

Bio Factsheet



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Number 1

The kidney: excretion and osmoregulation

Kidneys have two main functions.

1. They are excretory organs, removing nitrogenous and other waste from the body.
2. They play an important part in maintaining a constant internal environment by helping to regulate pH, water and sodium ion concentrations in the blood and tissues. This Factsheet will focus on the role of the kidney in excretion and osmoregulation.

Excretion

Surplus nitrogen-containing compounds such as amino acids have to be broken down in the body because they are toxic and are then excreted as ammonia, urea or uric acid (Table 1).

Table 1. Nitrogenous excretory products

| Excretory product | Source |
|-------------------|--|
| Urea | Deamination of amino acids via the ornithine cycle in the liver |
| Uric acid | Deamination of purines (adenine and guanine) |
| Ammonia | Deamination of amino acids. Ammonia is secreted into the urine by cells in the kidney tubule |

Exam Hint - Don't confuse urea and urine. Urea is made by the deamination of amino acids in the liver. Urine is the fluid produced by the kidneys.

Some important biological properties of these three substances are summarised in Table 2.

Table 2. Biological properties of excretory products.

| | Ammonia | Urea | Uric acid |
|---|------------|--------|-------------|
| Solubility | Very high | High | Very low |
| Amount of water necessary to remove from body | Very large | Medium | Very little |
| Toxicity | High | Medium | Low |
| Molecules of ATP needed | 0 | 4 | 8 |

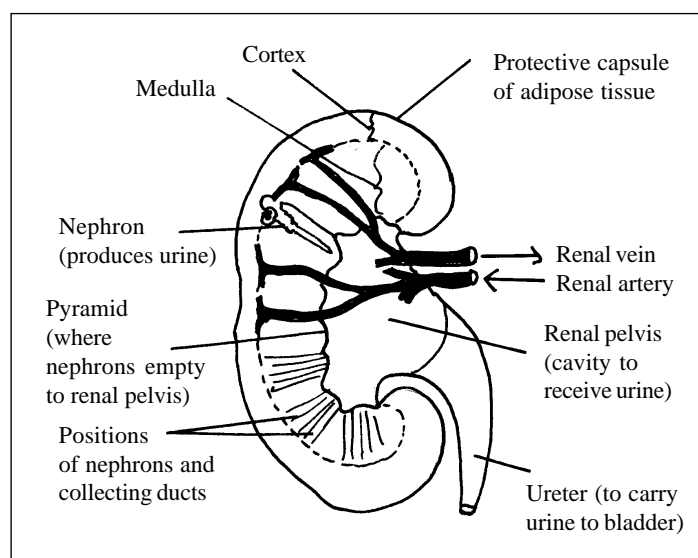
From this you can work out that:

- Freshwater fish excrete ammonia. Although it is very poisonous, fish are surrounded by large amounts of water so the ammonia can easily be diluted to safe levels.
- Mammals excrete nitrogen mainly as urea. Urea requires more energy in the form of ATP for its production but is much less toxic than ammonia and fairly soluble. It therefore does not require large amounts of water to remove it from the body.
- Birds excrete nitrogen mainly as uric acid. Flight demands a low body mass. Removing nitrogenous waste as uric acid means that large amounts of water are not required. Insects also excrete uric acid. As they are so small, they are very prone to water loss so it is important that they do not lose large amounts of water in excreting nitrogenous waste.

Basic kidney structure

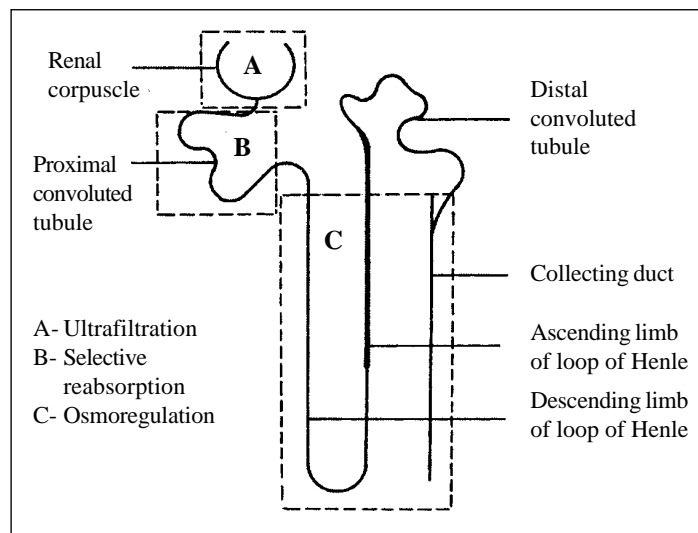
The basic structure of the mammalian kidney is shown in Figure 1.

Figure 1. Vertical section through mammalian kidney.



Each kidney contains a million coiled tubes called nephrons and it is in the nephron that urine formation occurs. Each nephron is divided into a number of distinct regions with particular functions labelled A, B, C (Figure 2).

Figure 2. The kidney nephron



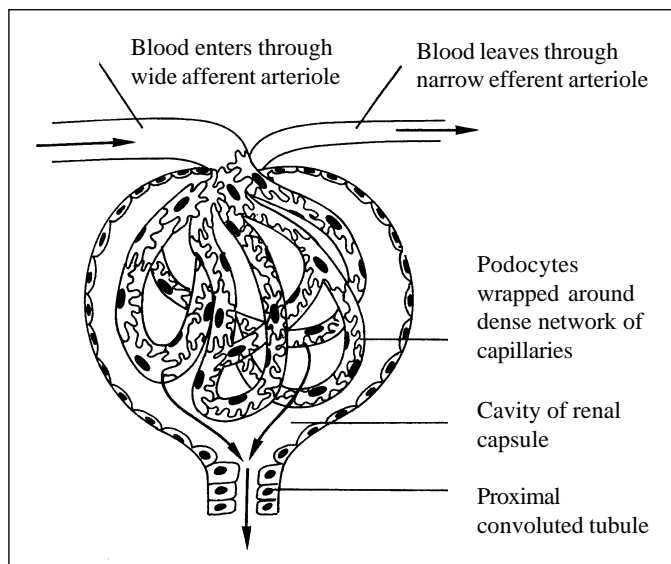
A. Ultrafiltration (Figure 3).

The Bowman's capsule contains a dense capillary network called the glomerulus. Blood flows into these capillaries through a wide **afferent** arteriole and leaves through a narrower **efferent** arteriole. The blood pressure inside these capillaries is high because:

1. The renal artery contains blood at very high pressure which enters the glomerulus via the short afferent arteriole.
2. The efferent arteriole has a smaller diameter than the afferent arteriole.

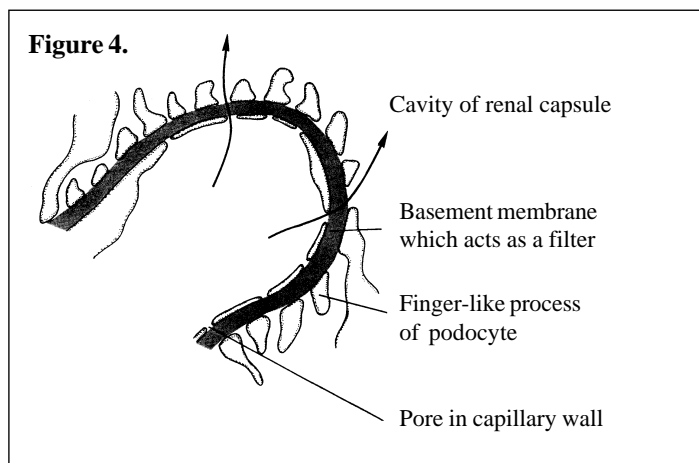
The high pressure forces small molecules such as water, glucose, amino acids, sodium chloride and urea through the filter i.e. from the blood in the glomerular capsule across the basement membrane of the Bowman's capsule and into the nephron. This type of high-pressure filtration is known as **ultrafiltration**. The fluid formed in this way is called **glomerular filtrate**. Large molecules such as plasma proteins and blood cells do not pass through the filter because they are too big.

Figure 3. Structure of Bowman's capsule.



The structure of the filter (Figure 4).

Blood plasma is separated from the filtrate by two rows of cells, the lining cells of the capillary and the **podocytes** which make up the inner layer of the capsule. The capillaries have pores in their walls which the molecules in the plasma are able to pass directly through. The small molecules then pass through the basement membrane and once through this, they can pass between the processes of the podocyte directly into the cavity of the renal capsule. The actual filter is just the basement membrane and this is extremely thin.



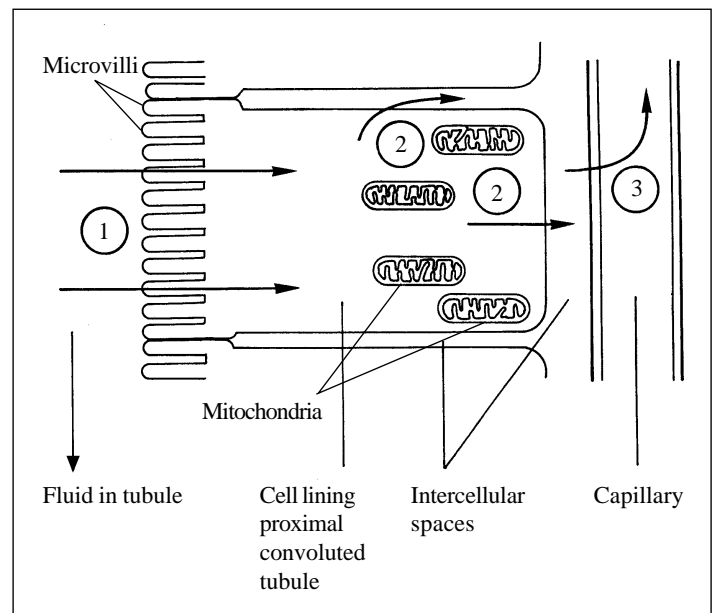
Typical exam question

Ultrafiltration often comes up in application questions, i.e. those questions which test a candidate's ability to apply factual knowledge to new situations. Often, candidates will be asked to make inferences about kidney malfunction from an analysis of the constituents of urine. If large molecules such as plasma proteins or red blood cells are present, the implication is that the filtration mechanism in the Bowman's capsule is not working properly. The presence of many small molecules such as amino acids would tell us nothing about the filtration mechanism, but would imply damage to the proximal convoluted tubule, where selective reabsorption occurs.

B. Selective reabsorption in the proximal convoluted tubule

The filtrate contains toxic substances such as urea which it is necessary to remove from the body but it also contains substances such as glucose which are required by the body. The function of the proximal convoluted tubule is to reabsorb these useful substances (Figure 5).

Figure 5. Reabsorption in the proximal convoluted tubule.



1. Glucose **diffuses** into the cells which line the proximal convoluted tubule. Microvilli increase the surface area for efficient absorption.
2. The glucose is **actively** transported out of the cells into the intercellular spaces. Mitochondria supply the necessary ATP.
3. Once in the intercellular spaces, the glucose diffuses through the walls of the capillaries and is transported away by the blood.
4. Active transport of glucose out of the tubule cells maintains a concentration gradient so more glucose is able to diffuse out of the tubule fluid.

Similar mechanisms result in the reabsorption of many of the **amino acids** and up to 90% of the **sodium ions** from the tubule fluid. The removal of all these soluble substances results in an osmotic gradient between the fluid in the tubule and the cells which line it. Water is therefore drawn out of the tubule fluid by osmosis, and passes into blood. This process is responsible for 85-90% of water reabsorption in the Nephron. It is only the remaining 10-15% which is regulated in the loop of Henle and collecting duct.

Typical exam question

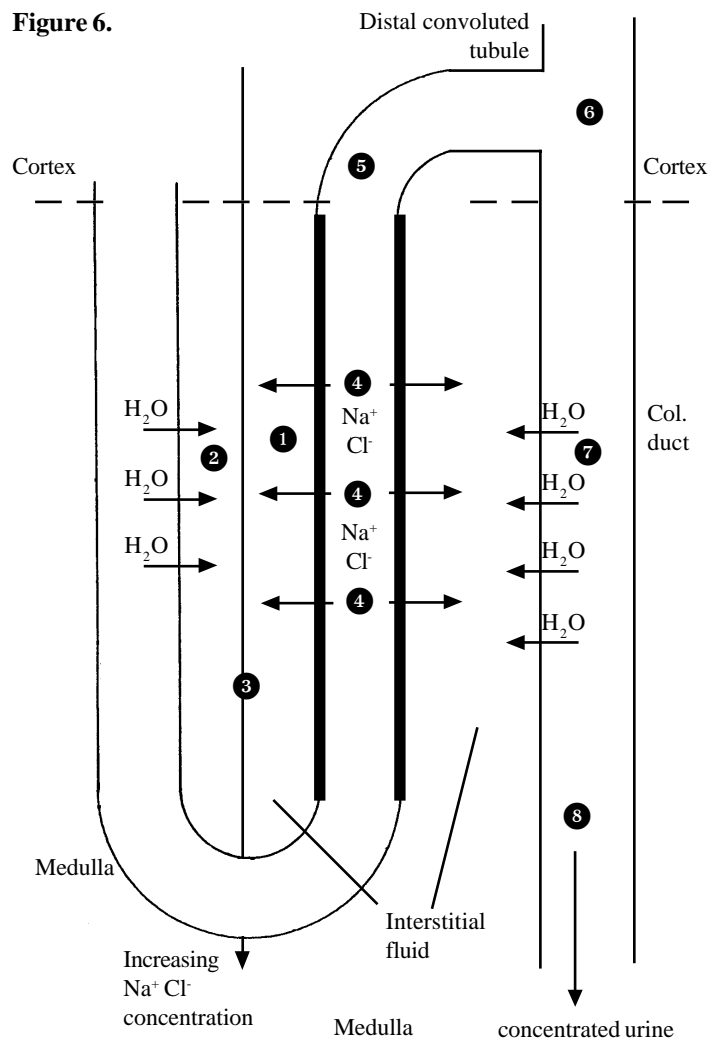
State three ways in which the cells of the proximal convoluted tubule are adapted for efficient reabsorption.

C. Osmoregulation (Figure 6)

The ability to produce concentrated urine is important in allowing terrestrial mammals to conserve water. The loop of Henle and the collecting duct form a system known as a **countercurrent multiplier** whose function is to remove water from the fluid in the tubule and produce a concentrated urine.

1. Na^+ and Cl^- ions are actively pumped out of the ascending limb. The ions accumulate in the interstitial fluid. This lowers the water potential of the interstitial fluid. The tendency is for water to osmotically follow the Na^+ and Cl^- ions but it cannot since most of the ascending limb is impermeable to water.
2. Water is drawn out of the descending limb and into the interstitial fluids by osmosis. This makes the fluid in the descending limb more and more concentrated.
3. By the time the fluid in the descending limb has reached the bottom of the limb, it has lost a lot of water and is very concentrated. The fluid surrounding the bottom of the loop - in the medulla of the kidney - is also very concentrated because of the accumulation of Na^+ and Cl^- ions. The direction of the concentration gradient is shown by the arrow.
4. The fluid then enters the ascending limb. As it moves up the ascending limb, sodium ions are actively pumped out of it.
5. This makes the fluid at the top of the ascending limb very dilute again.
6. The fluid then empties into collecting ducts which pass through the very concentrated medullary region.
7. Under the influence of the hormone ADH, the wall of the collecting duct becomes permeable to water which is therefore osmotically drawn out of the collecting duct and into the blood capillaries in the region.
8. By drawing water out of the fluid in the collecting duct, a very concentrated urine can be produced. By regulating the permeability of the collecting duct (via ADH), the amount of water in the blood and the concentration of the urine can be controlled.

Figure 6.



What controls ADH?

The osmotic concentration of the blood is monitored by **osmoreceptors** in the hypothalamus. Blood pressure is monitored by **baroreceptors** which are widely dispersed throughout the circulatory system. Both types of receptor can send impulses to the posterior pituitary gland to start/stop ADH release.

If too much water is lost from the body:

1. The volume of blood plasma falls, its osmotic concentration therefore increases and blood pressure falls.
2. Osmoreceptor and baroreceptors detect these changes and an impulse is sent to the posterior pituitary gland.
3. ADH is released.
4. ADH increases the permeability to water of the collecting duct and the distal convoluted tubule.
5. More water is therefore drawn out of the collecting duct and distal convoluted tubule back into the blood. This restores the volume and pressure of the blood and reduces its osmotic concentration.
6. The stimulus to the posterior pituitary is switched off.

If the osmotic concentration of the blood falls or if blood pressure increases, less ADH is released, less water is reabsorbed, resulting in a large volume of dilute urine. This restores the osmotic concentration and pressure of the blood.

Typical exam question

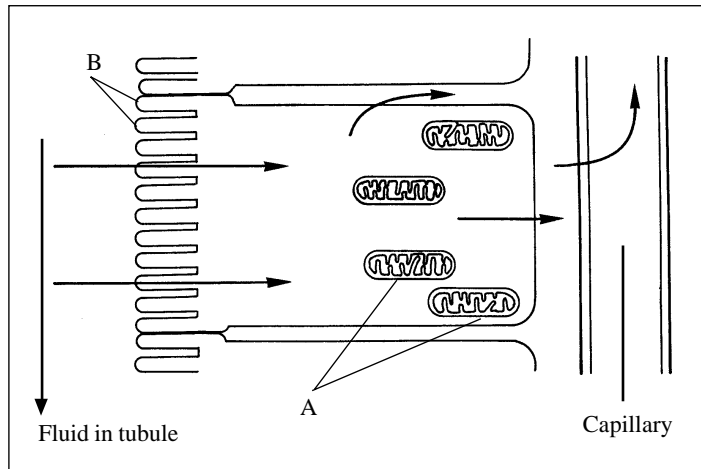
Individuals who are unable to produce ADH suffer from diabetes insipidus. Describe the likely symptoms of this condition.

Exam Hint - The longer the loop of Henle, the more concentrated the urine that can be formed. A nephron from a frog or a toad doesn't have a loop of Henle so these animals are unable to produce concentrated urine. Small mammals such as gerbils that live in deserts have nephrons with very long loops of Henle. These animals can produce extremely concentrated urine, thus reducing water loss from the body. This is often tested as an application question.

Practice questions

Semicolons indicate marking points.

1. The diagram shows a cell from the proximal convoluted tubule in the nephron.

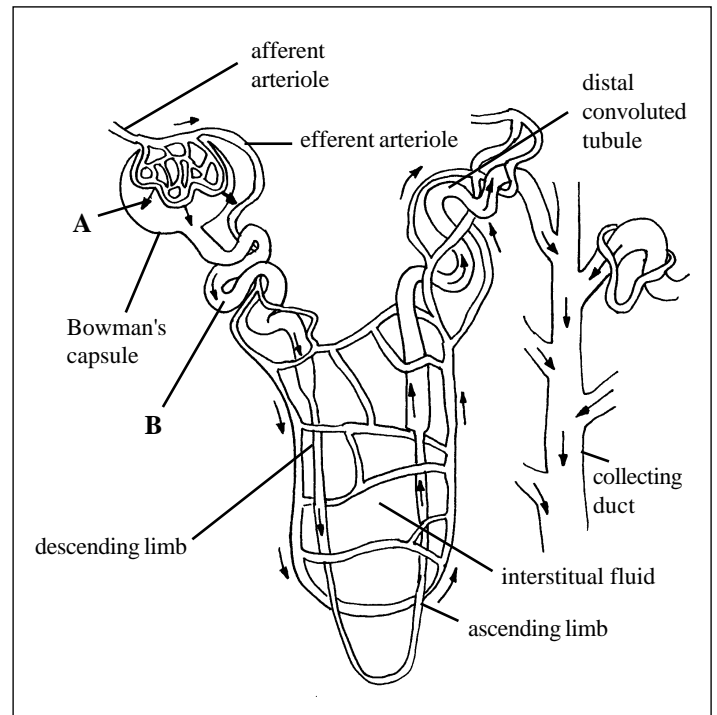


- (a) Outline the function of:
- (i) Component A (2 marks)
 - (ii) Component B (2 marks)
- (b) Suggest explanations for each of the following:
- (i) The presence of glucose in the urine of a person who has consumed large amounts of glucose (2 marks)
 - (ii) The presence of protein in the urine of a person suffering from high blood pressure. (2 marks)
2. (a) Outline the process of ultrafiltration (3 marks)
- (b) The diameter of the efferent arteriole can be decreased by muscle contraction. Suggest what effect this would have on the process of ultrafiltration (2 marks)
3. The table shows the composition of fluids drawn from different regions of a mammalian kidney.

| Substance | Concentration in fluid (g/100cm ³) | | |
|-----------|--|----------------|-------|
| | Plasma | Glom. filtrate | Urine |
| Glucose | 0.08 | 0.07 | 0 |
| Sodium | 0.33 | 0.31 | 0.33 |
| Urea | 0.028 | 0.028 | 1.9 |
| Protein | 7 | 0 | 0 |

- (a) Suggest an explanation for the difference in composition of the plasma and urine (3 marks)

4. The diagram represents part of a mammalian kidney nephron.



- (a) State the name of the major process which occurs in region:
- (i) A (1 mark)
 - (ii) B (1 mark)
- (b) Suggest why some desert mammals have very long loops of Henle (2 marks)

Answers

1. (a) (i) Provide ATP; for active transport of glucose into intercellular spaces;
- (ii) Provide large surface; for diffusion of glucose;
- (b) (i) No. of glucose molecules exceeds No. of carriers in proximal cell; therefore unable to be actively transported;
- (ii) High pressure forces proteins through basement membrane; pressure may damage membrane;
2. (a) High blood pressure; because of short afferent arteriole; narrow efferent arteriole; forces small molecules through basement membrane; (any 3)
- (b) Increase it; by increasing pressure;
3. (a) All glucose reabsorbed in proximal convoluted tubule; Sodium concentration remains the same because active pumping out of ions is balanced by corresponding water loss; Urea is concentrated through reabsorption of water in distal convoluted tubule and collecting duct;
4. (a) (i) Ultrafiltration
(ii) Selective reabsorption
- (b) To conserve water; the longer the loop the more water can be reabsorbed;

Acknowledgements;

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