Unit
2A

Chapter 8
Output: the kidneys

Unit content

Body systems
The respiratory, circulatory, digestive and excretory systems are specialised to control inputs and outputs in supporting metabolism.

Excretory system
Structure and function related to:

- formation of urine in the kidney
- deamination of amino acids in the liver.

Relevance of human biology to everyday life
Lifestyle choices can compromise body functioning in the short-term and affect future health.

Lifestyle choices that compromise health:

- use of drugs, including alcohol and smoking
- diet.

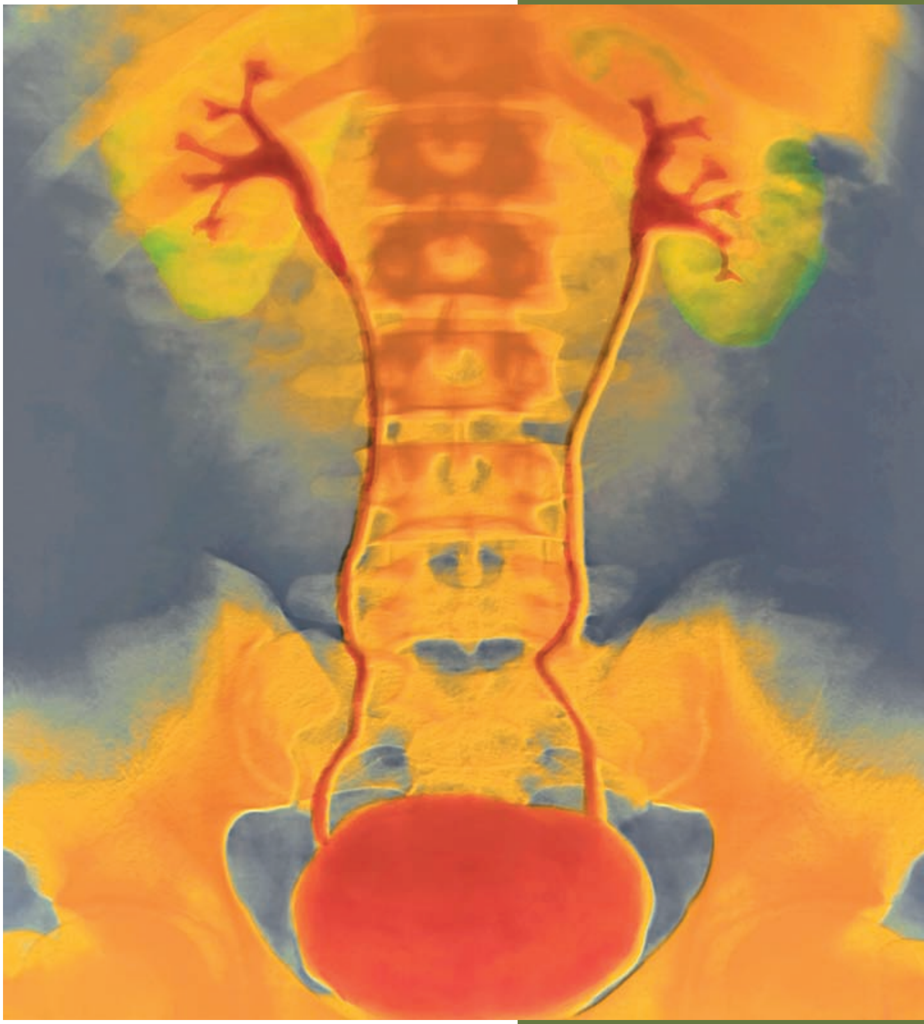


Figure 8.1 The kidneys are the principal excretory organs for metabolic wastes. In this X-ray a dye has been used to show the tubes leading from the kidneys (top) to the bladder (bottom)

All chemical processes in the body produce by-products, some of which are able to be used by the body, while others are wastes. Most of the wastes are toxic and would be harmful to health if allowed to accumulate. Every cell produces waste products, so their removal before concentrations become harmful is extremely important. Removal from the body of the wastes of metabolism is called **excretion**.

Several organs in the body take part in excretion:

- The **lungs** are involved in the excretion of carbon dioxide. Carbon dioxide and water are produced by all body cells during cellular respiration.
- **Sweat glands** in the skin secrete sweat, which is largely water, for cooling. Sweat contains by-products of metabolism such as salts, urea and lactic acid.
- The **alimentary canal** passes out bile pigments, which enter the small intestine with the bile. These pigments are the breakdown products of haemoglobin from red blood cells.
- The **kidneys** are the principal excretory organs. They are responsible for maintaining the constant concentration of materials in the body fluids. The most toxic wastes removed by the kidneys are the nitrogenous wastes urea, uric acid and creatinine. Urea is produced in the liver from the breakdown of amino acids, which come from protein metabolism.

The kidneys

The **kidneys** are a pair of reddish brown organs located in the abdomen. Each kidney is approximately 11 cm long. Their position and relative size can be seen in Figure 8.2.

Microscopic structure of the kidney

When examined under a microscope, the kidney is seen to be composed of a large number of structures called **nephrons** and **collecting ducts**. The nephron is the functional unit of the kidney as it is where the urine is formed. There are about 1.2 million nephrons in each human kidney and each is surrounded by a complex network of blood capillaries (Fig. 8.3).

Each nephron consists of a renal corpuscle and a renal tubule. The nephron begins with an expanded end called the **glomerular capsule** (formerly known as the Bowman's capsule). It looks like a double-walled cup that surrounds, and almost completely encloses, a knot of arterial capillaries called the **glomerulus**. Leading away from the glomerular capsule is a tube about 5 cm long called the **renal tubule**. It begins with a winding, or convoluted, section called the **proximal convoluted tubule**. Beyond this, each tubule has a straight portion before it forms a loop, the **loop of Henle**. The loop of Henle is like a hairpin bend with a straight section leading into the bend and another straight section leading away from the bend. The tubule then becomes convoluted and highly coiled again. This second coiled section is known as the **distal convoluted tubule**. The distal convoluted tubules of several nephrons join into a **collecting duct** that opens into a chamber in the kidney called the **renal pelvis**. The renal pelvis is shaped like a funnel and it channels fluid from the collecting ducts into the ureter (see Fig. 8.2).

The nephrons of the kidney are responsible for removing wastes from the blood and regulating blood composition. To be able to do this, they are well supplied with blood vessels. Blood enters the kidney through the **renal arteries** (see Fig. 8.2). These arteries are quite large, so that together the two kidneys receive about a quarter of the blood from the left side of the heart. Approximately 1.2 L of blood pass through the two kidneys every minute.

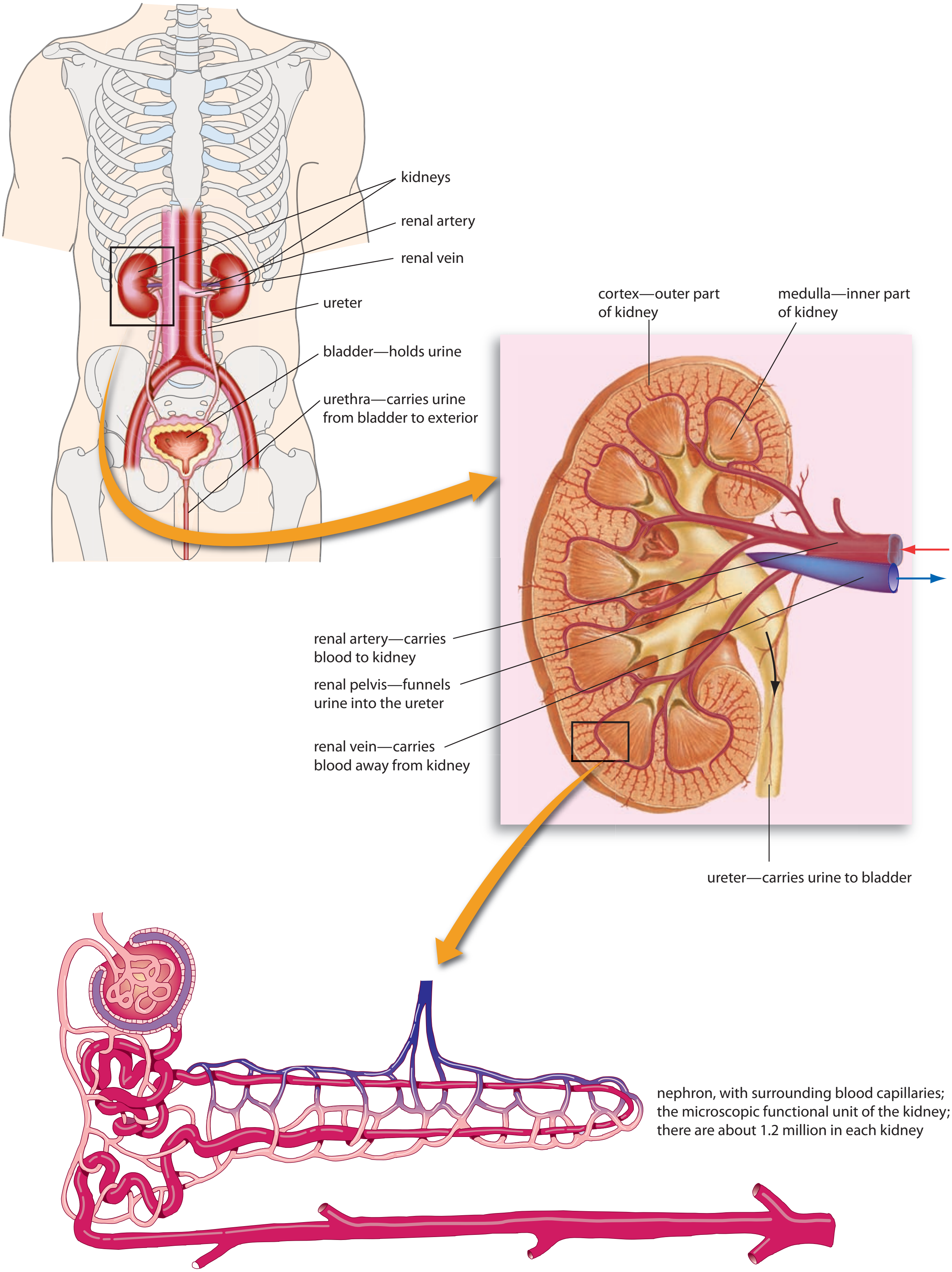


Figure 8.2 The structure and functions of the urinary system

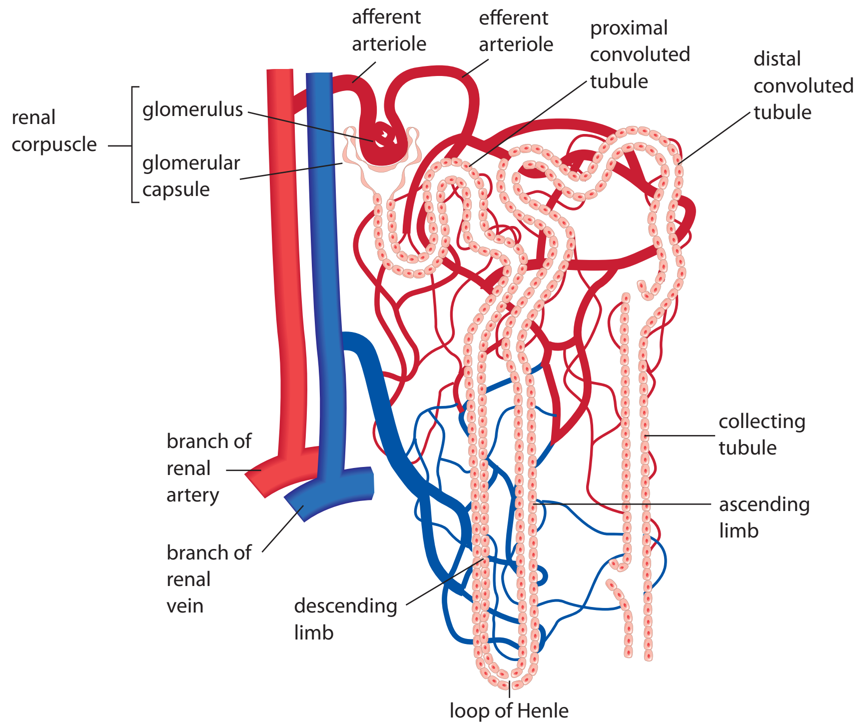


Figure 8.3 A nephron, showing arrangement of the blood vessels

The renal artery, shortly after entering the kidney, divides into small arteries and arterioles. Each renal corpuscle is supplied by an arteriole, the **afferent arteriole**, which then forms a knot of capillaries called the **glomerulus** (Fig. 8.4). This knot of capillaries is located within the glomerular capsule. The capillaries eventually unite to form another arteriole, the **efferent arteriole**, which passes out of the renal corpuscle.

Shortly after leaving the renal corpuscle, the efferent arteriole breaks up into a second capillary network. These capillaries surround the proximal and distal convoluted tubules of the nephron, the ascending and descending limbs of the loop of Henle, and the collecting duct. They are known as **peritubular capillaries**. Venous blood drains away from this network of capillaries and eventually leaves the kidney in the **renal vein**.

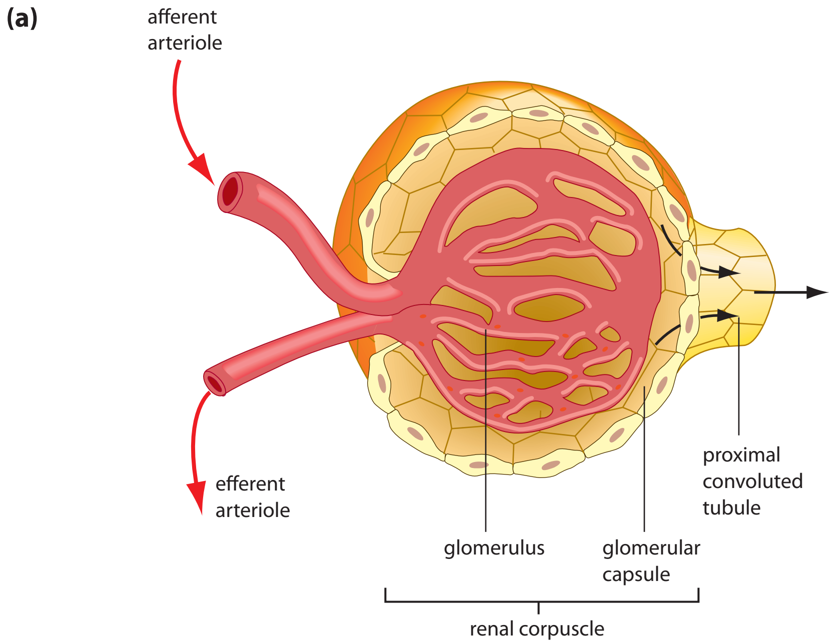
Urine formation

The formation of urine by the nephrons of the kidneys involves three major processes: glomerular filtration, selective reabsorption and secretion by the tubules.

Glomerular filtration

The first step in the production of urine is **glomerular filtration**. This process takes place in the renal corpuscle when fluid is forced out of the blood and is collected by the glomerular capsule. Fluid is normally forced out of the capillaries in all parts of the body, but in the glomerulus the process is enhanced by the high pressure of blood in the glomerulus. The afferent arteriole leading to the glomerulus has a wider diameter than the efferent arteriole leaving it. This narrowing of the efferent arteriole increases resistance to the flow of blood and produces a higher pressure in the glomerulus.

The pressure outside the capillaries in the glomerular capsule is negligible, and the blood in the capillaries in the glomerulus is separated from the cavity of the capsule



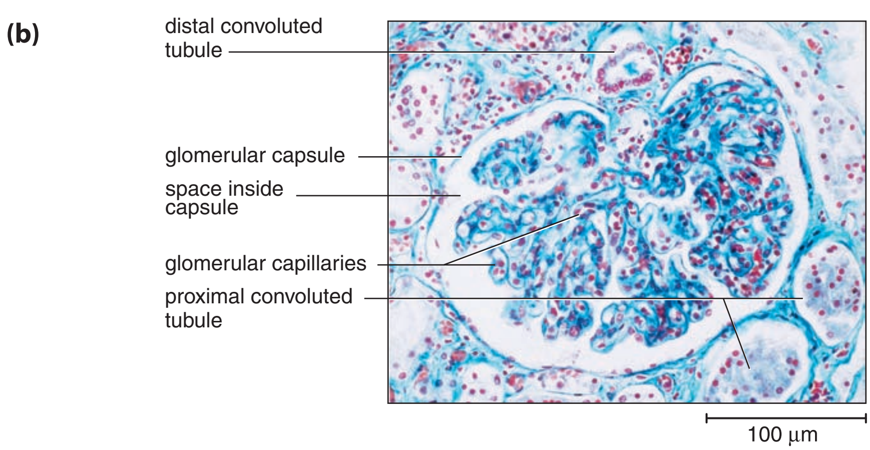


Figure 8.4 (a) The renal corpuscle. **(b)** Photomicrograph showing a renal corpuscle

by only two single layers of thin, flat cells. One layer makes up the capillary wall and the other the wall of the capsule. Therefore, when blood enters the glomerulus, the high pressure forces water and dissolved blood components through the differentially permeable cell membranes and into the capsule. The resultant fluid is termed the **filtrate**.

In a healthy person, the filtrate consists of all the materials present in the blood except the red and white blood cells and plasma proteins. These are too large to pass through the differentially permeable membranes of the cells making up the walls of the glomerulus and capsule. Therefore, the filtrate consists of water, salts, amino acids, fatty acids, glucose, urea, uric acid, creatinine, hormones, toxins and various ions.

As blood flows through the capillaries of the glomerulus, 20% of the plasma present is filtered through the capillary walls into the glomerular capsule. Complete filtration of all the plasma cannot take place as the blood in the capillaries is continually being pushed on by the blood behind it. With about 1.2 million nephrons in each kidney the amount filtered every minute is still quite high. In normal adults, the total filtrate produced by all the renal corpuscles of both kidneys is about 125 mL of filtrate per minute. This amounts to about 180 litres in a day! Although this large amount is filtered, only about 1% actually leaves the body as urine. Most is reabsorbed.

Reabsorption

Many of the components of the plasma that are filtered from the capillaries of the glomerulus are of use to the body, and their excretion would be undesirable. Therefore, some **selection** and **reabsorption** of the filtrate must take place. These processes are carried out by the cells that line the renal tubule. Materials that are reabsorbed include water, glucose and amino acids. In addition, ions such as sodium, potassium, calcium, chloride and bicarbonate are also reabsorbed. Some wastes, such as urea, are partially reabsorbed as well (Fig. 8.5).

Like the body's other exchange surfaces, a large surface area is required. The large surface area for effective reabsorption of materials is achieved by the long length of the kidney tubule—two sets of convolutions and the long loop of Henle—and by the huge number of nephrons in each kidney.

Reabsorption of much of the water in the filtrate can be regulated. Depending on the body's water requirements, the permeability of the plasma membranes of the cells making up parts of the tubules can be changed. Thus, more or less water can be reabsorbed depending on the body's requirements. This is an active process, under hormonal control, and is often referred to as **facultative reabsorption**.

Tubular secretion

The third process involved in the formation of urine is **tubular secretion**. Whereas selective reabsorption removes substances from the filtrate into the blood, tubular secretion *adds* materials to the filtrate from the blood, as Figure 8.5 shows. Materials secreted in this way include potassium and hydrogen ions, creatinine, and drugs such as penicillin.

Tubular secretion can be either active or passive, and it has two main effects. It removes certain unwanted materials from the body and, by so doing, controls the pH of the blood. The body has to maintain the blood within its normal pH range of 7.4–7.5,

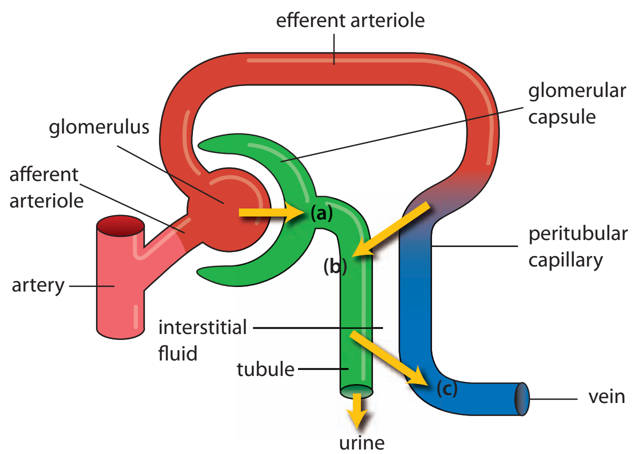


Figure 8.5 The process of filtration, reabsorption and secretion. **(a)** As blood flows through the kidneys, some of the plasma is filtered out of the glomerular capillaries and into the glomerular capsules. **(b)** Some materials within the blood that are not filtered into the renal tubules at the glomerular capsules can be secreted into other portions of the tubules. **(c)** As fluid flows along the renal tubules, water, ions, glucose and other substances required by the body are reabsorbed from the tubules and returned to the blood

despite the fact that our diets usually contain many acid-producing foods that tend to lower pH. To raise the pH of the blood, the tubules secrete hydrogen and ammonium ions into the filtrate. These two substances make the urine slightly acidic, with a normal pH of 6. (See Chapter 3 for a discussion of active and passive transport.)

The water, and other substances not reabsorbed, drain from the collecting ducts into the renal pelvis. From the pelvis, the urine, as it is now called, drains into the ureters and is pushed by waves of muscle contraction to the urinary bladder where it is stored (Fig. 8.2). The two ureters, one from each kidney, are essentially extensions of the pelvis of the kidneys. They extend 25–30 cm to the urinary bladder. The bladder is a hollow muscular organ from which the urethra exits. The urethra carries the urine from the bladder to the exterior of the body.

The relationship between structure and function

Like all organs of the body, the structure of the kidney is directly related to its function.

Some of the ways in which the structure of the kidney, particularly the nephrons, is related to its function of excretion of waste and regulation of the water content of the body are listed below.

1. The glomerular capsule surrounds the glomerulus to collect the fluid filtered out of the blood capillaries.
2. The arteriole leading out of the glomerulus has a smaller diameter than the arteriole leading in. This raises the blood pressure so that more fluid is filtered out of the blood.
3. The tubule has two sets of convolutions and a long loop so that each tubule has a large surface area for reabsorption and secretion.
4. Each kidney has over a million nephrons so the total surface area available for reabsorption and secretion is extremely large.

By carefully reading the information about kidney structure you will be able to think of other ways in which kidney structure is related to its functions. A summary of the functioning of the kidney is given in Table 8.1.

Table 8.1 Summary of the functioning of the kidney

Region of nephron	Activities taking place
Renal corpuscle	Filtration of blood from capillaries of glomerulus
	Formation of filtrate in the glomerular capsule
Proximal convoluted tubule and loop of Henle	Reabsorption of sodium, potassium, chloride and bicarbonate ions
	Reabsorption of glucose
	Passive reabsorption of water by diffusion
Distal convoluted tubule	Reabsorption of sodium ions
	Active reabsorption of water depending on the body's water needs
	Secretion of hydrogen and potassium ions, creatinine and certain drugs like penicillin
Collecting duct	Active reabsorption of water depending on the body's water needs

EXTENSION

A countercurrent exists between the two limbs of the loop of Henle and between each nephron tubule and surrounding capillaries.

Find out:

- what a countercurrent is
- the importance of the countercurrents that exist in the kidney
- how changes in the concentration of the filtrate would affect the countercurrent exchange mechanisms
- other places in the body, apart from the kidney, where countercurrent exchanges operate.

Urine composition

The body must excrete its waste products, such as urea, sulfates and phosphates, on a regular basis. These substances have to be in solution, and so the elimination of these wastes requires a certain amount of water loss. Regardless of the amount of water available in the body, or the amount taken in, about half a litre of water must be lost each day simply to remove wastes. When water content of the body fluids is low, the urine that is excreted is very concentrated. Table 8.2 compares the composition of the fluid filtered from the blood and the urine. It also shows the amount of each component that is reabsorbed during a 24-hour period. The values shown can vary markedly between individuals, and with diet, and so they should be regarded only as a guide.

Table 8.2 Composition of filtrate, reabsorbed substances and urine over a 24-hour period

Chemical component	Filtrate	Reabsorbed substances	Urine
Water	180 L	178–9 L	1–2 L
Sodium, chloride and other ions	1500 g	1485 g	15 g
Proteins	2 g	1.9 g	0.1 g
Glucose	180 g	180 g	0 g
Urea	53 g	28 g	25 g
Uric acid	8.5 g	7.5 g	1 g
Creatinine	1.6 g	0 g	1.6 g

Thus, under normal circumstances:

- about 99% of the water that enters the nephron is reabsorbed
- the urine does not normally contain significant amounts of protein
- the urine does not normally contain any glucose
- the main materials making up the urine, besides water, are urea, ions, uric acid and creatinine.

Generally, a healthy adult passes about 1.5 L of urine a day, but this varies tremendously depending on diet, environment and other factors. Table 8.3 indicates the components that the urine of a healthy adult may contain. Again, this is highly variable and should be used only as a guide. The amber colour of urine is due to the presence of some bile pigments.

Table 8.3 Composition of urine

Component	%
Water	96.0
Urea	2.0
Various ions	1.5
Others	0.5

Lifestyle can affect kidney functions

Kidney failure

One in three adult Australians is at risk of developing kidney disease. A person can lose up to 90% of kidney function without realising it. At that stage it is almost impossible to prevent serious problems occurring.

Most kidney diseases affect the glomeruli, reducing their ability to filter the blood. Protein and sometimes red blood cells may leave the blood at the glomerulus and will then be present in the urine. If excessive proteins are lost in the urine, blood protein levels fall and fluid accumulates in the tissues, causing swelling of the hands, feet, face or other areas.

There are a number of lifestyle measures that you can take to maintain healthy kidneys.

- Regulate diet to maintain a healthy weight. Being overweight can lead to the development of diabetes or high blood pressure, both of which are major risk factors for kidney disease.
- Do not smoke. Compared with non-smokers, people who smoke are three times more likely to have impaired kidney function.
- Drink water instead of drinks containing sugar.
- Drink alcohol in moderation—one standard drink per day for women and two per day for men.

When kidneys lose their ability to excrete waste and control the level of fluid in the body it is known as **kidney failure**. Kidney failure may happen suddenly but is more likely to develop over a period of years. Factors such as diabetes, high blood pressure or kidney diseases slowly destroy the nephrons in the kidneys. Eventually, the only way to maintain life is by dialysis or a kidney transplant.

Dialysis

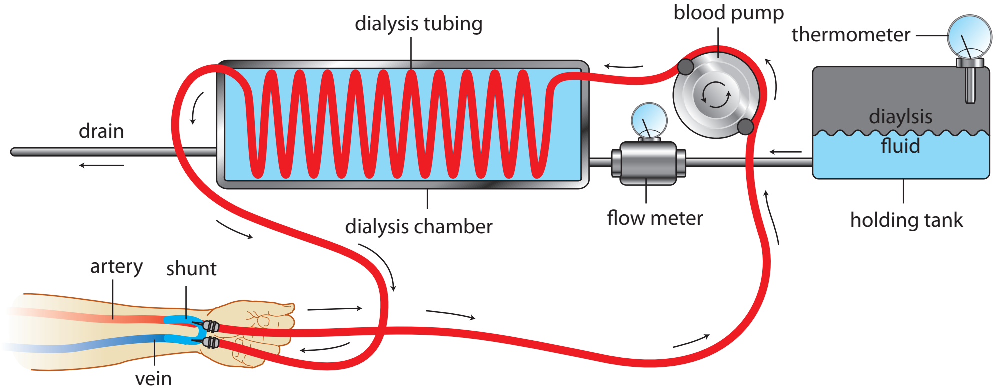
Dialysis is a method of removing wastes from the blood when kidney failure occurs. There are two types of dialysis: peritoneal dialysis and haemodialysis.

The **peritoneum** is a membrane that lines the inside of the abdominal cavity and covers abdominal organs such as the stomach, liver and intestines. It has a very rich blood supply. **Peritoneal dialysis** occurs inside the body using the peritoneum as a membrane across which waste can be removed. A tube, called a catheter, is placed through the wall of the abdomen. For an adult, 2–3 L of fluid are passed through the catheter into the abdominal cavity. The fluid contains glucose and other substances at concentrations similar to those found in the blood. However, there are no wastes in the fluid. This means that because of the concentration difference wastes will diffuse out of the blood into the fluid in the abdominal cavity. Useful substances stay in the blood because there is no concentration difference between the blood and the fluid. After a time the fluid that was placed in the abdominal cavity is drained out through the catheter, along with any wastes and extra water that have diffused from the blood. Peritoneal dialysis is usually done each day.

See how dialysis works at http://www.biotopics.co.uk/human2/andial.html

Haemodialysis involves passing the blood through an artificial kidney or dialysis machine. The blood passes through thousands of fine tubes, made of a differentially permeable membrane, and immersed in a bath of fluid. The concentrations of substances in the fluid are similar to those in the blood except that the fluid has no waste. Due to the concentration differences wastes diffuse from the blood into the fluid. Patients spend about 4–5 hours attached to the machine and dialysis is normally done three times per week.

Figure 8.6 Diagrammatic view of how a dialysis machine works



EXTENSION

Kidney disease causes protein to be excreted in the urine. The loss of protein from the blood causes fluid to accumulate in the tissues and there may be swelling of the hands, feet and face.

- Find out why loss of protein from the blood causes swelling of the tissues.

Role of the liver in excretion

Proteins are primarily 'body builders'; that is, they make up the structural materials of cells. As long as the body has a sufficient supply of carbohydrates and fats, or has a supply of stored fat, then little protein is used in energy-releasing reactions. However, excess protein from the diet cannot be stored in the body, and so processes are required to remove it from the body.

Some protein is broken down in the body all the time, although most of the breakdown is incomplete. Worn out cells, such as red blood cells, are a source of protein, and these are broken down to the constituent amino acids. Some of these amino acids are then used to make new proteins. However, a very small amount of amino acid and protein is lost from the body via the urine, skin, hair and fingernails.

The proteins, which have been built up from amino acids, become the primary constituents of cell structures, enzymes, antibodies and many glandular secretions. However, if other energy sources are used up, the body is able to metabolise large amounts of proteins. To make use of proteins in this way, the amino group (NH_2) must first be removed from the amino acids. This process, called **deamination**, occurs in the liver with the aid of enzymes. Once the amino group has been removed, it is converted by the liver cells to ammonia (NH_3) and then finally to urea. The urea is eliminated from the body in the urine. The remaining part of the amino acid, which is primarily made up of carbon and hydrogen, is converted into a carbohydrate. This carbohydrate can be readily broken down by the cells to release energy, carbon dioxide and water. Deamination can be summarised as an equation:

$$\text{amino acid} + \text{oxygen} \xrightarrow{\text{enzymes}} \text{carbohydrate} + \text{ammonia}$$

Ammonia is extremely soluble in water and in large quantities is highly toxic to cells. One thousandth of a milligram of ammonia in a litre of blood is sufficient to kill a person. The cells of the liver rapidly convert ammonia to the less toxic molecule, urea. Moderate amounts of urea are harmless to the body. It is easily excreted by the kidneys and is eliminated from the body in the urine. Small amounts of urea are also lost in sweat from the sweat glands. The process can be expressed as:

$$\text{energy} + \text{carbon dioxide} + \text{ammonia} \longrightarrow \text{urea} + \text{water}$$

Working scientifically

Activity 8.1 Urine production

Choose a factor that you think may affect the rate of urine production.

- Propose a hypothesis relating your chosen factor to rate of urine production.
- Design an experiment to test your hypothesis.
- Your teacher may want you to present your experimental design in a particular way.

Activity 8.2 Urine analysis

The higher the quantity of dissolved substances in a given volume of urine, the heavier it will be. Therefore, a simple way of determining the concentration of urine is to weigh it. One litre of pure water has a mass of 1000 g; 1 L of urine has a mass of more than 1000 g because urine contains dissolved substances. Analysis of a person's urine by measuring the volume and recording the mass gave the results shown in Table 8.4. The results have been converted to a standard volume of 1 L so that they can be directly compared. The higher the mass, the more concentrated the urine.

Table 8.4 Change in urine concentration over a day

Time	Urine mass (g)
6.30 am	1073
8.45 am	1026
10.30 am	1049
1.00 pm	1062
3.15 pm	1078
5.00 pm	1033
7.00 pm	1014
10.15 pm	1022

The results shown above were collected in summer and the person worked outdoors during the day.

1. Using an appropriate format draw a graph of these results.
2. For each of the measurements taken during the day, explain why the concentration has increased or decreased.

REVIEW QUESTIONS

1. **(a)** What is meant by the term excretion?
   (b) Which organs of the body are involved in excretion?
   (c) Which organs are involved in the excretion of water?
2. **(a)** Draw a nephron and its associated blood vessels. Label the afferent and efferent arterioles, glomerulus, glomerular capsule, distal and proximal convoluted tubules, loop of Henle, collecting duct and peritubular capillaries.
   (b) Use arrows on your diagram to indicate the direction of blood flow and the direction in which the filtrate flows.
3. In what ways is the filtrate that enters the glomerular capsule different from the blood?
4. Describe what happens in the nephron during:
   (a) filtration
   (b) reabsorption
   (c) secretion
5. What lifestyle measures should you adopt to make sure that your kidneys remain healthy?
6. What is kidney failure?
7. **(a)** What is dialysis?
   (b) Describe the difference between peritoneal dialysis and haemodialysis.
8. **(a)** What is deamination?
   (b) Why must ammonia not be allowed to accumulate in the tissues? What happens to the ammonia produced in deamination?

APPLY YOUR KNOWLEDGE

1. To be effective, an organ where materials are taken into the body, or passed out of the body, must have a very large surface area. How is a large surface area achieved in the kidney?
2. In this chapter you were told the approximate length of a renal tubule and also the approximate number of tubules in a kidney. Using these figures, calculate the total tubule length for an average person, remembering that most people have two kidneys. Express your answer in appropriate units.
3. The desert hopping mouse lives on dry seeds and never drinks water. It has extremely long kidney tubules.
   (a) From where does the desert hopping mouse get its water? (Refer to Chapter 4.)
   (b) How is the desert hopping mouse able to reduce water loss in urine to a minimum?

4. The kidneys have a very important function in maintaining the composition of body fluids at a constant level. Write an account of the kidney's role in maintaining a constant internal environment for the cells.
5. Make a comprehensive list of ways in which the structure of the kidney is suited to the functions that it performs. For each structural feature on your list describe how that feature is related to the working of the kidney.
6. What effects would you expect the following to have on urine production?
   (a) a high salt diet
   (b) a low protein diet
   (c) a large intake of water
7. **(a)** Suggest why we tend to urinate more frequently in cold weather than in hot weather.
   (b) Suggest why urine is often more darkly coloured in hot weather than in cold weather.
8. Explain how the circulatory system forms a link between the respiratory, digestive and excretory systems.
9. Why do doctors sometimes order a urine test for a patient? What information about a person's health can be gained from an analysis of the urine?

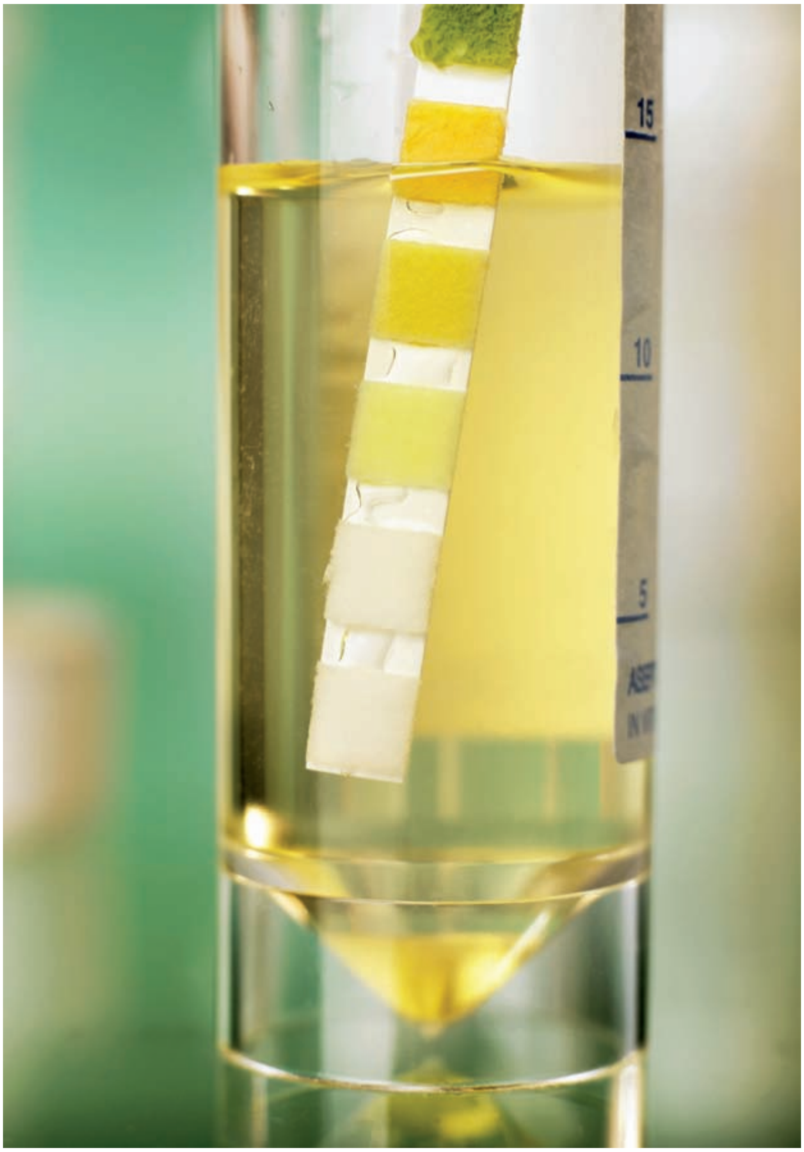


Figure 8.7 Urine analysis can be used to identify kidney problems