Kidneys

Learning outcomes

After studying this section you should be able to:

identify the organs associated with the kidneys

outline the gross structure of the kidneys

describe the structure of a nephron

explain the processes involved in the formation of urine

explain how body water and electrolyte balance is maintained.

The kidneys (Fig. 13.2) lie on the posterior abdominal wall, one on each side of the vertebral column, behind the peritoneum and below the diaphragm. They extend from the level of the 12th thoracic vertebra to the 3rd lumbar vertebra, receiving some protection from the lower rib cage. The right kidney is usually slightly lower than the left, probably because of the considerable space occupied by the liver.

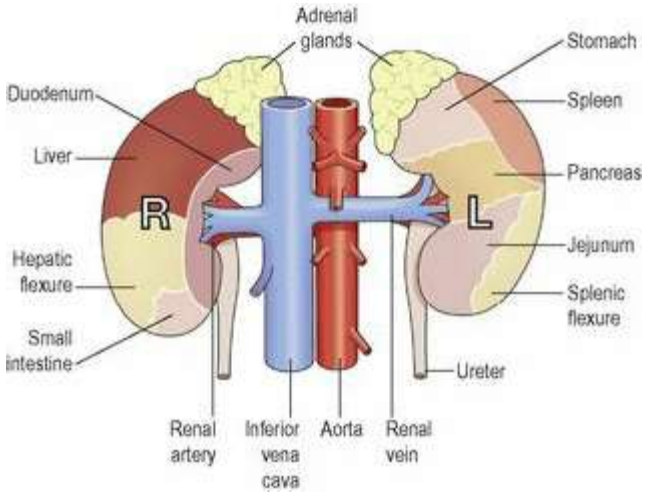

Figure 13.2 Anterior view of the kidneys showing the areas of contact with associated structures.

Kidneys are bean-shaped organs, about 11 cm long, 6 cm wide, 3 cm thick and weigh 150 g. They are embedded in, and held in position by, a mass of fat. A sheath of fibrous connective tissue, also known as the *renal fascia,* encloses the kidney and the renal fat.

Organs associated with the kidneys (Figs 13.1, 13.2 and 13.3

As the kidneys lie on either side of the vertebral column, each is associated with a different group of structures.

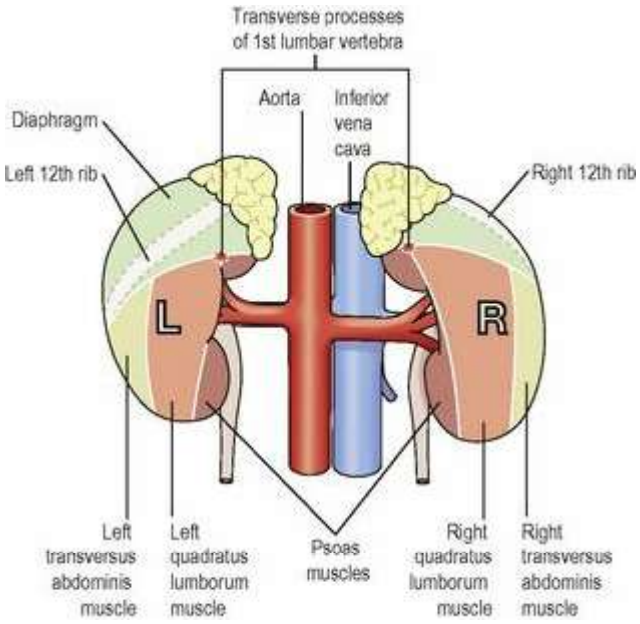

Figure 13.3 Posterior view of the kidneys showing the areas of contact with associated structures.

Right kidney

periorly – the right adrenal gland

teriorly – the right lobe of the liver, the duodenum and the hepatic flexure of the colon

steriorly – the diaphragm, and muscles of the posterior abdominal wall

Left kidney

periorly – the left adrenal gland

teriorly – the spleen, stomach, pancreas, jejunum and splenic flexure of the colon

steriorly – the diaphragm and muscles of the posterior abdominal wall

Gross structure of the kidney 13.2

There are three areas of tissue that can be distinguished when a longitudinal section of the kidney is viewed with the naked eye (Fig. 13.4):

n outer fibrous *capsule*, surrounding the kidney

he *cortex*, a reddish-brown layer of tissue immediately below the capsule and outside the pyramids

he *medulla*, the innermost layer, consisting of pale conical-shaped striations, the *renal pyramids*.

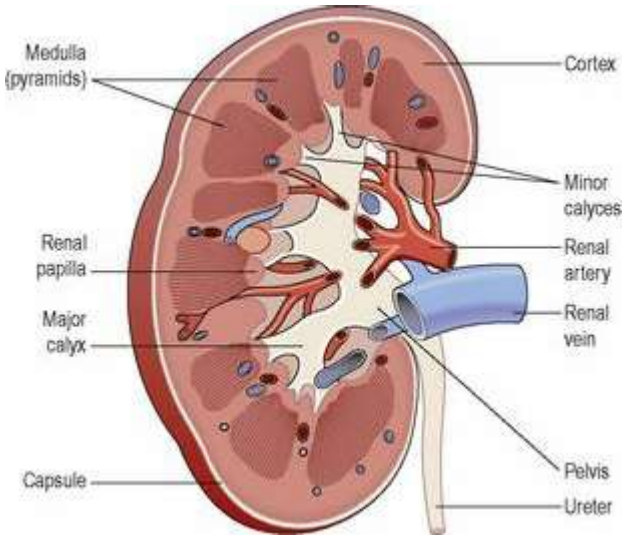

Figure 13.4 A longitudinal section of the right kidney.

The hilum is the concave medial border of the kidney where the renal blood and lymph vessels, the ureter and nerves enter.

The renal pelvis is the funnel-shaped structure that collects urine formed by the kidney (Fig. 13.4). Urine formed in the kidney passes through a renal *papilla* at the apex of a pyramid into a minor calyx, then into a major calyx before passing through the renal pelvis into the ureter. The walls of the pelvis contain smooth muscle and are lined with transitional epithelium. Peristalsis of the smooth muscle originating in pacemaker cells in the walls of the calyces propels urine through the renal pelvis and ureters to the bladder. This is an intrinsic property of the smooth muscle, and is not under nerve control.

Microscopic structure of the kidney 13.3

The kidney is composed of about 1–2 million functional units, the *nephrons*, and a smaller number of *collecting ducts*. The collecting ducts transport urine through the pyramids to the calyces and renal pelvis, giving the pyramids their striped appearance (Fig. 13.4). The collecting ducts are supported by a small amount of connective tissue, containing blood vessels, nerves and lymph vessels.

The nephron (Fig. 13.5)

The nephron consists of a tubule closed at one end, the other end opening into a collecting tubule. The closed or blind end is indented to form the cup-shaped *glomerular capsule* (Bowman's capsule), which almost completely encloses a network of tiny arterial capillaries, the *glomerulus*. These resemble a coiled tuft and are shown in Figure 13.6. Continuing from the glomerular capsule, the remainder of the nephron is about 3 cm long and is described in three parts:

- he proximal convoluted tubule
- he medullary loop (loop of Henle)
- he distal convoluted tubule, leading into a collecting duct.

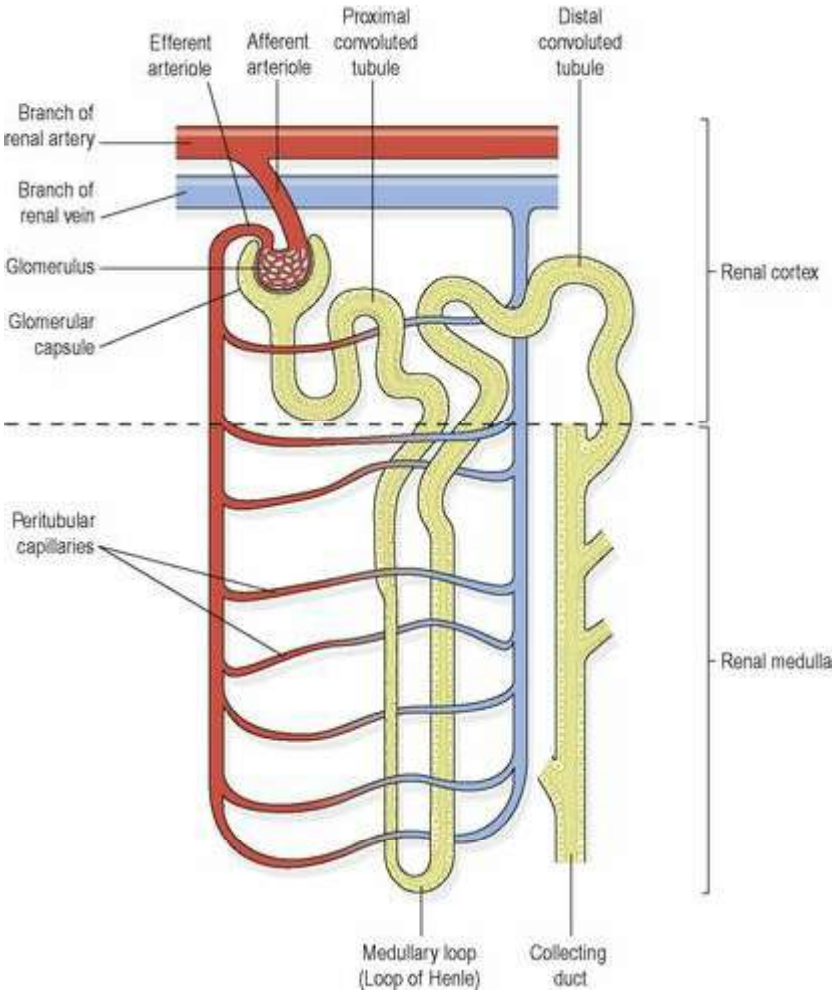

Figure 13.5 A nephron and associated blood vessels.

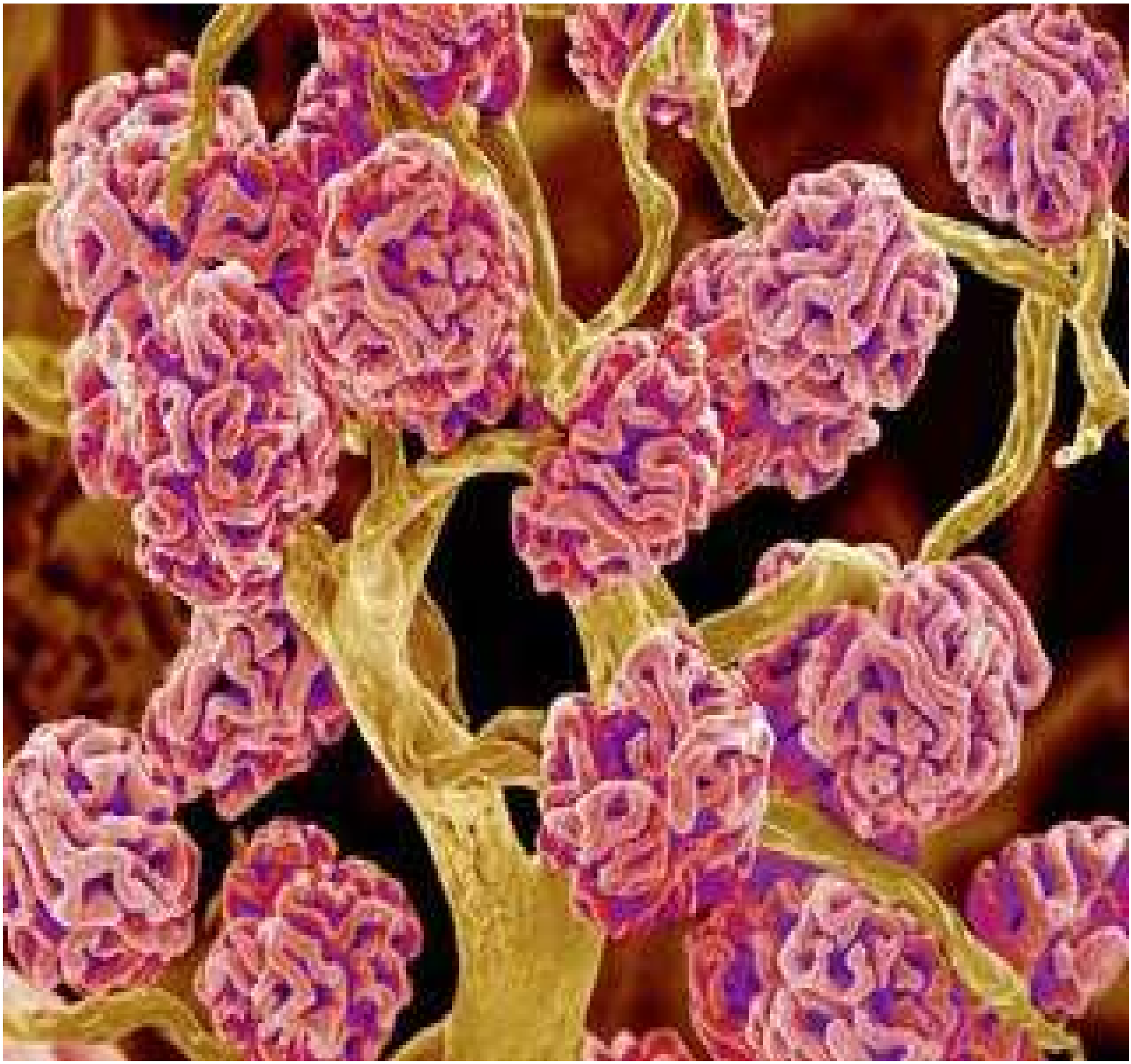

Figure 13.6 Coloured scanning electron micrograph of glomerular capillary tufts.

The collecting ducts unite, forming larger ducts that empty into the minor calyces.

The kidneys receive about 20% of the cardiac output. After entering the kidney at the hilum the renal artery divides into smaller arteries and arterioles. In the cortex an arteriole, the *afferent arteriole*, enters each glomerular capsule and then subdivides into a cluster of tiny arterial capillaries, forming the glomerulus. Between these capillary loops are connective tissue phagocytic *mesangial cells*, which are part of the monocyte–macrophage system (p. 36). The blood vessel leading away from the glomerulus is the *efferent arteriole*. The afferent arteriole has a larger diameter than the efferent arteriole, which increases pressure inside the glomerulus and drives

filtration across the glomerular capillary walls (Fig. 13.7). The efferent arteriole divides into a second peritubular (meaning ‘around tubules’) capillary network, which wraps around the remainder of the tubule, allowing exchange between the fluid in the tubule and the bloodstream (Figs 13.5, 13.8 and 13.10). This maintains the supply of oxygen and nutrients to the local tissues and removes waste products. Venous blood drained from this capillary bed eventually leaves the kidney in the renal vein, which empties into the inferior vena cava.

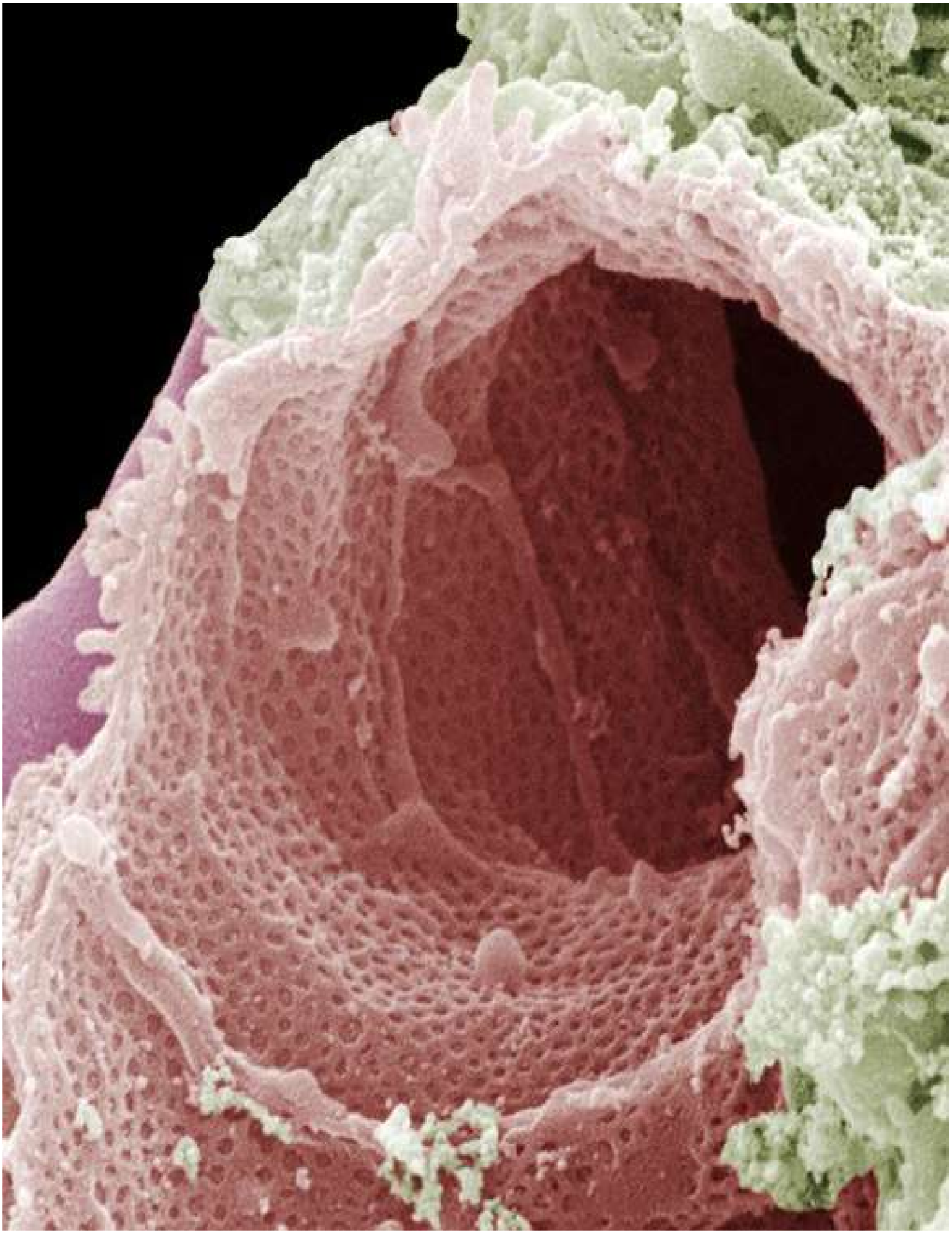

Figure 13.7 Coloured scanning electron micrograph of glomerular capillary.

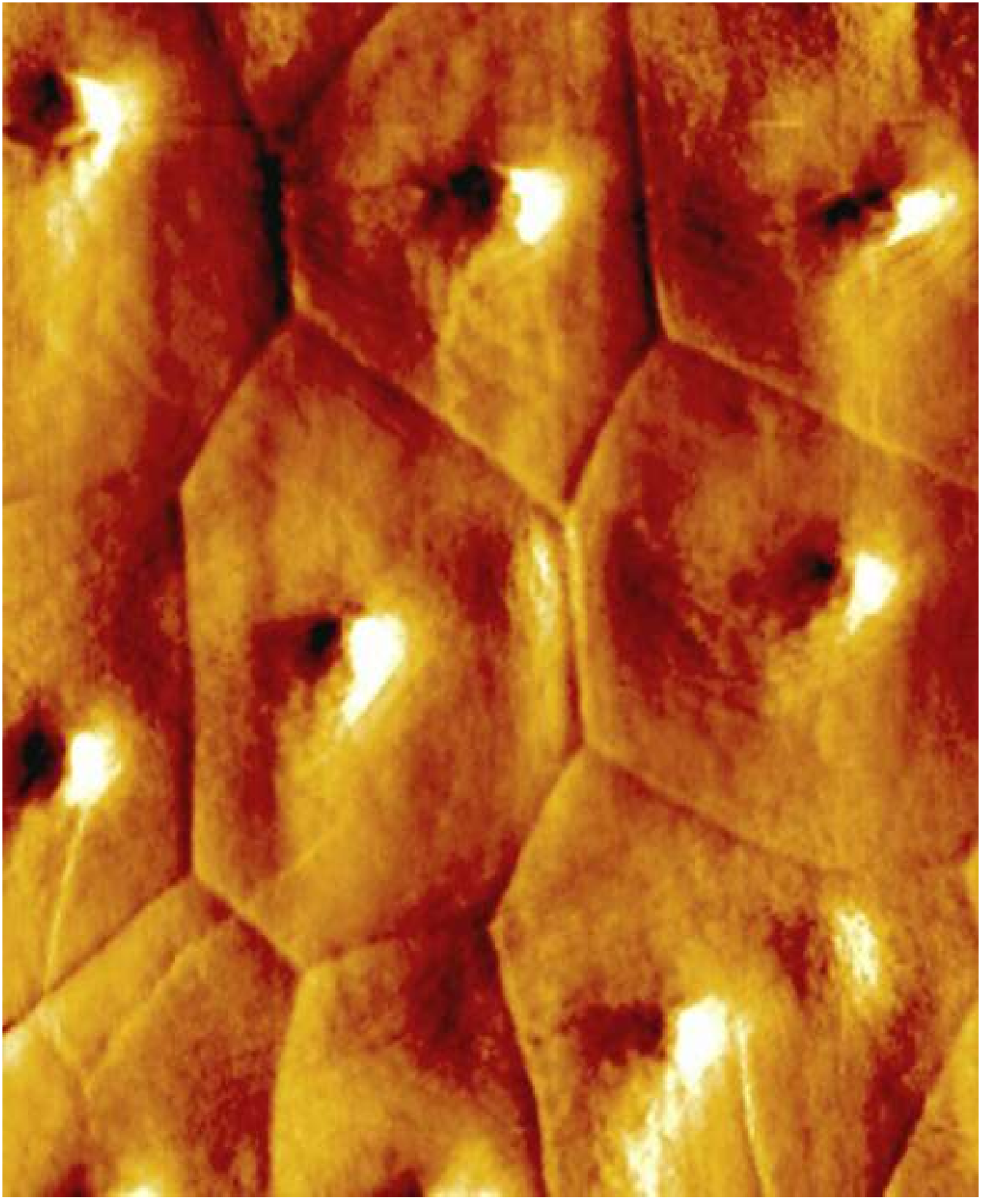

Figure 13.9 Simple squamous epithelium of the collecting ducts. Coloured atomic force micrograph.

The walls of the glomerulus and the glomerular capsule consist of a single layer of flattened epithelial cells. The glomerular walls are more permeable than those of other capillaries. The remainder of the nephron and the collecting duct are formed by a single layer of simple squamous epithelium (Fig. 13.9).

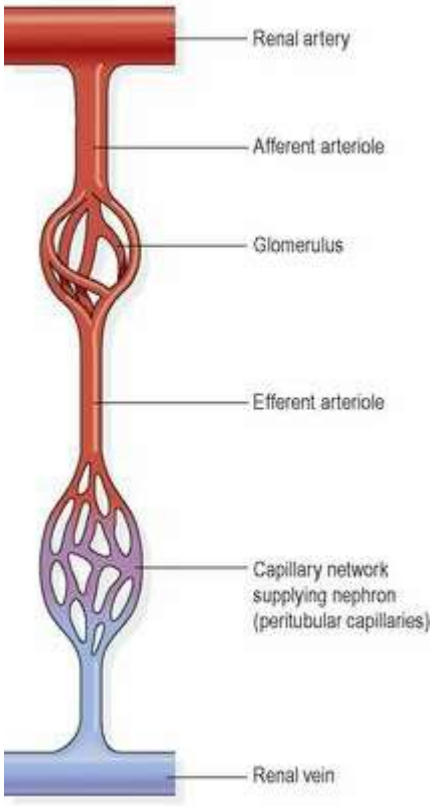

Figure 13.8 The series of blood vessels in the kidney.

The blood vessels of the kidney are supplied by both sympathetic and parasympathetic nerves. The presence of both branches of the autonomic nervous system controls renal blood vessel diameter and renal blood flow independently of autoregulation (p. 334).

Functions of the kidney

Formation of urine

The kidneys form urine, which passes through the ureters to the bladder for storage prior to excretion. The composition of urine reflects exchange of substances between the nephron and the blood in the renal capillaries. Waste products of protein metabolism are excreted, electrolyte levels are controlled and pH (acid–base balance) is maintained by excretion of hydrogen ions. There are three processes involved in the formation of urine:

iltration

elective reabsorption

ecretion.

Filtration (Fig. 13.11) 13.4, 13.5

This takes place through the semipermeable walls of the glomerulus (Fig. 13.10) and glomerular capsule. Water and other small molecules pass through, although some are reabsorbed later. Blood cells, plasma proteins and other large molecules are too large to filter through and therefore remain in the capillaries (see Box 13.1). The filtrate in the glomerulus is very similar in composition to plasma with the important exceptions of plasma proteins and blood cells.

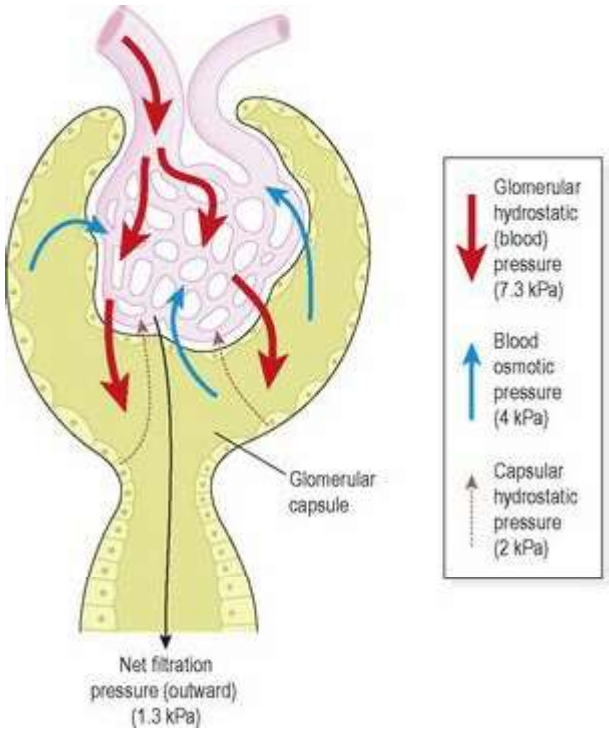

Figure 13.11 Filtration in the glomerulus.

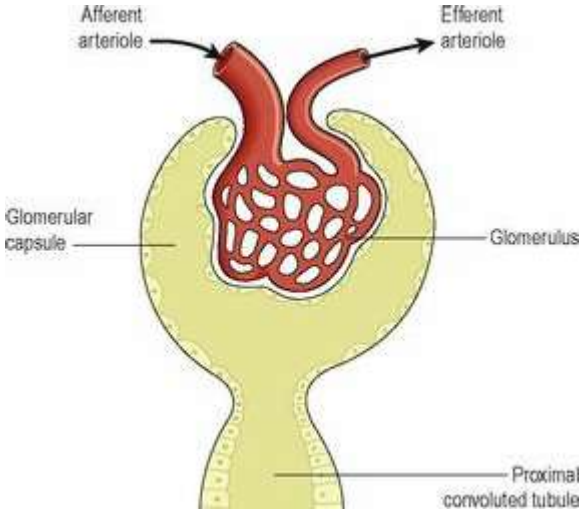

Figure 13.10 The glomerulus and glomerular capsule.

Box 13.1 Constituents of glomerular filtrate and glomerular capillaries

Blood constituents in glomerular filtrate	Blood constituents remaining in glomerular capillaries
Water	Leukocytes
Mineral salts	Erythrocytes
Amino acids	Platelets
Ketoacids	Plasma proteins
Glucose	Some drugs (large molecules)
Some hormones	
Creatinine	
Urea	
Uric acid	
Some drugs (small molecules)	

Filtration takes place because there is a difference between the blood pressure in the glomerulus and the pressure of the filtrate in the glomerular capsule. Because the efferent arteriole is narrower than the afferent arteriole, a *capillary hydrostatic pressure* of about 7.3 kPa (55 mmHg) builds up in the glomerulus. This pressure is opposed by the *osmotic pressure* of the blood, provided mainly by plasma proteins, about 4 kPa (30 mmHg), and by *filtrate hydrostatic pressure* of about 2 kPa (15 mmHg) in the glomerular capsule. The net *filtration pressure* is, therefore:

$$7.3 - (4 + 2) = 1.3\,\text{kPa, or}$$

$$55 - (30 + 15) = 10\,\text{mmHg.}$$

The volume of filtrate formed by both kidneys each minute is called the *glomerular filtration rate* (GFR). In a healthy adult the GFR is about 125 ml/min, i.e. 180 litres of filtrate are formed each day by the two kidneys. Nearly all of the filtrate is later reabsorbed from the kidney tubules with less than 1%, i.e. 1 to 1.5 litres, excreted as urine. The differences in volume and concentration are due to selective reabsorption of some filtrate constituents and tubular secretion of others.

Autoregulation of filtration

Renal blood flow is protected by a mechanism called *autoregulation*, whereby renal blood flow is maintained at a constant pressure across a wide range of systolic blood pressures (from around 80 to 200 mmHg). Autoregulation operates independently of nervous control, i.e. if the nerve supply to the renal blood vessels is interrupted, autoregulation continues to operate. It is therefore a property inherent in renal blood vessels; it may be stimulated by changes in blood pressure in the renal arteries or by fluctuating levels of certain metabolites, e.g. prostaglandins.

In severe shock, when the systolic blood pressure falls below 80 mmHg, autoregulation fails and renal blood flow and the hydrostatic pressure decrease, impairing filtration within the nephrons.

Selective reabsorption (Fig. 13.12) 13.6

Most reabsorption from the filtrate back into the blood takes place in the proximal convoluted tubule, whose walls are lined with microvilli to increase surface area for absorption. Materials essential to the body are reabsorbed here, including some water, electrolytes and organic nutrients such as glucose. Some reabsorption is passive, but some substances are transported actively. Only 60–70% of filtrate reaches the loop of the nephron. Much of this, especially water, sodium and chloride, is reabsorbed in the loop, so only 15–20% of the original filtrate reaches the distal convoluted tubule, and the composition of the filtrate is now very different from its starting values. More electrolytes are reabsorbed here, especially sodium, so the filtrate entering the collecting ducts is actually quite dilute. The main function of the collecting ducts therefore is to reabsorb as much water as the body needs.

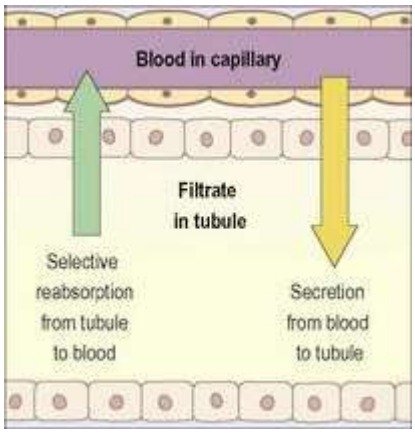

Figure 13.12 Directions of selective reabsorption and secretion in the nephron.

Active transport takes place at carrier sites in the epithelial membrane, using chemical energy to transport substances against their concentration gradients (p. 32).

Some ions, e.g. sodium and chloride, can be absorbed by both active and passive mechanisms depending on the site in the nephron.

Some constituents of glomerular filtrate (e.g. glucose, amino acids) do not normally appear in urine because they are completely reabsorbed unless blood levels are excessive.

Reabsorption of nitrogenous waste products, such as urea, uric acid and creatinine is very limited.

The kidneys' maximum capacity for reabsorption of a substance is the *transport maximum*, or renal threshold. For example, the normal blood glucose level is 3.5 to 8 mmol/l (63 to 144 mg/100 ml) and if this rises above the transport maximum of about 9 mmol/l (160 mg/100 ml), glucose appears in the urine. This occurs because all the carrier sites are occupied and the mechanism for active transport out of the tubules is overloaded. Other substances reabsorbed by active transport include sodium, calcium, potassium, phosphate and chloride.

The transport maximum, or renal threshold, of some substances varies according to body need at a particular time, and in some cases reabsorption is regulated by hormones.

Hormones that influence selective reabsorption 13.7

Parathyroid hormone

This comes from the parathyroid glands and together with *calcitonin* from the thyroid gland regulates the reabsorption of calcium and phosphate from the distal collecting tubules.

Antidiuretic hormone

Also known as ADH, this is secreted by the posterior lobe of the pituitary gland and increases the permeability of the distal convoluted tubules and collecting tubules, increasing water reabsorption. Secretion of ADH is controlled by a negative feedback system (Fig. 13.13).

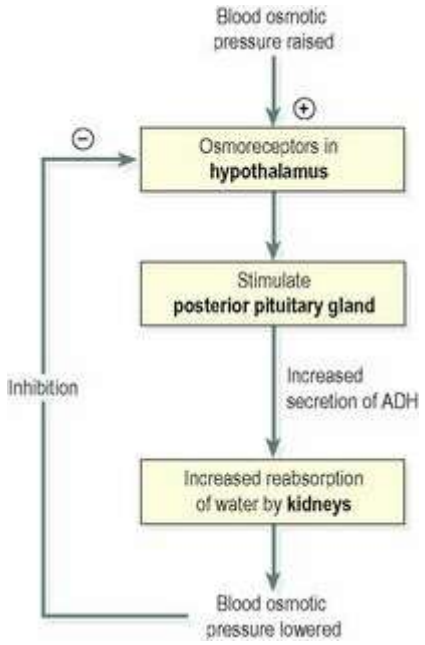

Figure 13.13 Negative feedback regulation of secretion of antidiuretic hormone (ADH).

Aldosterone

Secreted by the adrenal cortex, this hormone increases the reabsorption of sodium and water, and the excretion of potassium. Secretion is regulated through a negative feedback system (Fig. 13.14).

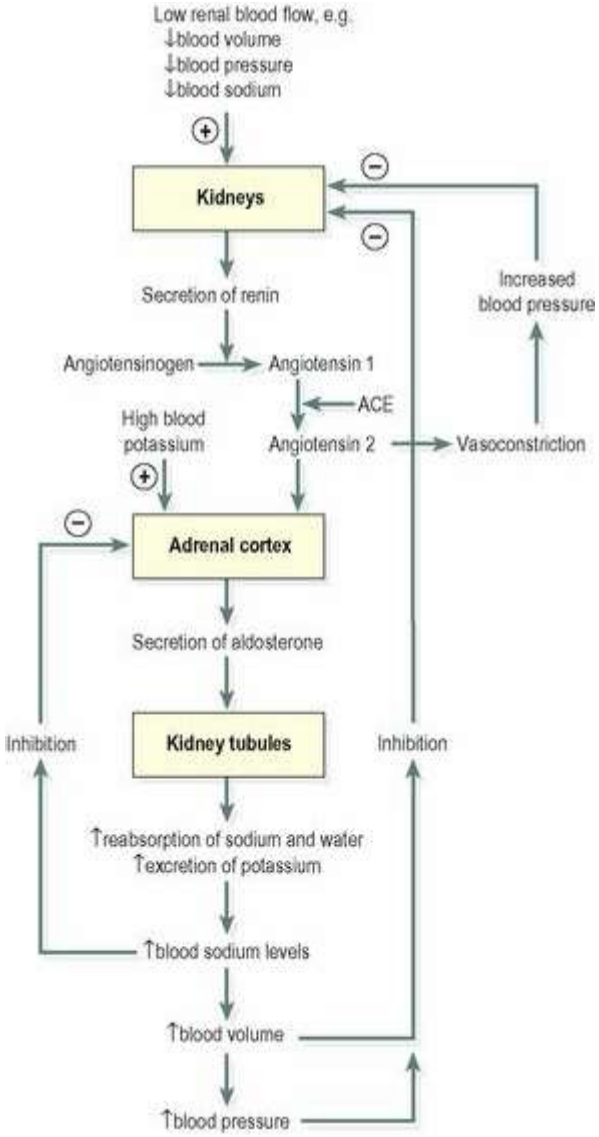

Figure 13.14 **Negative feedback regulation of aldosterone secretion.** ACE = angiotensin converting enzyme.

Atrial natriuretic peptide

Also known as ANP, this hormone is secreted by the atria of the heart in response to stretching of the atrial wall. It decreases reabsorption of sodium and water from the proximal convoluted tubules and collecting ducts. Secretion of ANP is also regulated by a negative feedback system (Fig. 13.15).

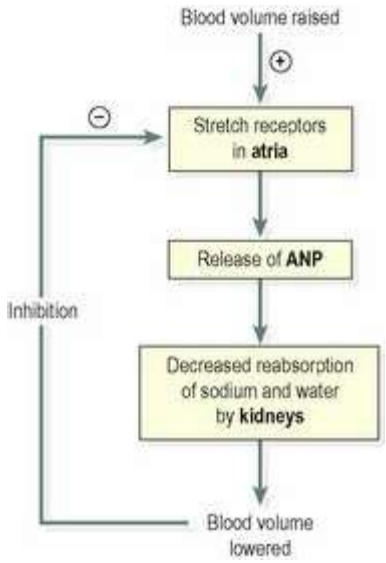

Figure 13.15 Negative feedback regulation of secretion of atrial natriuretic peptide (ANP).

Tubular secretion (Fig. 13.12) 13.8

Filtration occurs as the blood flows through the glomerulus. Substances not required and foreign materials, e.g. drugs including penicillin and aspirin, may not be cleared from the blood by filtration because of the short time it remains in the glomerulus. Such substances are cleared by secretion from the peritubular capillaries into the convoluted tubules and excreted from the body in the urine. Tubular secretion of hydrogen ions (H^+) is important in maintaining normal blood pH.

Summary of urine formation

The three processes involved – filtration, selective reabsorption and tubular secretion – are described above and summarised in Figure 13.16.

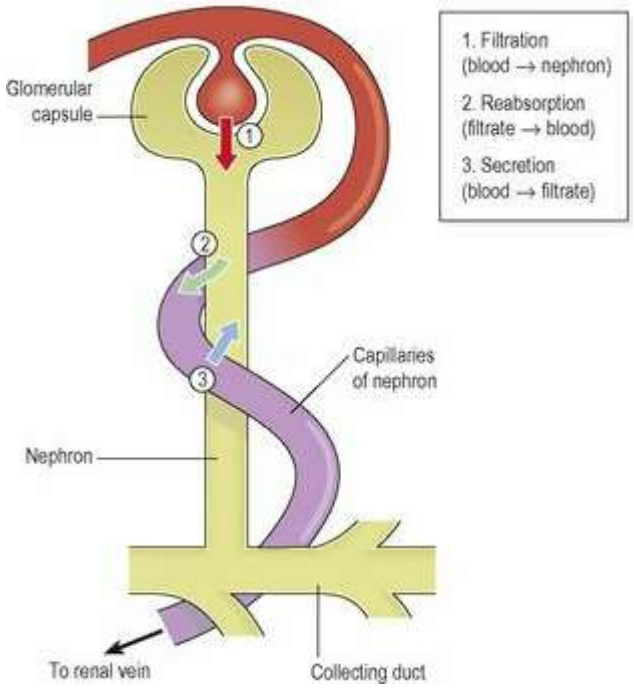

Figure 13.16 Summary of the three processes that form urine.

Composition of urine

ıter 96%

ea 2%

Urine is clear and amber in colour due to the presence of urobilin, a bile pigment altered in the intestine, reabsorbed then excreted by the kidneys (see Fig. 12.37, p. 303). The specific gravity is between 1020 and 1030, and the pH is around 6 (normal range of 4.5 to 8). A healthy adult passes 1000 to 1500 ml per day. The amount of urine produced and the specific gravity vary according to fluid intake and the amount of solute excreted. Urine production is decreased during sleep and exercise.

Water balance and urine output

The source of most body water is dietary food and fluid, and a small amount (called 'metabolic water') is formed by metabolic processes. Water is excreted as the main constituent of urine, in expired air, faeces and through the skin as sweat. The amount lost in expired air and faeces is fairly constant, and the amount of sweat produced is associated with environmental and body temperatures (p. 358).

The balance between fluid intake and output is controlled by the kidneys. The minimum urinary output, i.e. the smallest volume required to excrete body waste products, is about 500 ml per day. Urinary volume in excess of this is controlled mainly by antidiuretic hormone (ADH) released into the blood by the posterior lobe of the pituitary gland. The posterior pituitary is closely related to the hypothalamus in the brain (see Fig. 9.3A and B, p. 210).

Sensory nerve cells in the hypothalamus (osmoreceptors) detect changes in the osmotic pressure of the blood. Nerve impulses from the osmoreceptors stimulate the posterior pituitary to release ADH. When the osmotic pressure is raised, i.e. the blood is becoming more concentrated, ADH output is increased and as a result, water reabsorption by the distal convoluted tubules and collecting ducts is increased, reducing the blood osmotic pressure and ADH output. This negative feedback mechanism maintains the blood osmotic pressure (and therefore sodium and water concentrations) within normal limits (see Fig. 13.13).

The feedback mechanism may be suppressed when there is an excessive amount of a dissolved substance in the blood. For example, in diabetes mellitus when the blood glucose level is above the transport maximum of the renal tubules, excess water is excreted with the excess glucose. This *polyuria* may lead to dehydration despite increased production of ADH but is usually accompanied