14 Homeostasis

14.1 Homeostasis in mammals

Cells function most efficiently if they are kept in near constant conditions. In mammals, core temperature, blood glucose concentration and blood water potential are maintained within narrow limits to ensure the efficient operation of cells.

a) The importance and principles of homeostasis in mammals

Homeostasis in mammals requires complex systems to maintain internal conditions near constant.

- **homeostasis** – maintenance of a constant internal environment

- the internal environment of an organism is the conditions in which its cells function
- in mammals, a cell's immediate environment is the tissue fluid that surrounds it
- the composition, pH and temperature of tissue fluid are kept constant by exchanges with the blood *(see ch-8)*, and many features of it influence how well the cell functions -
  1) temperature
     - in very low temperatures, metabolic reactions slow down
     - in very high temperatures, proteins (including enzymes) get denatured
  2) water potential
     - when water potential increases, water may enter the cell, it swells and maybe bursts
     - when water potential decreases, water leaves the cells, metabolic reactions may slow or stop
  3) concentration of glucose
     - lack of glucose causes respiration to slow or stop, depriving the cell of an energy source
     - too much glucose may cause water to move out of the cell, disturbing the metabolism

Homeostatic mechanisms work by controlling the composition of blood, which ∴ controls the composition of tissue fluid.

Examples of some physiological factors controlled in homeostasis:

1) core body temperature
2) concentration of metabolic waste substances (e.g., CO_2, urea)
3) blood pH
4) water potential (Ψ) of blood
5) concentration of respiratory gases (CO_2, O_2) in the blood

b) Negative feedback and homeostatic mechanisms

Most control mechanisms in living organisms use a negative feedback control loop to maintain homeostatic balance -

- a receptor senses a **stimulus** (can be internal or external) and sends this **input** through the nervous system to a **control centre** in the brain or spinal cord
  - a stimulus is any change in a factor (e.g., change in blood temperature or blood water potential)
- the control centre signals an **effector** (muscles and glands) to respond to the stimuli
- the response to the stimulus is usually an action being carried out i.e., **output**
- these actions are sometimes called **corrective actions** as their effect is to correct (or reverse) the change
- continuous monitoring of the factor by receptors produces a steady stream of information that makes continuous adjustments, which causes the factor to fluctuate around a **set-point**
- this mechanism is known as negative feedback

➢ **negative feedback** – mechanism that keeps changes to a factor within narrow limits

Negative feedback mechanisms consist of reducing the output or activity of an organ or system back to its normal functionality. However, a positive feedback mechanism is also possible.

➢ **positive feedback** – enhances or accelerates the output created by an activated stimulus

The two coordination systems that transfer information between different part of the body for homeostatic mechanisms are –

1) **nervous system** – information is in the form of impulses and is carried by neurones *(see ch-15)*

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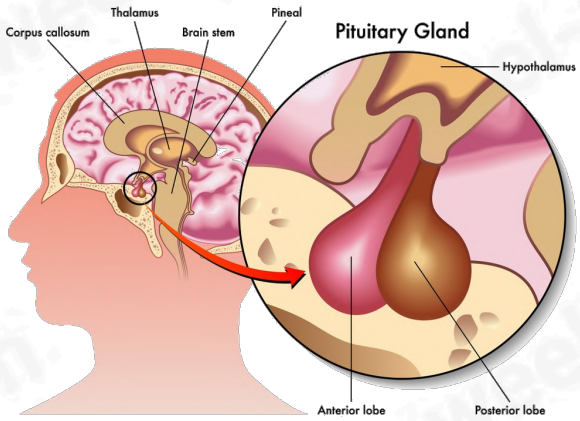
2) **endocrine system** – hormones travel in blood, in a form of long-distance cell signalling

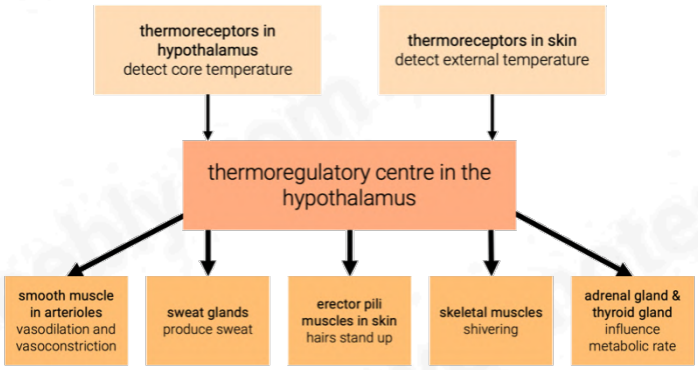
c) Roles of the nervous system and endocrine system in co-ordinating homeostatic mechanisms

1) thermoregulation - control of body temperature

- the heat that mammals generate is released during respiration
- much of this heat is produced by liver cells that have a huge requirement for energy
- the heat they produce is absorbed by blood flowing through the liver and distributed around the rest of the body



- the hypothalamus in the brain is the central control for body temperature
- this region of the brain receives a constant input of sensory information about the temperatures of the blood and surroundings
- it has thermoreceptor cells that continually monitors the temperature of the blood flowing through it (the **core temperature**)



Responses to low temperatures

1) **vasoconstriction** – muscles in the walls of arterioles that supply blood to capillaries near the skin surface contract, decreasing the lumen size; blood supply is reduced so less heat is lost from blood
2) **less sweat produced** – reduces heat loss by evaporation from the skin surface
3) **body hairs are raised** – traps air, which is an insulator, although not very effective for humans
4) **shivering** – involuntary contraction of skeletal muscles generates heat
5) **adrenaline secreted** – increases rate of heat production from the liver

When the temperature of the environment decreases gradually

1) the hypothalamus secretes a hormone which stimulates the anterior pituitary gland to release thyroid stimulating hormone (TSH)
2) TSH stimulates the thyroid gland to secrete thyroxine into the blood
3) thyroxine increases the metabolic rate which increases heat production, especially in the liver

When the temperature of the environment starts to increase again, the hypothalamus responds by reducing the release of TSH by the anterior pituitary gland.

Responses to high temperatures

1) vasodilation
2) increased sweating – water has high latent heat of evaporation
3) body hairs are lowered

2) osmoregulation – control of the osmotic pressure of an organism's body fluids

- detected by osmoreceptors
- controlled by the kidneys *(see 14.1g)*

3) control of blood glucose concentration

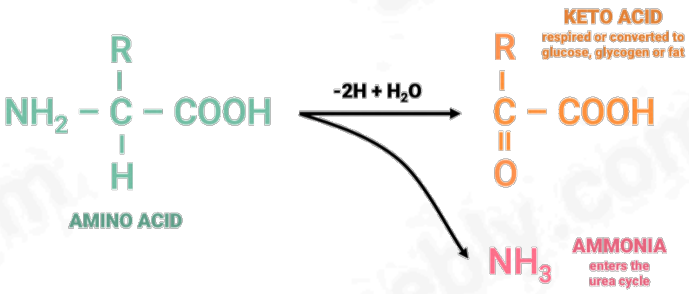
- regulated by the pancreas *(see 14.1h, i)*

d) Deamination and the formation of urea

Extra proteins cannot be stored in the body. To make use of the amino acids in them, the liver removes $-NH_2$ along with an extra hydrogen atom, producing a keto acid and ammonia.

The ammonia produced is extremely toxic, so it's converted to urea in the urea cycle and excreted.

The keto acid that remains may enter the Krebs cycle and be respired, or it may be converted to glucose, glycogen or fat for storage.



1) **deamination**

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$$\underset{\text{ammonia}}{2NH_3} + CO_2 \rightarrow \underset{\text{urea}}{CO(NH_2)_2} + H_2O$$

2) **urea formation**

Nitrogenous excretory products of humans

1) **urea** – the main nitrogenous excretory product in humans
2) **creatinine** – made in the liver from certain amino acids
   - a substance called creatine which is made in the liver from certain amino acids is used in the form of creatine phosphate in the muscles as an energy store *(see Ch-15)*
   - some of this is creatine is converted to creatinine and excreted
3) **uric acid** – made from the breakdown of purines from nucleotides, not amino acids

e) Structure of the kidney and nephrons

1) Position of the kidneys and associated structures in the human body

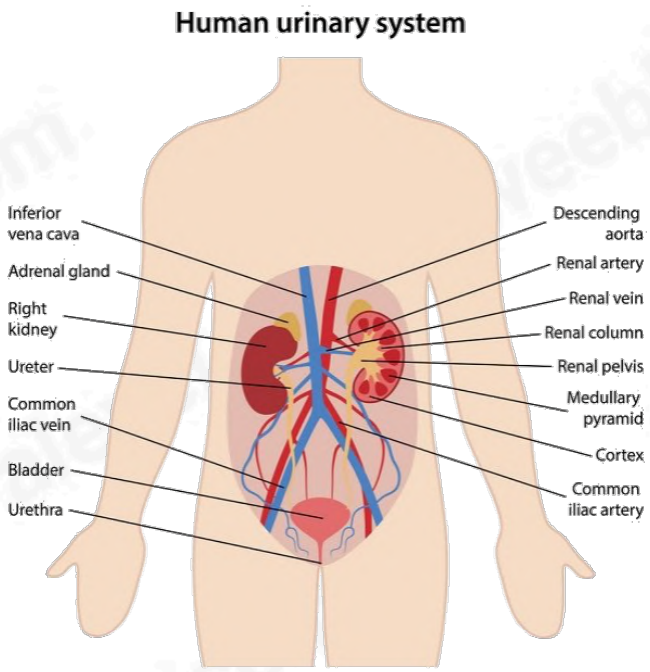


Image: https://biologydictionary.net/urinary-system/

- the kidneys remove wastes from the blood and are the effectors for controlling the water potential of the blood
- each kidney receives blood from a **renal artery** and returns blood via a **renal vein**
- the **ureter** carries urine from the kidney to the bladder
- from the bladder, urine is excreted out through a single tube called the **urethra**

2) Section through a kidney

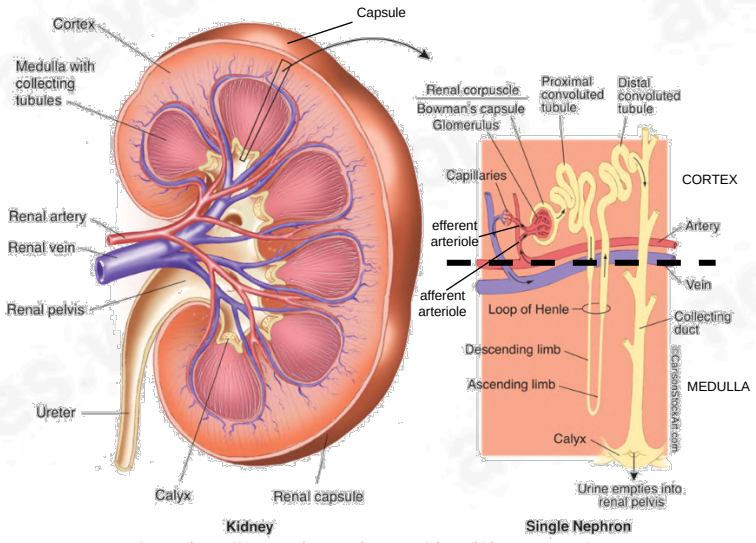
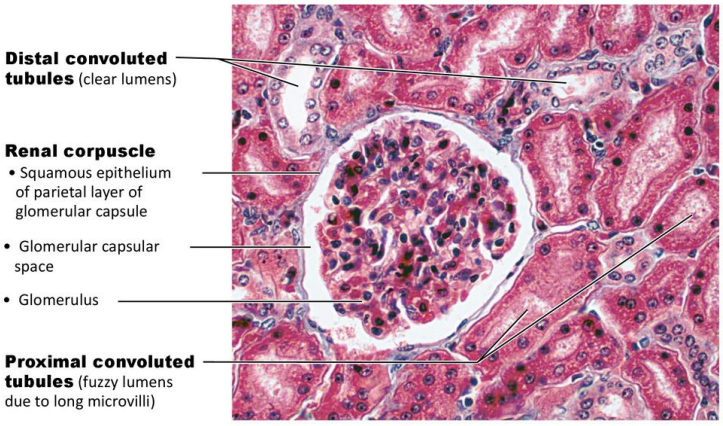


Image: https://www.carlsonstockart.com/photo/kidney-anatomy/

- the whole kidney is covered by a fairly tough **capsule**
- the kidney has three main areas – the **cortex** (lies beneath the capsule), **medulla** (the central area), and the **pelvis** (the area where the ureter joins)
- the kidney is made up thousands of tiny tubes called **nephrons** and many blood vessels

3) Histology of the cortex



(a) Photomicrograph of renal cortical tissue (180x)

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Structure of a nephron

- one end of the tube forms a cup-shaped structured called the **Bowman's capsule** which surrounds a tight network of capillaries called a **glomerulus** in the cortex
- from the capsule, the tube runs towards the medulla, first forming a twisted region called the **proximal convoluted tubule**, and then a long hairpin loop in the medulla called the **loop of Henle**
- the tubule then runs back upwards towards the cortex, where it forms another twisted structure called the **distal convoluted tubule**
- lastly, this is joined with the collecting duct which leads down through the medulla and into the pelvis

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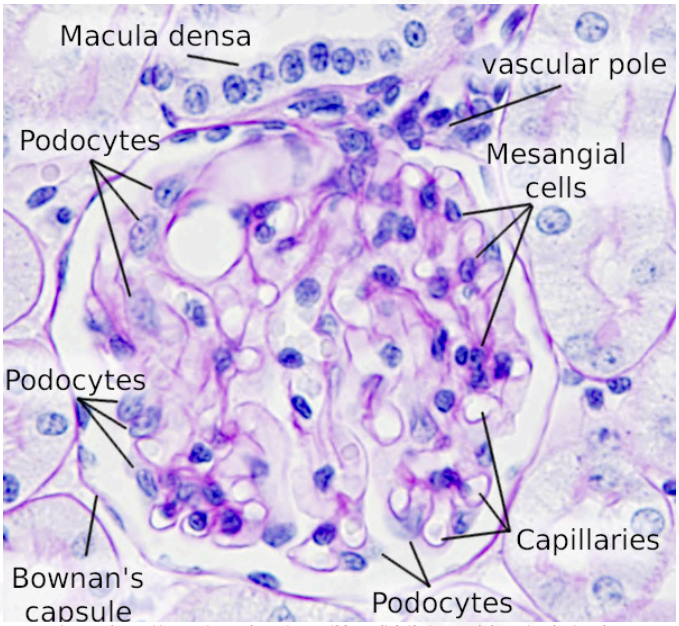

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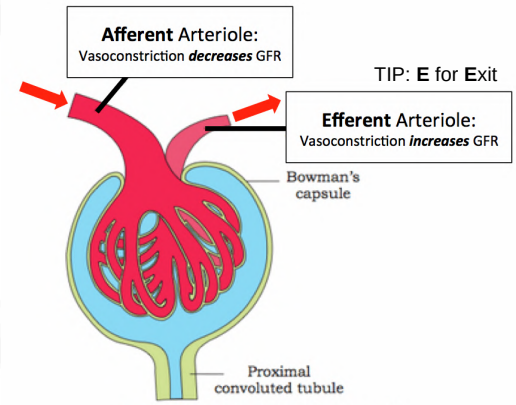
- each glomerulus is supplied with blood by a branch of the renal artery called an **afferent arteriole**
- the capillaries of the glomerulus re-join to form an **efferent arteriole** which then flows into a branch of the renal vein via another network of capillaries



Microvascular modulation of glomerular filtration rate (GFR)

4) Histology of the medulla

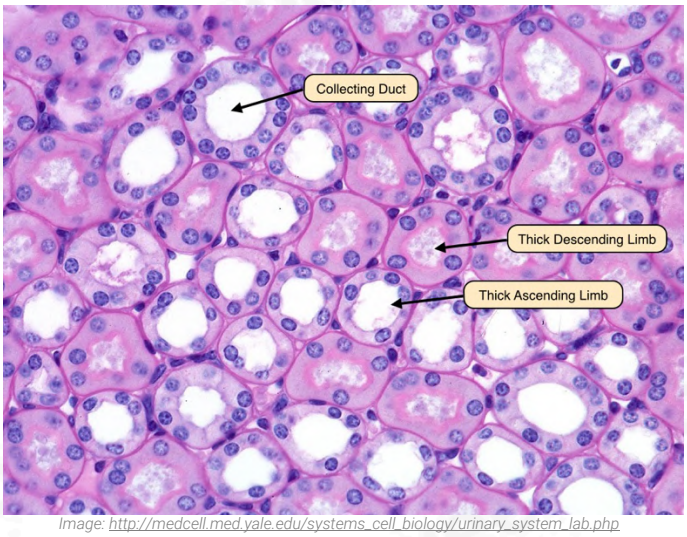


Image: http://medcell.med.yale.edu/systems_cell_biology/urinary_system_lab.php

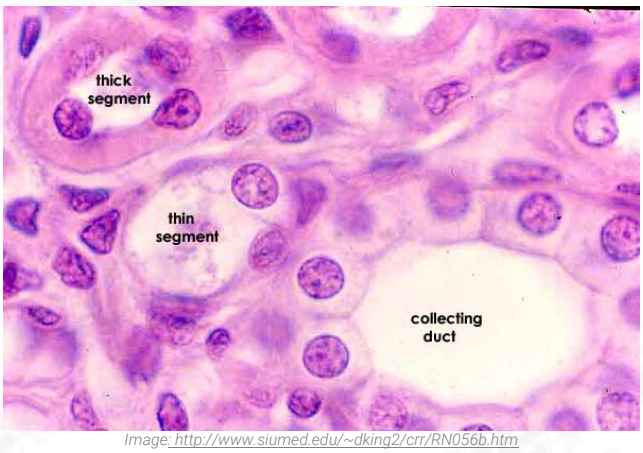


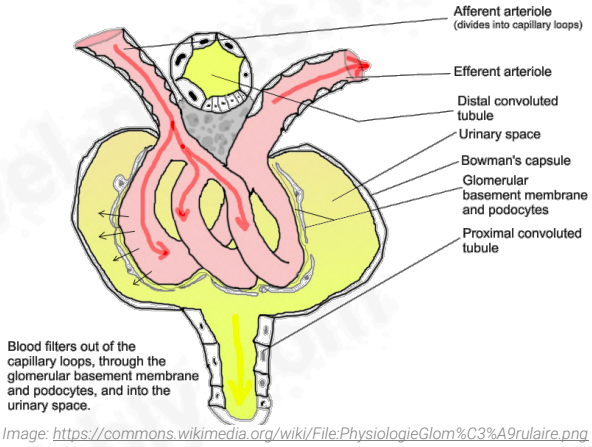
Image: http://www.siumed.edu/~dking2/crr/RN056b.htm

f) Formation of urine in the nephron

The kidney makes urine in two stages – ultrafiltration and selective reabsorption.

1) Ultrafiltration

This is where small molecules in the tubular fluid such as water, glucose, amino acids, salts, and urea are filtered out of the blood in the glomerular capsule across the basement membrane of the Bowman's capsule, due to high hydrostatic pressure.



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The blood in the glomerular capillaries is separated from the lumen of the Bowman's capsule by two cell layers and a basement membrane:

1) **endothelium of the capillary** ***(first cell layer)*** – contains more gaps compared to other capillaries
2) **basement membrane** – made up of a network of collagen and glycoproteins
3) **epithelial cells** ***(second cell layer)*** – make up the inner lining of Bowman's capsule and have many tiny finger-like projections with gaps in between them, and are called **podocytes**

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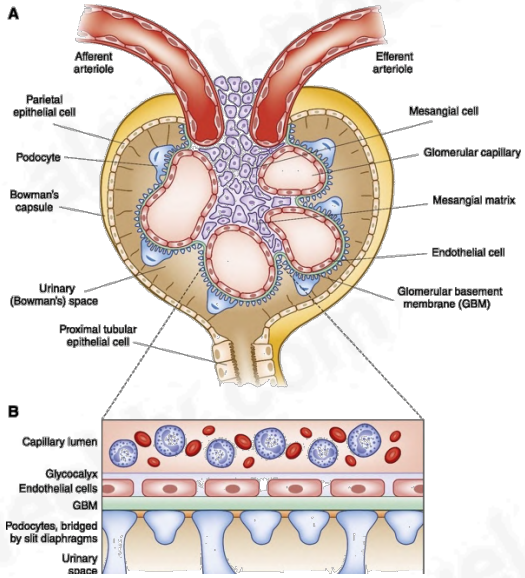


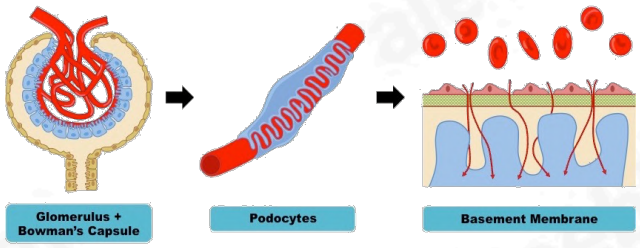


Image: https://ib.bioninja.com.au/higher-level/topic-11-animal-physiology/113-the-kidney-and-osmoregu/ultrafiltration.html

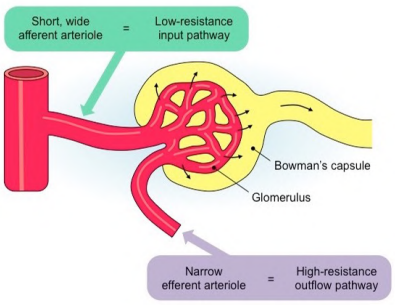
- **glomerular filtration rate** – the rate at which fluid filters from the blood in glomerular capillaries into the Bowman's capsule *(~125 $cm^3 min^{-1}$ in humans)*
- this is determined by differences in water potential between the plasma in glomerular capillaries and filtrate in the Bowman's capsule

➢ **water potential is lowered by the presence of solutes**
➢ **water potential is raised by high pressures**

Factors affecting the glomerular filtration rate

1) **blood pressure inside the glomerular capillaries is high as the diameter of the afferent arteriole is wider than that of the efferent arteriole**

This raises the water potential of blood plasma above the water potential of the contents of the Bowman's capsule. The net pressure gradient within the glomerulus forces blood to move into the capsule space (forming filtrate).



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2) **solute concentration in blood plasma in capillaries is higher** *(∴ water potential is lower here)* **than solute concentration in filtrate in the Bowman's capsule**

This is because while most of the contents of blood plasma are filtered through the basement membrane, the plasma protein molecules are too big to get through and so stay in the blood.

Overall, **the effect of pressure differences outweighs this effect**. This means that the water potential of the blood plasma in the glomerulus is higher than water potential of the filtrate in the capsule, **so water continues to move down the water potential gradient from blood into the capsule**.

2) Selective reabsorption

This is where any useful molecules from the fluid in the nephron is taken back as it flows along. Most of the reabsorption takes place in the proximal convoluted tubule.

Molecules reabsorbed include:

1) all of glucose *(except in diabetics – see 14.1L)*
2) vitamins
3) water
4) some inorganic ions (e.g., Na^+, Cl^-)
5) amino acids

Reabsorption in the proximal convoluted tubule

The lining of the proximal convoluted tubule is made of a single layer of **cuboidal epithelial cells** which have the following adaptations for reabsorption:

1) **microvilli** present to increase surface area of inner-surface facing lumen
2) **tight junctions** that hold adjacent cells together so fluid doesn't pass between cells (all substances reabsorbed must go through cell)
3) **many mitochondria** to provide energy for Na^+/K^+ pump
4) **co-transporter proteins** in the membrane facing lumen

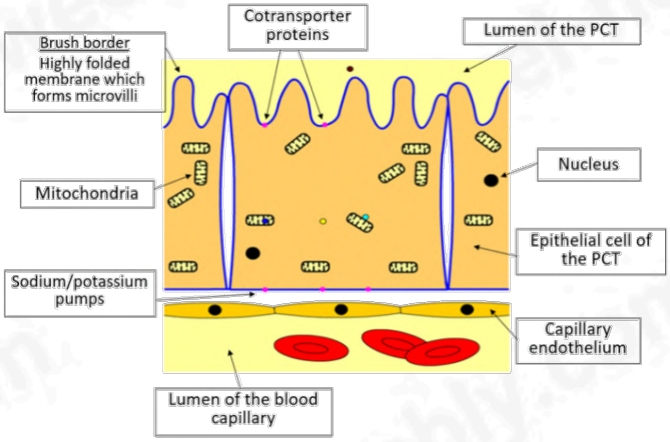

Image: https://www.tes.com/teaching-resource/selective-reabsorption-aqa-a-level-biology-12185238

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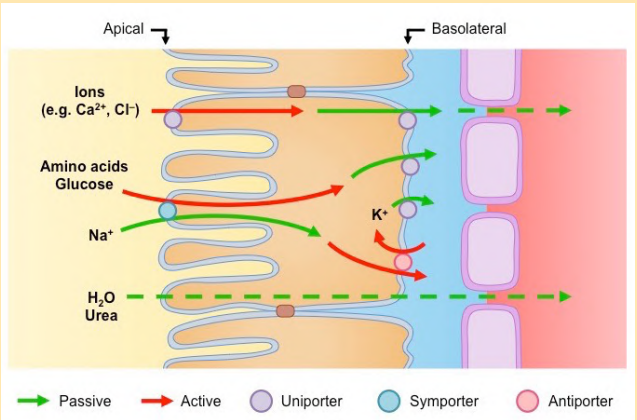
Q) Explain the process of re-absorption in the proximal convoluted tubule

1) Na^+/K^+ pumps in the basal membranes of cells lining the proximal convoluted tubule pump out Na^+ out of the cell via active transport into the blood
2) this lowers Na^+ concentration inside the cell, so more Na^+ diffuses from the fluid in the lumen of the tubule via co-transporter molecules in the membrane
3) the passive movement of Na^+ provides energy to move glucose (even against a concentration gradient), this is an example of indirect/secondary active transport
4) one glucose is inside the cell, it diffuses via GLUT proteins in the basal membrane into the blood
5) removal of solutes increases water potential of filtrate; a water potential gradient is established so water moves down this gradient



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Reabsorption in the loop of Henle

- there are two types of nephrons in our kidney, about ⅓ of these have long loops of Henle that dip down into the medulla

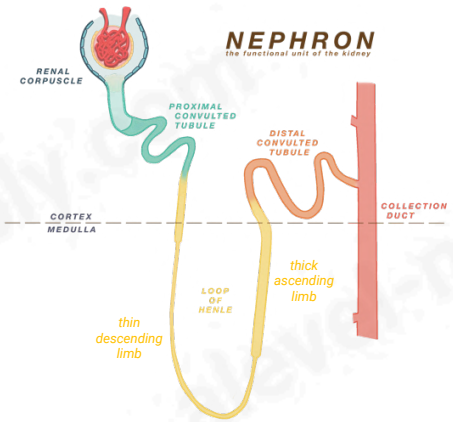

Image: http://thecuriousbiologist.com/nephron-the-functional-unit-of-the-kidneys/

- the function of these long loops is to create a very high concentration gradient of Na+ and Cl- in the tissue fluid of the medulla
- this will enable a lot of water to be reabsorbed from the fluid in the collecting duct, as it flows through the medulla
- this allows for the production of very concentrated urine, which means water is conserved in the body, rather than lost in urine, helping to prevent dehydration

Structure of the loop of Henle

It consists of a descending and ascending limb which differ in their permeabilities to water.

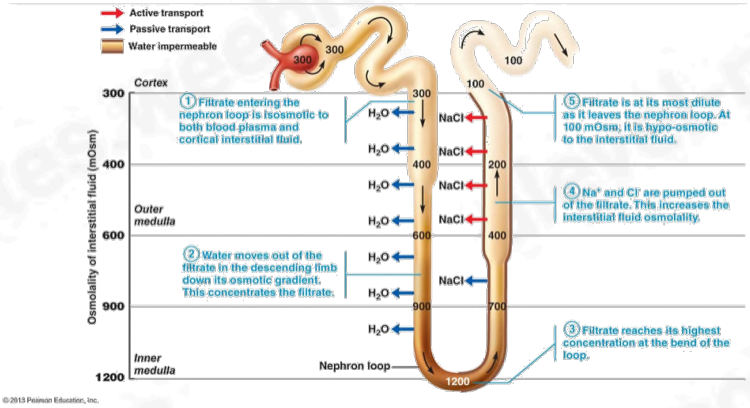

Image: http://classes.midlandstech.edu/carterp/Courses/bio211/chap25/chap25.htm

The ascending limb of the loop of Henle is permeable to salts but not water

1) the cells that line this region of the loop actively transport Na^+ and Cl^- out of the fluid in the loop into the tissue fluid (of the medulla)
2) this decreases the water potential in the tissue fluid and increases the water potential of the fluid inside the ascending limb
   - this decrease in water potential in the surrounding results in water being able to move passively out of the collecting duct and be reabsorbed back into the blood, leaving as more concentrated urine

The descending limb of the loop of Henle is permeable to water and *small**** salts and urea

1) the cells lining the descending limb are permeable to water and also to Na^+ and Cl^-
2) water leaves passively from the filtrate here because of the salty environment (produced due to the action of the cells of the ascending limb)
3) at the same time, Na^+ and Cl^- diffuse into the loop, down their concentration gradient
   - therefore, the filtrate inside is very concentrated by the time it reaches the bottom of the loop
   - the longer the loop, the more concentrated the fluid can become
4) this concentrated fluid then flows up the ascending limb, where Na^+ and Cl^- leave and pass into the tissue fluid due to the high concentration of fluid inside (despite the medulla also having a very high concentration of salts)
5) all the way up the ascending limb, the concentration of Na^+ and Cl^- is never very different from the

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concentration in the tissue fluid, so it's never too difficult to pump out Na^+ and Cl^- *(what "began" the whole process)*

Counter-current multiplication

This the process of using energy to generate an osmotic gradient that enables water to be reabsorbed from the tubular fluid and produce concentrated urine.

- having the two limbs of the loop of Henle running side by side by fluid going down in one and up in the other enables maximum concentration to be built both inside and outside the tube at the bottom of the loop
- additionally, the vasa recta blood network that surrounds the loop of Henle flows in the opposite direction, further contributing to this mechanism

Reabsorption in the distal convoluted tubule (and collecting duct)

The first part of the distal convoluted tubule functions the same way as the ascending limb of the loop of Henle.

The second part functions the same way as the collecting duct.

1) Na+ ions are actively pumped out of fluid in the distal convoluted tubule and collecting duct into the tissue fluid, where they pass into blood
2) K+ ions are actively transported into the tubule and collecting duct
3) the collecting duct passes through the medulla where a low water potential has been produced by the loop of Henle
4) water may then move from collecting duct into the tissues of medulla, further increasing the concentration of urine inside
5) this urine then flows into the ureter and is transported to the bladder

g) Osmoregulation

- **osmoregulation** – control of the water potential of body fluids

This process involves the hypothalamus, posterior pituitary gland, and the kidneys.

Hypothalamus

1) osmoreceptors, which are specialised sensory neurones, in the hypothalamus detect changes in the water potential of the blood
2) osmoreceptors shrink when a decrease in water potential of blood is detected, and nerve impulses are sent along to the posterior pituitary gland

Posterior pituitary gland

3) ADH is released from the posterior pituitary gland

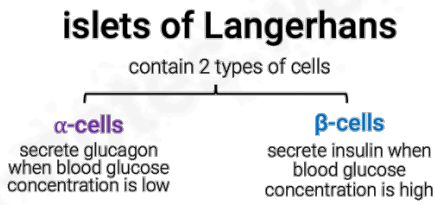
- remember that ADH is transported from the hypothalamus (where it's produced) to the posterior pituitary gland (where it's stored)

Kidneys

4) ADH affects the cells of the collecting duct by increasing permeability
5) this is caused by ADH binding to receptor proteins on the cell surface membrane which activates an enzyme cascade (ends with the production of an active phosphorylase enzyme)
6) phosphorylase causes ready-made vesicles containing aquaporins to move to the cell surface membrane and bind with it, increasing the permeability
7) this causes more water reabsorption

h) Control of blood glucose concentration by insulin

- the homeostatic control of the blood glucose concentration is carried out by the hormones **insulin** and **glucagon** which are **secreted by the islets of Langerhans in the pancreas**
- regulated by negative feedback



- α- and β-cells act as the receptors of the central control
- insulin and glucagon coordinate actions of the effector

Q) Describe the role played by insulin the control of blood glucose concentration

1) hypothalamus detects change in blood glucose concentration
2) autonomic nerve impulses cause β-cells in the islets of Langerhans to secrete insulin into the blood when blood glucose concentration increases
3) insulin has several effects on the body and its cells –

- vesicles with GLUT proteins are moved to the cell surface membrane and fuse with it, this makes the cell more permeable to glucose
- the respiration rate of glucose is increased
- inhibits the secretion of glucagon (decreases gluconeogenesis)
- Insulin increases the absorption of glucose in the liver by phosphorylating it. This is done by the enzyme glucokinase. Phosphorylated glucose is trapped inside the cell as it can't pass through transporters in the cell surface membrane

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- causes the conversion of glucose → glycogen by stimulating the enzymes phosphofructokinase and glycogen synthase which add glucose molecules to glycogen. This is called glycogenesis

GLUT proteins

These are transport proteins which allow glucose to pass across the cell surface membranes. There are several different types of GLUT proteins –

GLUT4 – muscle cells
GLUT 2 – liver cells (always present in cell membrane)
GLUT 1 – brain cells (always present in cell membrane)

Normally, GLUT proteins are kept in the cytoplasm the same way as aquaporins are kept in collecting duct cells.

i, j) Control of blood glucose concentration by adrenaline and glucagon

There are three main stages of cell signalling in the control of blood glucose concentration by adrenaline and glucagon –

- hormone-receptor interaction at the cell surface
- formation of cyclic AMP which binds to kinase proteins
- an enzyme cascade involving activation of enzymes by phosphorylation to amplify the signal

Q) Describe how glucagon increases blood glucose concentration

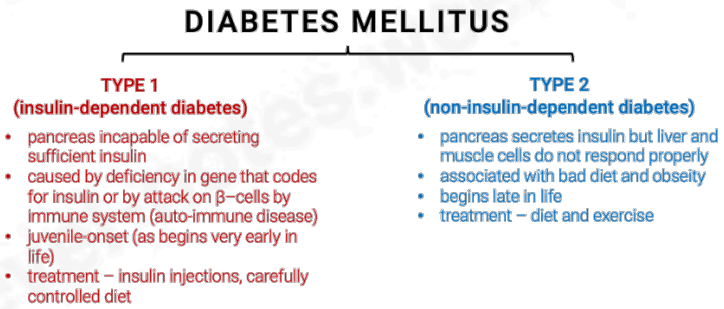
1) hypothalamus detects change in blood glucose concentration
2) autonomic nerve impulses cause α-cells in the islets of Langerhans to secrete glucagon into the blood when blood glucose concentration decreases
3) glycogen binds to receptor molecules in the cell surface membrane of liver cells
4) the receptor changes conformation
5) a G-protein is activated (because of binding)
6) this in turn activates the enzyme adenylyl cyclase which catalyses the conversion of ATP to cyclic AMP
7) cyclic AMP is the second messenger
8) cyclic AMP binds to kinase enzymes that activate other enzymes by phosphorylating them
9) this enzyme cascade amplifies the original signal from glucagon
10) at the end of the cascade, glucose phosphorylase is activated which catalyses the breakdown of glycogen to glucose by removing glucose from 1,6 branches
11) concentration of glucose then increases inside the cell, so it diffuses out via GLUT2, down its concentration gradient, into the blood
12) glucagon can also stimulate gluconeogenesis which is the formation of 'new' glucose from amino acids and lipids

- the hormone adrenaline also increases the blood glucose concentration by activating the same enzyme cascade
- it does so by binding to different receptors on the surface of liver cells that activate the same enzyme cascade and lead to the same end result

When asked to describe how adrenaline affects blood glucose concentration, write the above steps but just swap out 'glucagon' for 'adrenaline'

- muscle cells do not have glucagon receptors and therefore do not respond to it
- they can, however, respond to adrenaline
- adrenaline stimulates the breakdown of glycogen stores in muscle during exercise
- the glucose produced remains in the muscle cells where it is needed for respiration

k) Dipsticks and biosensors



The symptoms of both types of diabetes are the same –

1) urinating often
2) feeling very thirsty and hungry
3) extreme fatigue
4) blurry vision
5) poor wound healing

- The **renal threshold** is the concentration of a substance dissolved in the blood, in this case glucose, above which the kidneys begin to remove it into the urine.
- If glucose concentration in the blood is too high (above the renal threshold), the kidneys are unable to reabsorb all the glucose back so some of it passes out in urine.
- The amount of glucose present in urine is measured qualitatively by dip sticks and quantitatively by biosensors.

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Dipsticks

Dipsticks can be used to test urine for a range of different factors including pH, glucose, ketones and protein.

Dipsticks for detecting glucose have the following features:

1) the end the stick has a pad containing the immobilised enzymes glucose oxidase and peroxidase
2) the pad is dipped in urine
3) glucose reacts to produce hydrogen peroxide (catalysed by glucose oxidase)
4) hydrogen peroxide reacts with a colourless substance (chromagen) present on the stick to give a coloured substance
5) this is compared with a colour chart
6) more glucose gives a darker colour

ADVANTAGES	DISADVANTAGES
non-invasive, painless	does not indicate the current blood glucose concentration, but whether the concentration was greater than the renal threshold while the urine was collecting in the bladder
cheap, easy to use	
less risk of infection	cannot be reused

Biosensors

Biosensors allow people with diabetes to check their blood to see how well they're controlling their glucose concentration.

1) pad contains glucose oxidase
2) glucose oxidase reacts with glucose in the blood
3) oxygen is detected
4) electric current is generated which is detected by an electrode
5) this gives a numerical value of the blood glucose concentration
6) more glucose present → larger current → larger reading

ADVANTAGES	DISADVANTAGES
does not involve colour matching	invasive
shows current blood glucose concentration	
gives a specific digital reading, not a range of values, no need to interpret a colour chart	risk of infection
gives a rapid reading in about 2 seconds	costs more than a dipstick
can be re-used again	

l) Urine analysis

- for people with diabetes, the uptake of glucose into cells is slow even when the blood glucose concentration is very high
- because cells lack glucose, they metabolise fats and proteins as alternate energy sources
- this leads to a build-up in ketones/keto-acids and decreases the blood pH
- therefore, the presence of glucose and ketones in urine indicates that a person may have diabetes
- proteins may also be found in the urine of a diabetic person – this is due to the high blood sugar concentration causing the kidneys to over filter the blood, causing damage to the kidneys, allowing proteins to leak into the urine
- these substances will only be present if the urine if their concentration exceeds the renal threshold; they are not re-absorbed in entirety in the proximal convoluted tubule and then show up in urine

14.2 Homeostasis in plants

a) The opening and closing of stomata

Stomatal aperture is regulated in response to the requirements for the uptake of carbon dioxide for photosynthesis and conserving water.

Stomata show daily rhythms of opening and closing:

STOMATA OPEN DUE TO	STOMATA CLOSE DUE TO
1) high light intensity 2) low CO_2 concentration	1) darkness 2) high CO_2 concentration 3) low humidity 4) high temperature 5) water stress (when supply from roots is limited / high rates of transpiration)

- stomata opening during the day maintains the inward diffusion of CO_2 and the outward diffusion of O_2
- it also allows for the outward diffusion of water vapour in transpiration *(see Ch-7)*
- the closure of stomata at night when photosynthesis cannot occur reduces rates of transpiration and conserves water

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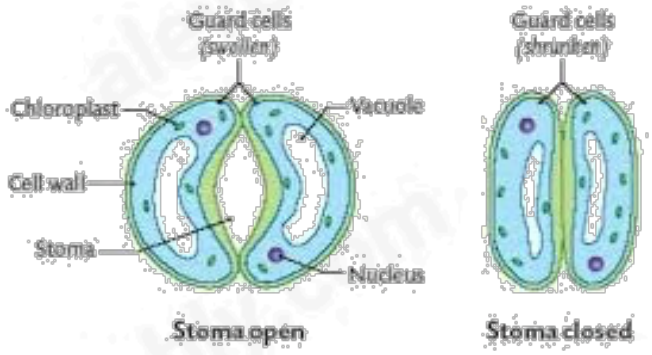
b) Structure and function of guard cells



1) guard cells have unevenly thickened cell walls
    - wall adjacent to the pore is very thick
    - wall furthest from the pore is thin
2) bundles of cellulose microfibrils are arranged as hoops around cells so that as the cell becomes turgid, the cell mostly increases in length and not diameter
3) thin outer wall bends more readily than the thick inner one, causing the guard cell to become curved
    - this opens the pore between 2 cells

The mechanism by which guard cells open stomata

1) ATP-powered proton pumps in the cell surface membrane actively transport H^+ out of the guard cell
2) the low H^+ concentration and negative charge inside the cell causes K^+ channels to open; K^+ diffuses into the cell down an electrochemical gradient
    - the removal of hydrogen ions has left the inside of the cell negatively charged compared to the outside
    - as K^+ ions have a positive charge, they are drawn down an electrical gradient towards the negatively charged region
    - they also diffuse into the cells down a concentration gradient
    - such a combined gradient is called an electrochemical gradient
3) the high concentration of K^+ inside the guard cell lowers the water potential (Ψ)
4) water moves in by osmosis, down a water potential gradient, through aquaporins
5) the entry of water increases the turgor of the guard cells, so they expand – the thin outer wall expands the most so the cells curve apart, opening the pore between the two cells

The mechanism by which guard cells close stomata

1) stomata close when the H^+ pump proteins stop and K^+ leave the guard cells and enter neighbouring cells
2) this establishes a water potential gradient in the opposite direction
3) water leaves guard cells so they become flaccid and close the stoma

c) Abscisic acid (ABA) and stomatal closure

Closing of the stomata has significant effects on the plant –

1) it reduces the uptake of CO_2 for photosynthesis
2) also reduces transpiration which is used for cooling the plant and for maintaining the transpiration stream that supplies water and mineral ions to the leaf

Stomatal closure only occurs when reducing the loss of water vapour and conserving water is the most important factor

- abscisic acid (ABA) is a stress hormone that is secreted in response to difficult environmental conditions such as very high temperatures or reduced water supply
- ABA triggers the closure of stomata to reduce transpiration and prevent water loss

The role of abscisic acid (ABA) in the closure of stomata during times of water stress

1) ABA binds to cell surface receptors on guard cells
2) it inhibits proton pumps and stops H^+ from being pumped out
3) ABA also stimulates the movement of Ca^{2+} into the cytoplasm through the cell surface membrane and tonoplast
4) Ca^{2+} acts as a second messenger to activate channel proteins to open that allow negatively charged ions to leave the guard cells
5) this stimulates the opening of channel proteins which allows the movement of K^+ out of the cells
6) Ca^{2+} also stimulates the closure of the channel proteins that allow K^+ to enter
7) the loss of ions raises the water potential of the cells, water passes out by osmosis, the guard cells become flaccid and the stomata close

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