Bio Factsheet

Number 59

Excretion

Excretion is the removal of toxic waste products of metabolism from the body to the external environment. This enables these waste products to be recycled for reuse by living organisms. This factsheet will concentrate on those aspects of nitrogenous excretion and carbon dioxide excretion by organisms that are on current syllabuses.

Exam questions about nitrogenous excretion usually test knowledge and understanding of:

1. **The kidney and its role in excretion.**
2. **Ammonia, urea and uric acid as nitrogenous excretory products in relation to the lives of different organisms.**
3. **The mechanisms of ammonia and urea formation.**
4. **The transport of carbon dioxide in blood and across the lung surface.**

Nitrogenous excretory products

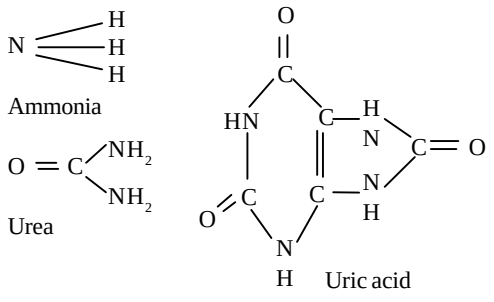
Animals require a constant supply of amino acids in order to synthesise the proteins they require throughout life. These amino acids are obtained from the diet. However, the amine group of amino acids is very toxic to cells and so amino acids cannot be stored, and the concentration of free amino acids in body tissues must be kept to a very low level.

Remember *– when in proteins the amine groups of the amino acids are tied up in peptide bonds and so are no longer toxic.*

Because of this, surplus amino acids undergo a process of **deamination** to remove their amine groups as **ammonia**. The ammonia may be excreted as such, or may undergo modification into **urea** or **uric acid** before excretion. Fig 1 shows the molecular structure of these products, which the student **should be able to recognise**.

Exam Hint - *A common inaccuracy, made by students, is to say 'surplus amino acids taken up in the diet are all deaminated'. Some ammino acids maybe transformed into amino acids that are in short supply in a process known as transamination.*

Fig 1. Molecular structure of nitrogenous excretory products



It is important to know the relative toxicities and solubilities, in water, of ammonia, urea and uric acid, because this determines the main nitrogenous excretory product of different organisms, which is related to their access to water supplies. This may vary between different stages of their life cycles.

Ammonia is very soluble and diffuses rapidly through water. This aids its rapid excretion as ammonium ions (NH_4^+) in most aquatic organisms before it reaches concentrations which are toxic. It is very toxic and cannot be kept in the body. (Mammals cannot tolerate concentrations of ammonia over 0.2 mg dm^{-3} blood).
Protozoa and Cnidaria excrete ammonia by diffusion through their body surfaces into the surrounding water. Most bony fish and larval Amphibia (tadpoles) excrete ammonia into the surrounding water using primitive kidneys.

Urea is made in the liver via the **ornithine cycle** by combining the ammonia made by deamination with carbon dioxide made from respiration. Urea is less soluble than ammonia and much less toxic. Thus some can be retained in the body and excreted more slowly, so enabling a measure of water conservation which is particularly important for a land animal. (The normal concentration of urea in human blood is 2.5 – 7.5 mmol dm^{-3}).
Adult amphibia and mammals, being land animals, have urea as their main excretory substance. Elasmobranchs (cartilaginous fish) also mainly excrete urea.

Uric acid and its salts (urates) have low solubility and relatively low toxicity. Thus they can be stored in organisms, and excreted in a minimum volume of water (semi-solid urine). This is particularly useful for land animals which need to conserve water and which lay eggs. The uric acid can be laid down on the inside of the shell or egg membrane where it will not harm the developing embryo.
Uric acid and ammonium urate are the main excretory products of insects, most reptiles and birds. Mammals also excrete small quantities of uric acid, but this originates from breakdown of nucleic acids and not from protein metabolism.

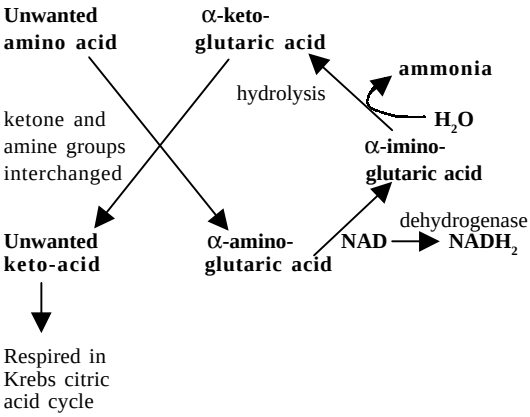
In the inherited condition in men, called gout, high concentrations of uric acid in the blood cause uric acid crystals to precipitate in the kidneys and joint membranes. This can cause excruciating pain and swelling in the joints, particularly in the big toes.

Another nitrogenous excretory product in vertebrates is **creatinine** which is formed from creatine. Creatine is made from the amino acids arginine, methionine and glycine, and in the form creatine phosphate is used as an energy store in muscles to enable rapid conversion of ADP to ATP.

The removal of ammonia from unwanted amino acids

This process is called **transdeamination** and uses a specific keto acid, α-keto- glutaric acid (made in Krebs citric acid cycle) to remove the ammonia from the unwanted amino acid. The process is outlined in Fig 2. (It is not necessary to know more precise chemical details). The process occurs mainly in the hepatic cells of the liver.

Fig 2. Transdeamination

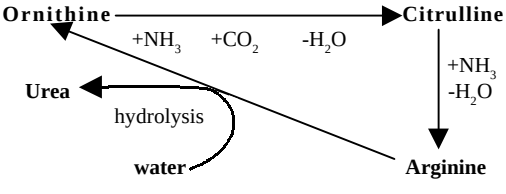


Note that besides being an excretory process, transdeamination is also respiratory, so that the energy available in the unwanted amino acid is not wasted. Thus it produces keto acids which can be respired in the Krebs cycle and $NADH_2$ which will produce ATP in the respiratory chain.

Remember – *a similar process of deamination is carried out by many soil bacteria and fungi when respiring and thus recycling amino acids within the soil organic matter. Thus the strongest candidate may to refer to deamination in questions on the nitrogen cycle.*

The ammonia may then be combined with waste respiratory carbon dioxide in the **ornithine cycle** to synthesise urea. This process is outlined in Fig 3. (It is not necessary to know more precise chemical details).
In the ornithine cycle, the amino acid ornithine is used as a carrier on which to assemble waste ammonia and carbon dioxide into urea. This process occurs mainly in the hepatic cells of the liver.

Fig 3. The ornithine cycle



The urea is then transported, dissolved in the blood plasma, to the kidneys for excretion in urine.

Exam Hint - *Candidates are supposed to know the main blood vessels of the body and examiners sometimes ask for the route of a substance through the circulation. In the case of urea the route would be: liver; hepatic vein; posterior vena cava; right atrium; right ventricle; pulmonary arteries; lungs; pulmonary veins; left atrium; left ventricle; aorta; renal arteries; kidneys;*

Excretion through the urinary system

Urea and other excretory products are removed from the blood by the kidneys. The urine produced is passed down the ureters into the bladder where it is stored until a suitable time for release. The structure of the urinary system is shown in Figs 4, 5 and 6.

Fig 4. The urinary system in ventral view

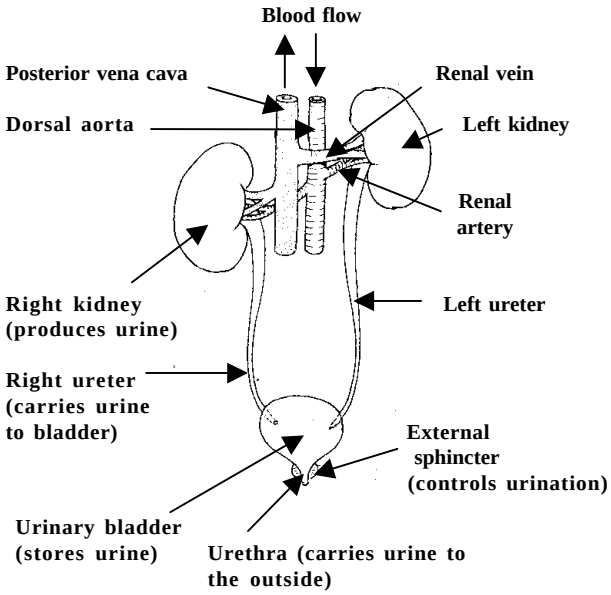
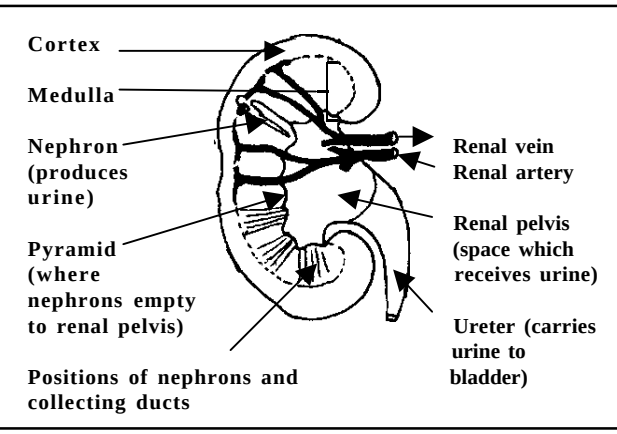


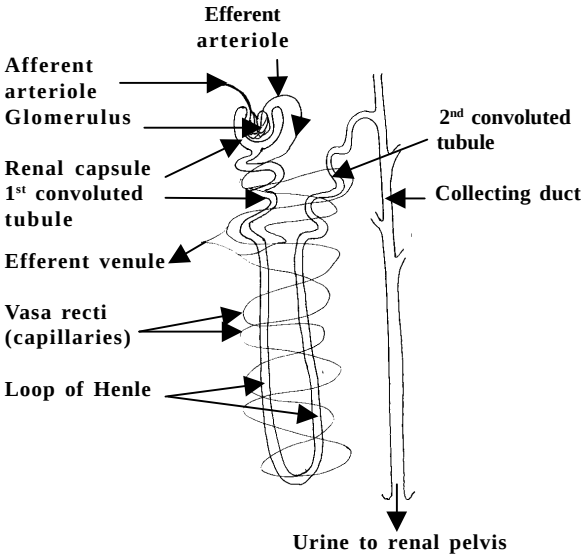
Fig 5. Vertical section through the kidney



The kidney is made up from thousands of nephrons, which produce urine, and has a very large blood supply to and from the nephrons. This enables the nephrons to perform their functions of excretion and homeostasis.

Remember – *the kidney is also concerned with homeostasis. For example, it carries out osmoregulation of body fluids and controls the pH of the blood. These aspects of kidney function are not excretory and so are not covered here. They were explained in* ***Factsheet Number 1, September 1997, The kidney: excretion and osmoregulation.***

Fig 6. The structure of a nephron



The **afferent arteriole** supplies blood to the capillaries of the **glomerulus**, which lies in the **renal capsule**. The **efferent arteriole** drains blood from the glomerulus into the vasa recti. These are capillaries that closely surround the tubules of the nephron. The blood is drained from the vasa recti via the **efferent venule**.

Small molecules for excretion, such as hydrogen ions, certain salts, ammonia, urea, uric acid, creatinine, bile pigments (from haemoglobin breakdown) and drug breakdown products, pass from the blood across the glomerular capillary and renal capsule walls, forming glomerular filtrate in the capsule, during the normal process of **ultrafiltration**. Ultrafiltration (pressure filtration) is driven by the high blood pressure in the glomerulus and is responsible for forming the glomerular filtrate.

As the glomerular filtrate passes through the tubules of the nephron it is **modified** by exchange with the blood in the surrounding vasa recti. Most of the modifications are concerned with homeostasis, but a few are related to excretion. For example:

- A small quantity of urea is **actively reabsorbed** back to the blood in the first convoluted tubules. The reason for this is not known, but it reduces the rate of urea excretion and so possibly helps to reduce water loss in the urine. It may be that the presence of some urea in blood is needed for osmotic or pH control.
- Various substances are excreted by **active secretion** from the blood in the vasa recti into the second convoluted tubules. Such substances include hydrogen ions, hydrogen carbonate ions, ammonium ions, potassium ions and creatinine. The concentration of these substances is thus lowered in the blood and raised in the urine.

Remember - *active transport across a membrane, whether reabsorption or secretion, requires a specific carrier molecule in the membrane, the use of ATP as driving energy and can go against the concentration gradient.*

Excretion of carbon dioxide

Carbon dioxide is the waste product of cellular respiration and diffuses from the cells through the lymph and into the blood stream. Here it is carried in three forms:

- About 5% is carried as **dissolved CO_2** in the plasma.
- About 25% of the CO_2 diffuses into the red cells and combines with the amino acid side chains of the haemoglobin, forming **carbaminohaemoglobin**.
- The remainder of the CO_2 diffuses into the red cells and is converted into **hydrogen carbonate ions** which then pass back to the plasma for transport.

The red blood cells contain the enzyme **carbonic anhydrase** which speeds up the conversion of carbon dioxide and water to carbonic acid about 250x. The carbonic acid formed then dissociates to hydrogen ions and hydrogen carbonate ions.

$$CO_2 + H_2O \underset{\text{alveoli of lung}}{\overset{\text{respiring tissues}}{\rightleftharpoons}} H_2CO_3 \text{ (carbonic acid)}$$

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

In the respiring tissues the concentration of CO_2 is high and so the reactions are pushed towards the hydrogen carbonate ions. These diffuse down the concentration gradient from the red cells to the plasma. Since this leaves a deficiency of negative ions in the red cells, negative chloride ions diffuse in from the plasma to compensate (chloride shift).

In the lungs CO_2 is blown off during exhalation via the alveoli. This alters the chemical equilibrium so that the reactions in the red cells move from hydrogen carbonate ions back to CO_2. This draws the hydrogen carbonate ions back into the red cells and the compensating chloride ions diffuse back to the plasma.

The dissolved CO_2 also diffuses out of the blood into the moist serous fluid lining the alveoli and then into the air in the alveoli which is then exhaled. The carbaminohaemoglobin also releases its CO_2 for exhalation.

Other routes of excretion

Although **sweat** is a secretion released for cooling the body down, it does contain excretory substances, for example, ammonia, urea, uric acid, unwanted amino acids, various salts, including hydrogen carbonate ions (CO_2 excretion) and lactic acid. Insensitive sweating is carried on continuously, but the volumes released increase when cooling is required.

Bile pigments are released via the **bile** into the duodenum and are lost in the **faeces**. Hydrogen carbonate ions are also released in the bile, pancreatic juice and intestinal juice. Although these have a function in regulating the intestinal pH they are also excretory (CO_2).

Excretion in plants

Plants manufacture their own amino acids as required and so do not have a problem of nitrogenous excretion. Waste oxygen from photosynthesis and waste carbon dioxide from respiration escape to the exterior by diffusion, mainly through stomata and lenticels.

Other waste products may be stored in inert, insoluble forms in the dead heartwood or in bark, or may be deposited in leaves and lost during leaf fall. Examples of substances disposed of in this way are: calcium oxalate, calcium pectate, tannic acid, nicotinic acid and chlorophyll breakdown products. The characteristic tints of autumn leaves before leaf fall are due to some of these compounds.

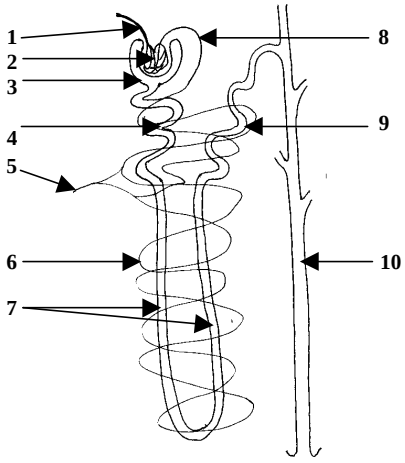
Practice Questions

1. Read through the following passage about nitrogenous excretion and then fill in the spaces with the most appropriate word or words.

Unwanted _____ undergo _____ in the _____ producing ammonia for excretion. The process is also respiratory because it produces a reduced coenzyme _____ and _____ which provide substrate for the _____. In _____ the ammonia may be combined with respiratory CO_2 in the _____ cycle. This occurs in the _____ and results in the formation of _____. This is _____ toxic than ammonia and requires _____ water loss during excretion.

(12 marks)

2. Label the diagram of the nephron below.



(10 marks)

3. Explain why:
   (a) Uric acid is the best nitrogenous end product for insects, reptiles and birds. (3 marks)
   (b) Leaves change colour prior to leaf fall. (2 marks)
   (c) Red blood cells are important in carbon dioxide excretion. (3 marks)
   (d) The process of deamination occurs in some soil organisms. (3 marks)

(11 marks)

4. The table below shows some features of nitrogenous excretory products. If a feature is correct place a tick (✓) in the appropriate box and if it is incorrect, place a cross (✗).

	NH_3	Urea	Uric acid
Main excretory product in birds and frogs			
Main excretory product in Amoeba and jellyfish			
Moderately soluble in water			
Excreted by mammals			
Made in the ornithine cycle			
Main waste product of nucleic acid metabolism			

(6 marks)

Answers

Marking points are shown by semicolons

1. amino acids; transdeamination/deamination; liver; NADH/$NADH_2$; keto-acids; Krebs/citric acid cycle; mammals/amphibia; ornithine; liver; urea; less; less;

2. (a) 1 = afferent arteriole;
   2 = glomerulus;
   3 = renal capsule; (the term 'Bowmans capsule' is no longer in use according to IOB recommendations)
   4 = first/proximal convoluted tubule;
   5 = efferent venule;
   6 = vasa recti/capillaries;
   7 = loop of Henle;
   8 = efferent arteriole;
   9 = second/distal convoluted tubule;
   10 = collecting duct;

3. (a) uric acid has low solubility and so incurs little water loss/ref water conservation/solid urine;
   these animals all lay eggs;
   uric acid has low toxicity so will not poison the developing organism in the egg;

   (b) colours are due to excretory products deposited in leaves;
   such as chlorophyll breakdown substances/tannic acid/any correct example;

   (c) red blood cells contain the enzyme carbonic anhydrase;
   in respiring tissues this catalyses combination of CO_2 and H_2O into carbonic acid/hydrogen carbonate ions for transport;
   in lung/alveoli catalyses hydrogen carbonate ions/ carbonic acid conversion to CO_2 for exhalation;

   (d) carried out by some bacteria/fungi;
   breaks down amino acids in dead/soil organic matter to ammonia;
   which can then be converted to nitrates/ref nitrification;

4.

	NH_3	Urea	Uric acid
Main excretory product in birds and frogs	✗	✗	✗ ;
Main excretory product in Amoeba and jellyfish	✓	✗	✗ ;
Moderately soluble in water	✗	✓	✗ ;
Excreted by mammals	✓	✓	✓ ;
Made in the ornithine cycle	✗	✓	✗ ;
Main waste product of nucleic acid metabolism	✗	✗	✓ ;

Acknowledgements;
This Factsheet was researched and written by Martin Griffin
Curriculum Press, Unit 305B, The Big Peg, 120 Vyse Street, Birmingham, B18 6NF

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