along the kidney tubules. There is also much water reabsorption from the cloaca of birds and from rectal glands in arthropods.
3. Production of non-toxic nitrogenous wastes e.g. in insects, birds and reptiles in a form of solid uric acid which is insoluble in water hence much water is reabsorbed from it into the blood stream because its excretion does not require alot of water.
4. Use of metabolic water in some desert animals. Metabolic water is formed during fat metabolism e.g. Camels possess a hump which stores large amounts of fat hence providing much metabolic water when metabolized.
5. Some animals have tissues which are tolerant to dehydration e.g. camels.
6. Some animals secrete large amounts of Anti diuretic hormone, increasing water reabsorption within the kidney tubules.

Behavioral adaptations.

1. Some animals change their habitats in times of extreme water shortage i.e. they move away from places of extremely high temperatures and extreme / excessive water loss is avoided.
2. Some animals burrow in tunnels to reduce water loss.
3. Drinking of water when animals become thirsty so that more water is absorbed into the blood stream to lower the osmotic pressure of blood and tissue fluid back to normal.
4. Aestivation, some animals go into a state of dormancy during dry season to avoid excessive water loss e.g. lung fish.
5. Some animals become sluggish during hot conditions to reduce water loss.

Adaptations to lack of water in the Kangaroo rat

The kangaroo rat, a desert inhabitant, may spend its entire life without drinking water. It lives on seeds and other dry plant materials.

1. It has no sweat glands, therefore no water lost as sweat.
2. Being nocturnal, it searches for food only when the external temperature is relatively cool.
3. Its faeces have a very low water content.
4. Its urine is highly concentrated.
5. Some cooling of the expired air takes place in its long nose, with condensation of water

OSMOREGULATION IN PLANTS.

Plant tissues contain a higher proportion of water than animal tissues. Plants do not have many challenges of osmoregulation as in animals since they have characteristics in relation to their habitats.

They are divided into four major groups ie

1. Hydrophytes
2. Halophytes
3. Mesophytes
4. Xerophytes

HYDROPHYTES.

These are fresh water aquatic plants e.g. the water hyacinth and the elodea weed.

The concentration of their cell sap is higher than that of the surrounding hence water enters their vacuolar sap by osmosis increasing the volume of the sap vacuole and in turn generating a high turgor pressure. The cells then become turgid and a point is reached when the water potential of the cell is equal to that of the surrounding water and no more water enters. This is termed as **mechanical osmoregulation**.

Fresh water plants are thus faced with a problem of only maintaining the ionic contents of the sap. This is solved by active uptake of ions from the surrounding.

Characteristics of hydrophytes.

- They have little or no lignified supporting tissues.
- Their xylem is poorly developed
- Their stems and leaves lack the waxy cuticle.
- Their stems and leaves have large continuous air spaces forming a reservoir for carbon dioxide which then provides buoyancy to the plant when submerged.
- They have many stomata on the upper epidermis than the lower epidermis.

HALOPHYTES.

These are plants inhabiting areas of high salinity e.g. in estuaries and marshes where salinity may exceed that of sea water therefore the main osmoregulatory problem of these plants is excessive water loss by osmosis to the surrounding medium and water loss by evaporation into the atmosphere.

They solve this problem in the following ways;

- Their roots grow in mud and the shoots in air
- They have large intercellular spaces in the stems and roots giving buoyancy to the plants in marshes.
- They have special salt-secreting glands located on the upper epidermis. These extract and remove excess salts absorbed into the tissues from the saline environment.
- They produce aerial stilt or prop roots which grow down into the soft mud and give the plant firm anchorage and support
- They have special aerial roots called pneumatophores which project upwards from the soil so as to take up oxygen through the numerous lenticels on their surface.
- They are viviparous i.e. the seeds germinate while the fruit is still on the parent plant
- Their seedlings are long and pointed to enable them penetrate the mud when they drop off from the parent plant

MESOPHYTES.

These are plants which live in habitats with adequate water supply e.g. majority of angiosperms.

Their problem is water loss by evaporation, they have solved this through;

- Some open their stomata at night and close them during the day preventing excessive water loss.
- They have variable leaf shapes i.e. some have small leaves reducing the surface area over which water is lost.
- They exhibit leaf abscission (leaf fall) to reduce excessive water loss by transpiration.
- The leaf surface of some plants is hairy thus trapping air which forms a humid insulating layer that lowers the rate of transpiration
- They have more stomata on the lower surface than on the upper surface to reduce on water loss through the stomata
- Some plants have a milky latex which, being viscous, reduce transpiration
- A thick waxy transparent cuticle on the upper surface which minimises water loss through the upper epidermis yet still permits light penetration into the leaf

However, some mesophytes have broad leaves but with thin reflex and a thin cuticle. They have a well-developed vascular system with normal stomatal opening rhythm.

XEROPHYTES.

These are plants that grow in dry regions and able to survive long periods of drought. Their characteristics include the following

i) Modified leaves

- Some have very small leaves to reduce the surface area for transpiration
- Some shed their small leaves in the dry season
- The leaves of some are reduced to small spines
- The leaves may be small, rolled-up and needle-like
- There's a waxy cuticle on the surface of the leaves to reduce on the transpiration rate

ii) Distribution of stomata

- They generally have few stomata, and these are mainly located on the lower leaf surface

- The stomata in cacti are located in grooves or sunken pits
 - In cacti, stomata open at night
- iii) Water storage in plant tissues. Some plants store water in leaves e.g. Bryophyllum and stems e.g. banana
- iv) They have deep and extensive rooting systems
- v) Some plants are very short-lived i.e. they grow, blossom and produce seeds in a short wet season
- vi) Milky latex. Some plants have a white latex in their stems which reduces on their rate of transpiration and also makes them distasteful to herbivores.

Adaptations of xerophytes for survival

Structural adaptations

- Possession of extremely deep roots to obtain water from deep below the water table e.g. acacia
- Shallow root systems for absorbing moisture even slight showering e.g. cactus
- Possession of fleshy succulent stems and leaves that store water in large parenchyma cells e.g. bryophyllum and cactus
- Hairy epidermis for trapping humid air and reduce on the transpiration rate
- Possession of stomata which are sunken in hairy leaf surfaces to trap air and reduce on the transpiration rate
- Rolling / folding of leaves to reduce on transpiration e.g. marram grass (*Ammophila*)
- Possession of a thick cuticle which is impermeable to water e.g. prickly pear (*Opuntia*)
- Reduction of surface area over which transpiration has to occur by having small leaves

Physiological adaptations

- Reversal stomatal rhythms in some plants i.e. 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 dessication i.e. 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 case.

EXCRETION IN PLANTS.

Excretory products of plants include;

- Carbondioxide and water and from respiration
- Oxygen from photosynthesis.
- Anthocyanins stored in petals, leaves, fruits and barks.
- Tannins deposited in dead tree tissues like barks and wood
- Calcium oxalate, calcium carbonates and latex (rubber)
- Alkaloids like quinine, cannabis, cocaine, caffeine, morphine etc.

Plants do not have many waste products as animals hence they have few challenges regarding excretion. This is because of the following reasons.

1. Catabolism in plants proceeds at a much lower rate than in animals hence there is hardly any accumulation of waste products of metabolism.
2. The waste nitrogenous compounds are built into new protein structures.
3. Plant metabolism relies mainly on carbohydrates and not proteins hence the biproducts are less poisonous and do not need to be excreted.
4. Plants do not synthesize excess organic materials. They only manufacture in amounts that are required.
5. Their waste products produced by certain metabolic activities are raw materials for other biological process e.g oxygen formed during photosynthesis is used for aerobic respiration while carbondioxide from respiration is used as raw material for photosynthesis.
6. Many organic waste products of plants are stored in dead tissues within leaves or barks of trees and these are periodically shed off.
7. Some organic acids which may be harmful to plants combine with excess cations and precipitate out as insoluble crystals which can be safely stored in plant cells without causing harm to the plant.
8. Other waste ions such as iron and manganese plus some organic acids such as tannic acid, nicotinic acids pass into the leaves before leaf falls. Some of these substances are eliminated through petals of flowers, fruits and seeds.
9. Aquatic plants lose most of their metabolic wastes by diffusion directly into the water surrounding them.

Question: Explain why plants do not need special excretory organs.