# The Anatomy and Physiology of the Renal System

CHAPTER 1

## INTRODUCTION

The renal system, also referred to as the urinary system, is essential for maintaining the body's internal balance by filtering the blood, removing waste products and regulating fluid and electrolyte levels. This system has a key role to play in homeostasis. It also supports other bodily systems, in particular the cardiovascular and endocrine systems.

Anatomically, the renal system consists of the kidneys, ureters, bladder and urethra. The kidneys are two bean-shaped organs located on either side of the spine, towards the back of the abdominal cavity. Each kidney contains around one million nephrons, which are the functional units responsible for filtering the blood and forming urine. From the kidneys, urine passes down through the ureters, narrow muscular tubes, into the bladder, where it is stored until the body is ready to eliminate it. The bladder is a hollow organ with elastic properties that permit the bladder to expand to hold urine and to contract during urination. The urine is finally expelled from the body via the urethra; this is a tube whose length and structure differ between men and women.

Table 1.1 outlines key structures associated with the renal system along with their position/location in the body.

The urinary system consists of the following:

- Kidneys
- Ureters
- Urinary bladder
- Urethra

Figure 1.1 demonstrates the organs of the renal system in a female.

Physiologically, the renal system performs several vital functions. It begins with the filtration of blood in the glomeruli of the kidneys, where waste products such as urea, creatinine and excess salts are removed. The filtrate then travels through the renal tubules, where essential substances, including water, glucose and electrolytes, are reabsorbed into the bloodstream, while additional waste products are secreted into the tubule. The final product, urine, is then excreted to maintain the body's chemical balance.

Beyond waste elimination, the kidneys also contribute to regulating blood pressure through the renin–angiotensin–aldosterone system, stimulate red blood cell production by releasing erythropoietin and play a role in calcium metabolism by activating vitamin D. These combined functions highlight the importance of the renal system not only in waste

**Table 1.1** Key structures associated with the renal system and their position/location in the body

| Structure | Position/location |
|---|---|
| Kidneys | The kidneys lie in the upper posterior abdomen, extending from approximately the 12th thoracic vertebra (T12) to the 3rd lumbar vertebra (L3) |
| Renal cortex | The outer region of the kidney, just beneath the renal capsule. |
| Renal medulla | The inner portion of the kidney, consisting of renal pyramids and tubules. |
| Renal pelvis | A central funnel-shaped cavity within the kidney that collects urine before it enters the ureter. |
| Ureters | Extend from the renal pelvis of each kidney and descend along the posterior abdominal wall to the bladder. |
| Urinary bladder | Located in the pelvic cavity, posterior to the pubic symphysis. In males, it lies anterior to the rectum; in females, anterior to the uterus and vagina. |
| Urethra (male) | Extends from the bladder through the prostate gland and penis to the external urethral orifice. |
| Urethra (female) | A shorter tube that extends from the bladder and opens just anterior to the vaginal opening. |
| Adrenal glands | Sit on top of each kidney; while not part of the renal system, they are anatomically associated and involved in fluid balance via aldosterone production. |

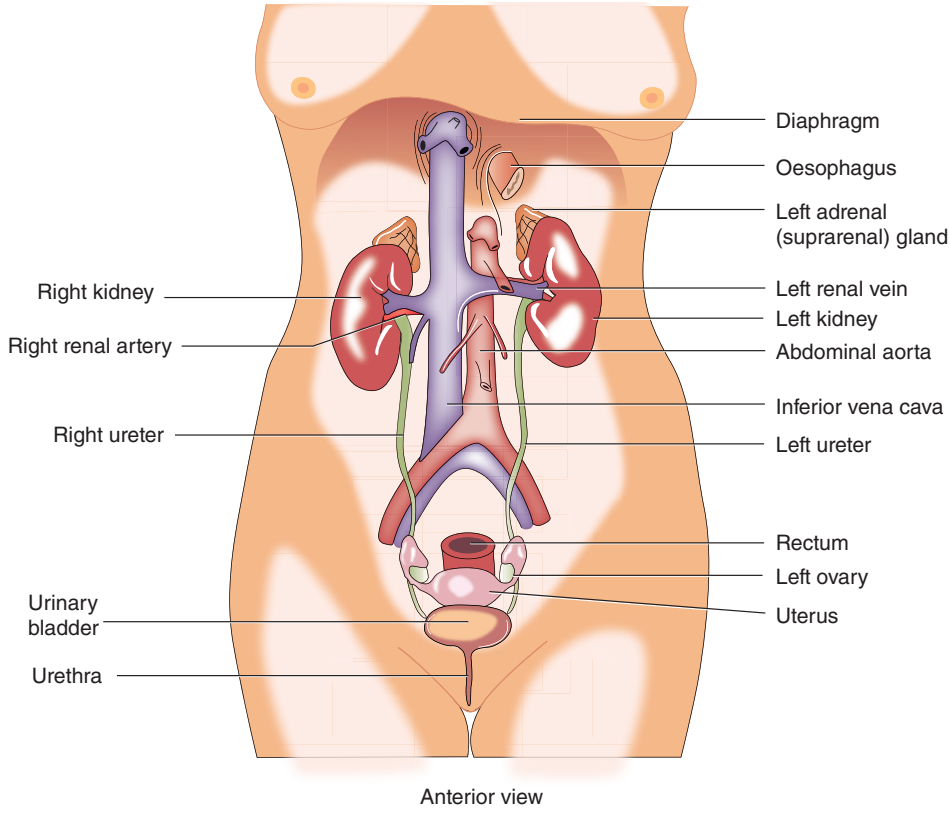


**FIGURE 1.1** Organs of the renal system. *Source*: Tortora and Derrickson (2014). With permission of John Wiley & Sons.

management but also in broader aspects of physiological regulation. Understanding the structure and function of the renal system is therefore crucial for healthcare professionals when assessing, diagnosing and managing a range of clinical conditions.

Together, the anatomical structures and physiological processes of the renal system are fundamental to the body's ability to detoxify, maintain fluid balance and support essential biological functions. Understanding the renal system is crucial for healthcare professionals, particularly in diagnosing and managing conditions such as renal failure, urinary tract infections and electrolyte imbalances.

This chapter will explore the structure and function of the renal system, examine the key processes involved in urine formation and homeostatic regulation, and discuss common clinical conditions affecting the kidneys and urinary tract. It will also highlight the importance of accurate assessment, early identification of dysfunction and the role of multidisciplinary care in supporting individuals with renal health needs.

## THE KIDNEY (EXTERNAL)

Most people have two kidneys, located on either side of the spinal column. However, there are some individuals who may be born with only one kidney or may lose a kidney due to illness or surgery. Each kidney typically measures about 11 cm in length, 5–6 cm in width and 3–4 cm in thickness. Shaped like beans, the kidneys have a convex outer edge and a concave inner border called the hilum (or hilus); this is where the renal arteries, renal veins, nerves and ureters enter and exit. The renal artery supplies blood to the kidney for filtration, and the renal vein carries the filtered blood away. The right kidney is located approximately 2–4 cm lower than the left; this is due to its position beneath the large right lobe of the liver.

The kidneys are supported and protected by three distinct layers:

1. Renal fascia
2. Adipose tissue
3. Renal capsule

The renal fascia is the outermost layer; it is made up of a thin layer of connective tissue that secures the kidneys to the abdominal wall and their nearby structures. The adipose tissue, or the fat layer, lies beneath the fascia and surrounds the kidney; adipose tissue provides cushioning and protection from physical trauma. The renal capsule, the innermost layer, consists of smooth connective tissue that continues with the outer layer of the ureter. This layer helps protect the kidneys from injury and helps preserve their shape. Figure 1.2 shows these external layers.

## THE KIDNEY (INTERNAL)

Within the kidney, there are three distinct regions:

1. Renal cortex
2. Renal medulla
3. Renal pelvis

The renal cortex is the outermost layer of the kidney. It forms a smooth, continuous outer surface with several inward projections that are known as renal columns, which extend between the renal pyramids. These columns are extensions of the cortex into the medulla. The cortex has a reddish colour and a granular appearance, caused by the presence of numerous capillaries and nephron structures.

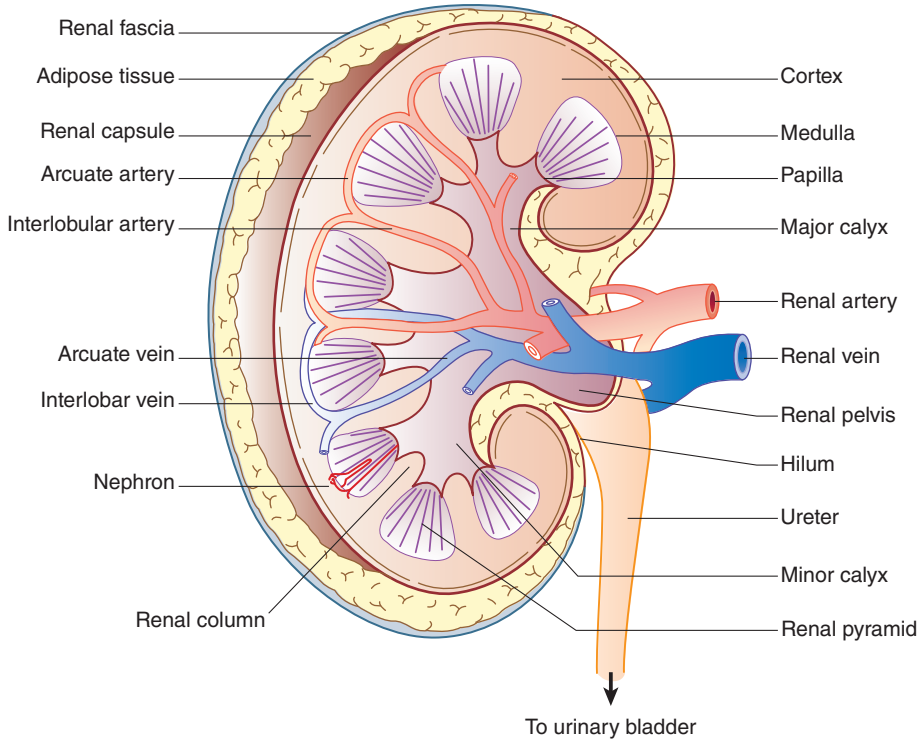


**FIGURE 1.2** The kidney showing the external layers

Beneath the cortex lies the renal medulla, which is lighter in colour and contains a dense network of blood vessels and nephron tubules (see Figure 1.3). The medulla is made up of about 8–12 renal pyramids, also known as Malpighian pyramids (Figure 1.2). These cone-shaped structures have a broad base facing the cortex and a pointed end directed inwards, known as the renal papilla.

Urine that has been produced by the nephrons drains through papillary ducts into small cup-like cavities called the minor calyces. Each kidney contains roughly 8–18 minor calyces, which collect urine from the renal papillae and pass it into two or three major calyces. The major calyces then join to form the renal pelvis, a funnel-shaped structure that represents the widened upper part of the ureter. The renal pelvis channels the urine into the ureter, which carries it to the bladder, where the urine is stored (see Figure 1.4).

## NEPHRONS

Nephrons are small structures that serve as the functional units of the kidney. Each nephron is made up of a glomerulus and a renal tubule (see Figure 1.5). There are around one million nephrons in each kidney. It is within these structures that urine is produced.

The nephrons have a key role to play in:

- Filtering blood
- Reabsorbing essential substances
- Excreting waste products from the filtered blood

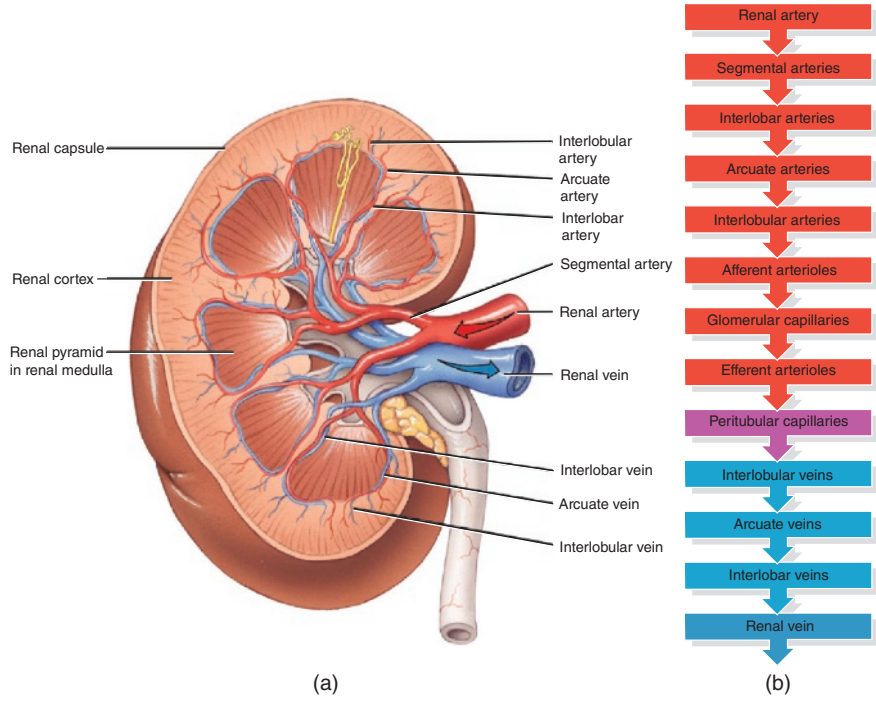


**FIGURE 1.3** (a) Frontal section of right kidney and (b) path of blood flow. *Source*: Tortora and Derrickson (2014). With permission of John Wiley & Sons.

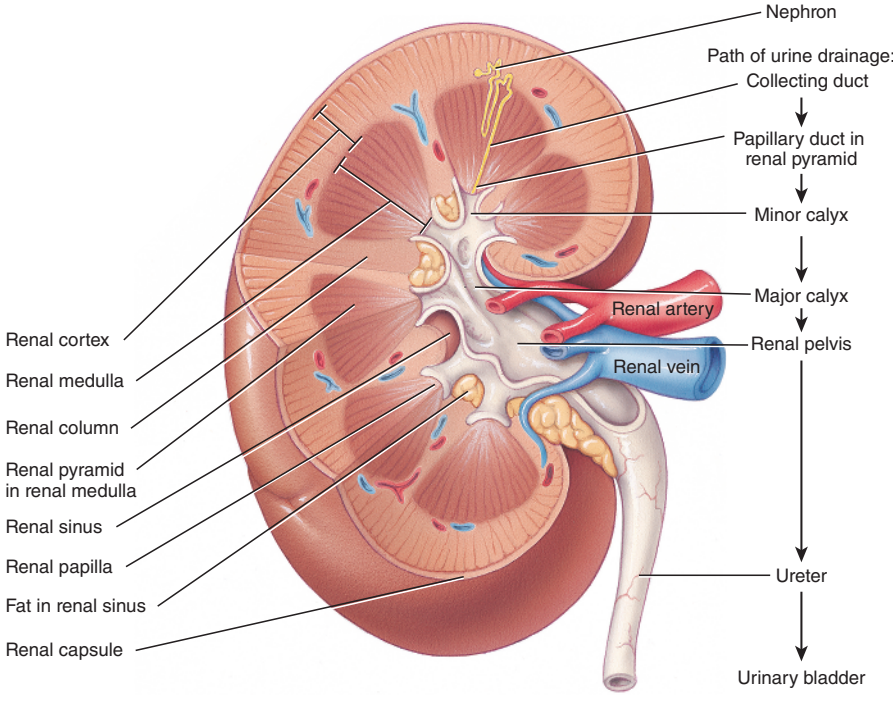


**FIGURE 1.4** Internal structures. *Source*: Tortora and Derrickson (2014). With permission of John Wiley & Sons.

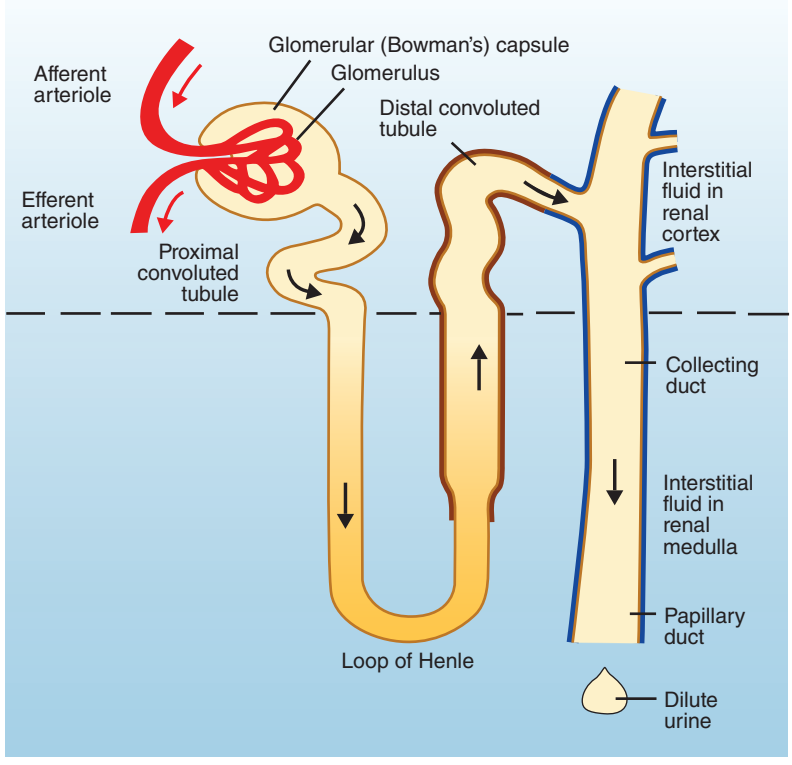


**FIGURE 1.5** A nephron. *Source*: Tortora and Derrickson (2014). With permission of John Wiley & Sons.

They are a key part of the body's homeostatic regulation; they help to control the levels of water, salts, glucose, urea and other minerals. As filtration units, nephrons are essential for maintaining internal balance and overall fluid and electrolyte control.

Each of the nephrons is divided into distinct sections, each of which plays a specific role:

- Bowman's capsule
- Proximal convoluted tubule
- Loop of Henle
- Distal convoluted tubule
- Collecting ducts

These sections work together to filter blood, reabsorb necessary substances and excrete waste. Their individual functions will be explored in the following sections.

## BOWMAN'S CAPSULE

Bowman's capsule is also referred to as the glomerular capsule (see Figure 1.6). This is a cup-shaped structure that forms the initial segment of the nephron and plays a crucial role in the kidney's filtration system. It serves as the site where blood filtration begins. As blood enters the nephron, it first passes into Bowman's capsule, where it is then separated into two components: a filtrate, which continues through the nephron for further processing, and the remaining blood components, which exit the capsule.

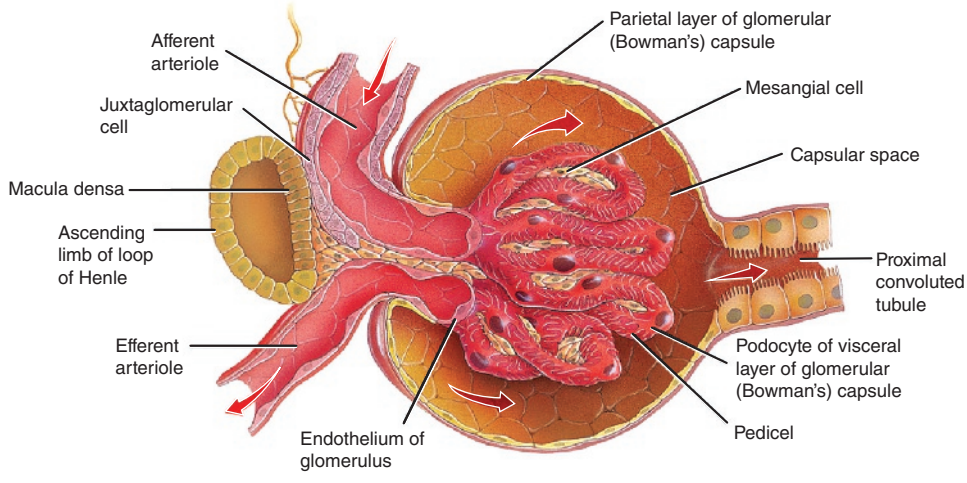


**FIGURE 1.6** Bowman's capsule. *Source*: Tortora and Derrickson (2014). With permission of John Wiley & Sons.

Bowman's capsule surrounds a network of capillaries that are known as the glomerulus, and together they form the renal corpuscle. The capsule itself is composed of two distinct layers:

- The visceral layer, which lies directly on the glomerular capillaries. This layer is made up of specialised epithelial cells called podocytes. These cells have foot-like projections that interlock, forming filtration slits that control the movement of substances from the blood into the nephron.
- The parietal layer is the outer wall of the capsule and is composed of simple squamous epithelium, which provides structural support.

It is within this structure that glomerular filtration occurs, which is the first step in the formation of urine. Water, ions, glucose and small solutes pass through the filtration barrier into the nephron, while larger molecules such as proteins and blood cells are retained in the circulation (Tortora and Derrickson 2023). The filtration in Bowman's capsule carefully chooses which substances pass from the blood into the nephron. This precise filtering is crucial because it helps the body regulate the right levels of fluids and minerals (electrolytes), which is important for keeping cells and organs working effectively and maintaining overall health.

## PROXIMAL CONVOLUTED TUBULE

The proximal convoluted tubule is the first segment of the renal tubule that extends from Bowman's capsule in the nephron. It is a twisted or 'convoluted' tube that is located in the kidney's cortex (see Figure 1.6).

After leaving Bowman's capsule, the filtrate then enters the proximal convoluted tubule (see Figure 1.6). The epithelial cells that line this part of the nephron are densely covered with microvilli, which significantly increase the surface area to enhance their ability to reabsorb substances. These microvilli contain numerous sodium pumps within their folded membranes. In this section of the tubule, salt, water and glucose are reabsorbed from the glomerular filtrate back into the bloodstream (see Box 1.1). Simultaneously, certain substances such as uric acid and drug metabolites are then actively secreted from the blood capillaries into the tubule to be eliminated from the body.

**BOX 1.1 RESPONSIBILITIES OF THE PROXIMAL CONVOLUTED TUBULE**

- Reabsorbing about 65–70% of filtered water and sodium
- Reabsorbing essential nutrients such as glucose, amino acids and bicarbonate
- Actively transports ions and helps maintain the body's acid–base balance
- Secreting certain waste products and substances such as hydrogen ions and some drugs into the tubule to be excreted

*Source*: Hwekwete (2025). With permission of John Wiley & Sons.

## LOOP OF HENLE

The proximal convoluted tubule then leads into a loop that is known as the loop of Henle. This loop extends from the cortex down into the medulla (called the descending limb) and then back up to the cortex (called the ascending limb). The loop of Henle is split into these two parts, with the ascending limb being much thicker than the descending limb.

The primary role of the loop of Henle is to create a concentration gradient that results in a high sodium concentration within the kidney's medulla. The descending limb is highly permeable to water but not very permeable to ions or urea; this allows water to leave the tubule by osmosis. In contrast, the ascending limb allows ions to pass through but is impermeable to water. This selective permeability enables the kidney to concentrate urine when needed, thanks to the high solute concentration in the medullary interstitium. Different sections of the loop of Henle perform specific functions:

- The descending limb is mostly impermeable to solutes but allows water to pass out; this makes the fluid inside the tubule more concentrated (hypertonic).
- The thin ascending limb is almost impermeable to water but permeable to solutes such as sodium and chloride. These ions move out of the tubule following their concentration gradient; in doing so, this causes the fluid inside the tubule to become first isotonic and then hypotonic as more ions leave. Urea, which has been absorbed into the medullary interstitium from the collecting duct, also diffuses into this part of the ascending limb, helping to retain urea in the medulla, where it contributes to urine concentration.
- The thick ascending limb and the early distal tubule are nearly impermeable to water. However, sodium and chloride ions are actively transported out of the tubule here, making the fluid inside the tubule very dilute (hypotonic).

## DISTAL CONVOLUTED TUBULE

The thick ascending segment of the loop of Henle connects to the distal convoluted tubule. The distal convoluted tubule is lined with simple cuboidal epithelial cells, and its lumen is wider than that of the proximal convoluted tubule, which has a brush border that is made of microvilli. The distal convoluted tubule serves several important functions:

- It actively secretes ions and acids.
- It helps regulate calcium levels by excreting excess calcium in response to the hormone calcitonin.

- It selectively reabsorbs water.
- It contains arginine vasopressin receptor 2 proteins.
- It contributes to pH regulation by absorbing bicarbonate and secreting hydrogen ions ($H^+$) into the filtrate.

The concentration of urine at this stage is controlled by the hormone antidiuretic hormone (ADH). When ADH is present, it makes the walls of the distal tubule and collecting duct permeable to water. Because the surrounding medulla has a high concentration of solutes, water moves out of the urine and back into the body, resulting in concentrated urine. In contrast, when ADH is absent, these tubules remain mostly impermeable to water, which causes more water to remain in the urine. This leads to the production of a larger volume of dilute urine. Essentially, ADH regulates how much water the body retains or loses through urine.

## COLLECTING DUCTS

The distal convoluted tubule then drains into the collecting ducts. Multiple collecting ducts merge and drain into larger structures known as papillary ducts, which subsequently empty into the minor calyx (plural: calyces). From the minor calyx, the filtrate, now called urine, flows into the renal pelvis. This stage marks the final opportunity for the reabsorption of sodium and water. When the body is dehydrated, about 25% of the filtered water is reabsorbed in the collecting ducts. Although the cells lining the collecting ducts are normally impermeable to water, the presence of ADH and specialised proteins called aquaporins allows water to be reabsorbed. Aquaporins are membrane proteins that regulate water movement by selectively transporting water molecules in and out of the cells while blocking ions and other solutes. Aquaporin 1 is mainly found in the proximal convoluted tubule and the descending thin limb of the loop of Henle, whereas aquaporins 2, 3 and 4 are located in the collecting ducts. Unlike other aquaporins involved mainly in kidney function, aquaporin 4 has a primary role in the brain.

## FUNCTIONS OF THE KIDNEY

The kidneys play a crucial role in maintaining fluid balance, electrolyte levels and acid–base equilibrium, which is essential for the body's overall health and effective functioning. These processes ensure that cells receive the right amount of water and nutrients, that electrical signals in nerves and muscles work correctly and that the body's internal environment remains stable. If these balances are disrupted, it can lead to serious problems such as dehydration, oedema, irregular heartbeats, muscle weakness or even life-threatening conditions such as acidosis or alkalosis. The body maintains a delicate balance between acids and bases to keep the blood's pH within a narrow, healthy range (around 7.35–7.45). When this balance is disturbed, it can result in either acidosis or alkalosis, conditions characterised by abnormal blood acidity or alkalinity. Table 1.2 summarises the key features of these two conditions, including their causes, effects on the body and common symptoms.

As blood circulates through the body, it carries waste products and excess fluids that need to be removed. Each day, approximately 190 L of blood flow into the kidneys through the renal arteries. Within the kidneys, there are millions of tiny filtering units called glomeruli that work to separate waste substances and excess water from the bloodstream. Most of these waste products originate from the food and drinks we consume. The kidneys carefully regulate the removal of salts and other minerals, ensuring that only the necessary amounts remain in the blood to meet the body's needs.

**Table 1.2** Acidosis and alkalosis

| Condition | Definition | Cause | Effects on the body | Common symptoms |
|---|---|---|---|---|
| Acidosis | Blood is too acidic (pH <7.35) | Excess acid production, kidney failure, respiratory problems | Impaired enzyme function, decreased oxygen delivery | Fatigue, confusion, headache, shortness of breath |
| Alkalosis | Blood is too alkaline (pH >7.45) | Excess loss of acid (vomiting), overuse of diuretics, hyperventilation | Muscle twitching, changes in nerve function | Muscle cramps, hand tremors, dizziness |

*Source:* Adapted from Rogers (2023).

By precisely controlling the removal of excess fluid, the kidneys maintain the body's fluid balance. In women, fluid typically makes up about 55% of total body weight, while in men, it accounts for roughly 60% (Hwekwete 2025). This balance is achieved by matching the amount of fluid leaving the body with the amount taken in. For example, when a person drinks a large volume of fluid, healthy kidneys usually respond by producing more urine to eliminate the excess. Conversely, when fluid intake is low, the kidneys conserve water, which results in a reduction in urine output. Fluid also leaves the body through sweating, breathing and bowel movements. On hot days, when sweating increases fluid loss, the kidneys reduce urine production to help conserve water.

In addition to filtration, the kidneys produce several important hormones. Renin and angiotensin regulate sodium and fluid retention in the body, as well as the dilation and constriction of blood vessels, which together help control blood pressure. Another hormone, erythropoietin, stimulates the bone marrow to produce red blood cells, which carry oxygen throughout the body. A shortage of healthy red blood cells leads to anaemia, which can result in symptoms such as fatigue, weakness, coldness and shortness of breath.

The kidneys also contribute to bone health by producing calcitriol, a hormone that helps maintain appropriate levels of calcium and phosphate in the blood and bones. These minerals are essential for strong, healthy bones. If the kidneys fail, they may produce insufficient calcitriol, leading to imbalances in calcium, phosphate and vitamin D, which can cause renal bone disease (this is a complication of chronic kidney disease where poor mineral balance leads to weakened, fragile bones) (Kidney Care UK 2024).

For a concise overview of the kidney's functions, refer to Table 1.3.

## BLOOD SUPPLY OF THE KIDNEY

Understanding the blood supply of the kidney is essential because it underpins many of the kidney's critical functions. A well-functioning renal blood supply is also crucial for the regulation of blood pressure. The kidneys produce hormones, such as renin, in response to changes in blood flow or pressure, which helps maintain circulatory stability. Any impairment in blood supply, such as narrowing of the renal arteries, can contribute to conditions such as hypertension or ischaemic kidney disease.

Understanding renal vasculature is particularly important when managing kidney diseases, many of which are related to problems with blood flow. Conditions such as glomerulonephritis or acute kidney injury often involve disruptions in renal perfusion. In clinical

**Table 1.3** An overview of kidney function

| Function | Description | Importance |
|---|---|---|
| Fluid balance | Regulate the volume of water in the body by adjusting urine concentration | Maintains hydration and prevents dehydration or overload |
| Electrolyte balance | Control levels of sodium, potassium, calcium, phosphate and other minerals | Ensures proper cell function and nerve/muscle activity |
| Acid–base balance | Maintain blood pH by excreting hydrogen ions and reabsorbing bicarbonate | Keeps blood pH within a narrow, healthy range |
| Waste removal | Filter out metabolic waste products, toxins and excess substances from the blood | Prevents build-up of harmful substances in the body |
| Hormone production | Produce hormones such as erythropoietin, renin and calcitriol | Supports red blood cell production, blood pressure regulation and bone health |
| Blood pressure regulation | Regulate blood volume and vessel constriction through hormone secretion | Maintains stable blood pressure |
| Bone health | Maintain calcium and phosphate balance via calcitriol production | Supports strong, healthy bones |

*Source:* Adapted from National Kidney Federation (2024).

practice, procedures including kidney biopsies, renal transplants or surgical interventions also require precise knowledge of the renal vascular anatomy to minimise complications.

The kidneys are responsible for filtering many medications, so understanding how blood flows through these organs is vital for safe and effective drug administration. The kidneys' ability to detect and respond to changes in the body's internal environment depends on adequate perfusion, which is essential for homeostasis.

The kidneys filter approximately 20–25% of the resting cardiac output. On average, about 1200 mL of blood flows through the kidneys every minute. Each kidney receives its blood supply directly from the abdominal aorta via the renal artery. The renal artery divides into anterior and posterior branches, which further give rise to several smaller arteries that supply the kidney:

- Renal artery: Arises from the abdominal aorta at the level of the first lumbar vertebra
- Segmental artery: Branch of the renal artery
- Interlobar artery: Branch of the segmental artery
- Arcuate artery: Renal columns leading to the corticomedullary junction
- Interlobular arteries: Divisions of the arcuate arteries

From the arcuate arteries, smaller interlobular arteries branch off and enter each nephron as afferent arterioles. Each nephron receives one afferent arteriole, which then forms a network of capillaries known as the glomerulus. After filtration in the glomerulus, the capillaries

reunite to form the efferent arteriole. These efferent arterioles then branch into peritubular capillaries, which surround the renal tubules and eventually drain into the interlobular veins. These veins converge into the arcuate veins, followed by the interlobar veins, and ultimately drain into the renal vein, which empties into the inferior vena cava.

Notably, the difference in diameter between the afferent and efferent arterioles is important because it helps generate and maintain the pressure required for efficient filtration in the glomerulus. When blood enters the glomerulus through the wider afferent arteriole, it flows in easily. However, because the efferent arteriole is narrower, it creates resistance to the outflow of blood. This resistance increases the pressure within the glomerular capillaries, which forces water and small solutes (such as electrolytes, glucose and waste products) out of the blood and into Bowman's capsule to form the filtrate.

This filtration pressure is essential for the kidneys to carry out their function of cleansing the blood, regulating fluid and electrolyte balance and maintaining overall homeostasis. Without this pressure difference, filtration would be less effective or could stop altogether, leading to a build-up of waste products and fluid in the body.

## URINE FORMATION

Urine is produced through three key processes:

- Filtration
- Selective reabsorption
- Secretion

## FILTRATION

The first step in urine formation is filtration, which takes place continuously in the renal corpuscles of the kidneys. This process occurs within the glomerulus. Blood enters the kidney via the renal artery, which branches into smaller arterioles. The afferent arteriole, which leads into Bowman's capsule, supplies blood to the glomerulus.

As blood flows through the glomerulus, a portion of its fluid, including both essential substances and waste products, is filtered through the capillary membranes into Bowman's capsule by osmosis and diffusion. This process is known as glomerular filtration. The filtered fluid, called glomerular filtrate, contains water, salts, glucose and waste products, but is free of proteins.

This filtrate includes substances such as sodium chloride, potassium, urea, uric acid and creatinine, which are by-products of normal cellular metabolism (Rogers 2023). After filtration, the remaining blood exits the glomerulus via the efferent arteriole and eventually returns to circulation through the renal vein.

## SELECTIVE REABSORPTION

The second stage, selective reabsorption, ensures that essential substances are reclaimed from the filtrate and returned to the bloodstream. This helps maintain the body's fluid and electrolyte balance, as well as the appropriate pH of the blood. Substances including sodium, potassium, calcium and chloride are selectively reabsorbed. If these substances are present in excess, they remain in the filtrate and are excreted in the urine.

Remarkably, 99% of the glomerular filtrate is reabsorbed and only about 1% is eventually excreted as urine. Reabsorption occurs through:

- Osmosis
- Diffusion
- Active transport

Glucose is one of the substances completely reabsorbed in the proximal tubules via active transport, meaning none is normally lost in the urine. Sodium and other ions are only partially reabsorbed, depending on the body's needs. Most sodium is actively transported back into the bloodstream, but the amount reabsorbed is influenced by dietary salt intake.

When salt intake increases, the kidneys reduce sodium reabsorption, allowing more to remain in the filtrate and be excreted in urine. Conversely, with lower salt intake, sodium reabsorption increases, reducing the amount lost in the urine. This dynamic adjustment helps maintain electrolyte balance and blood pressure.

## SECRETION

The final stage of urine formation, tubular secretion, is a critical process that ensures the body excretes substances that filtration alone may not remove. This step takes place in the renal tubules and collecting ducts of the nephron, where substances are actively transported from the surrounding peritubular capillaries into the tubular fluid (see Figure 1.7; Martini et al. 2017).

Unlike passive diffusion, active transport uses energy to move unwanted materials across cell membranes. This enables the kidney to fine-tune what is retained and what is expelled from the body. Among the substances secreted are:

- Potassium ions ($K^+$)
- Hydrogen ions ($H^+$)
- Ammonium ions ($NH_4^+$)
- Creatinine
- Urea
- Certain hormones and drugs

One of the most vital roles of tubular secretion is in regulating the blood's pH. By secreting hydrogen and ammonium ions, the kidneys help prevent the blood from becoming too acidic or too alkaline, which is essential for the proper functioning of enzymes and cellular processes. In this way, the kidneys act not only as filters but also as chemical regulators, maintaining a stable internal environment.

## HORMONAL CONTROL OF TUBULAR REABSORPTION AND SECRETION

The kidneys are tightly regulated by hormones to maintain fluid and electrolyte balance. There are four major hormones involved in this process:

1. Angiotensin II
2. Aldosterone
3. ADH
4. Atrial natriuretic peptide (ANP)

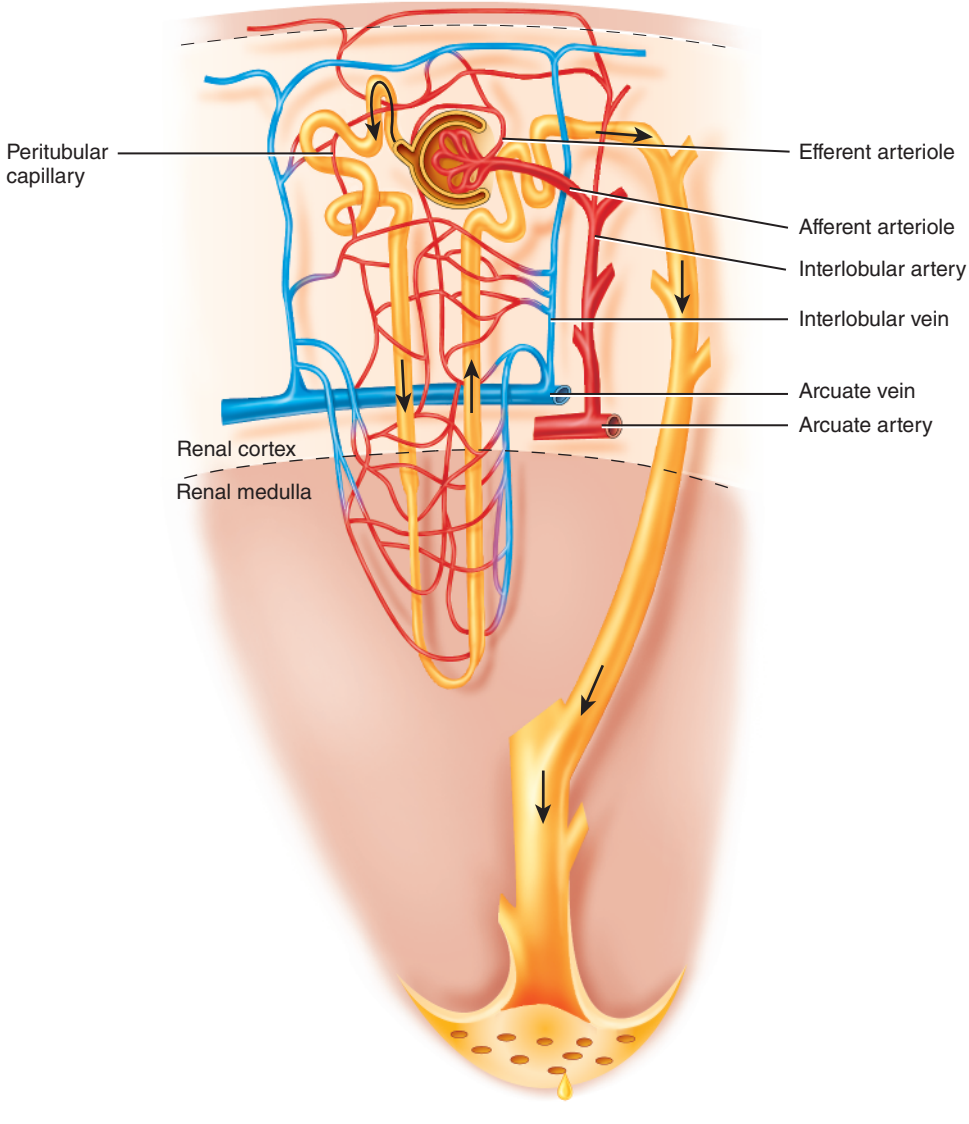


**FIGURE 1.7** Nephron with capillaries. *Source*: Tortora and Derrickson (2014). With permission of John Wiley & Sons.

## ANGIOTENSIN II AND ALDOSTERONE

When blood volume or blood pressure drops, specialised juxtaglomerular cells near the glomerulus release renin. This enzyme triggers a cascade that is known as the renin–angiotensin–aldosterone system (RAAS):

- Renin converts angiotensinogen (a plasma protein that is made by the liver) into angiotensin I.
- In the lungs, angiotensin-converting enzyme converts angiotensin I into angiotensin II.

- Angiotensin II is a potent vasoconstrictor; this causes blood pressure to increase. It also enhances the reabsorption of sodium, chloride and water in the proximal convoluted tubule and stimulates aldosterone release.

Aldosterone, a steroid hormone made by the adrenal cortex, further promotes sodium and water reabsorption (and potassium excretion) in the distal convoluted tubule and collecting ducts. This helps to increase blood volume and pressure. While aldosterone's main role is to regulate the balance of minerals, particularly sodium and potassium, by increasing sodium reabsorption and promoting potassium excretion in the kidneys, it also influences how the body uses and processes energy sources such as fats, carbohydrates and proteins.

## ANTIDIURETIC HORMONE

ADH, also called vasopressin, is produced by the hypothalamus and stored in the posterior pituitary gland. It plays a critical role in water conservation:

- ADH increases the permeability of cells in the distal collecting tubules and collecting ducts, allowing more water to be reabsorbed back into the bloodstream.
- In the presence of ADH, urine volume decreases. Without ADH, more water is lost in the urine.

The secretion of ADH is primarily controlled by plasma osmolarity (the concentration of solutes in the blood). Specialised osmoreceptors in the hypothalamus detect changes in osmolarity:

- When osmolarity rises, ADH secretion increases.
- When osmolarity falls, ADH secretion is suppressed.

## ATRIAL NATRIURETIC PEPTIDE

ANP is a hormone that is secreted by the muscle cells of the atria of the heart; this is in response to increased blood pressure or volume. It has several effects that collectively lower blood volume and pressure:

- Promotes sodium and water excretion by the kidneys.
- Inhibits aldosterone and ADH secretion.
- Acts as a vasodilator, reducing both venous return and arterial resistance.
- Enhances natriuresis (sodium excretion) and diuresis (increased urine production).

Through these actions, ANP plays a key role in long-term regulation of blood pressure and fluid balance.

Working together, these hormones can ensure that the kidneys are able to dynamically respond to the body's needs and maintain homeostasis under varying conditions.

## COMPOSITION OF URINE

Normally, urine is a clear, sterile fluid primarily composed of water and waste products that the body no longer needs. It typically has a translucent appearance and ranges in colour from pale yellow to amber. This colour is mainly due to urochrome, a pigment resulting from the breakdown

of haemoglobin in red blood cells. The concentration of the urine affects its colour; more concentrated urine appears darker, especially if fluid intake is low or in cases of dehydration.

While urine is normally light yellow, various factors can influence its appearance. Diet, medications and underlying health conditions can alter the colour, odour and composition of urine. Beetroot, for example, may give urine a pink tinge, certain medications can cause it to appear bright yellow or orange, and infections or liver disease may cause darker or cloudy urine.

Urine is typically slightly acidic, with a pH ranging from 4.5 to 8, though this can vary depending on the person's diet and their health. Diets rich in animal protein tend to make the urine more acidic, while vegetarian diets may lead to more alkaline urine. The body's acid–base balance, which helps maintain stable blood pH, is partly regulated through this urinary excretion.

The volume of urine produced depends largely on the body's fluid status and is tightly regulated by ADH. ADH controls how much water the kidneys reabsorb. When the body is dehydrated, ADH levels rise, promoting water reabsorption and reducing urine output. Conversely, when fluid intake is high, ADH secretion decreases, resulting in the production of a larger volume of dilute urine.

In terms of composition, urine is about 96% water and 4% solutes. These solutes include both organic and inorganic substances, such as:

- Urea: The main nitrogenous waste from protein metabolism
- Creatinine: From muscle metabolism
- Uric acid: From the breakdown of nucleic acids
- Electrolytes: Such as sodium, potassium and chloride
- Other substances: Including drugs and toxins filtered from the bloodstream

Normal urine does not contain protein, glucose or blood. If any of these are present, it may indicate that the reason has an underlying medical condition such as infection, kidney disease or diabetes and should prompt further investigation.

The characteristics of normal urine are detailed in Table 1.4.

**Table 1.4** Characteristics of normal urine

| Characteristic | Description |
|---|---|
| Appearance | Clear and transparent |
| Colour | Pale yellow to amber; due to the pigment urochrome |
| Odour | Mild and slightly aromatic; stronger odour may result from certain foods or dehydration |
| pH range | Typically, between 4.5 and 8; influenced by diet (e.g. protein-rich = acidic, vegetarian = alkaline) |
| Specific gravity | Ranges from 1.005 to 1.030; indicates urine concentration |
| Volume | About 1–2 L/day, depending on hydration, health and temperature |
| Composition | Approximately 96% water and 4% solutes |
| Solutes present | Urea, uric acid, creatinine, sodium, potassium, chloride and other electrolytes |
| Absent components | No glucose, proteins, blood, ketones or bilirubin in healthy individuals |

*Source:* Jones (2022). With permission of John Wiley & Sons.

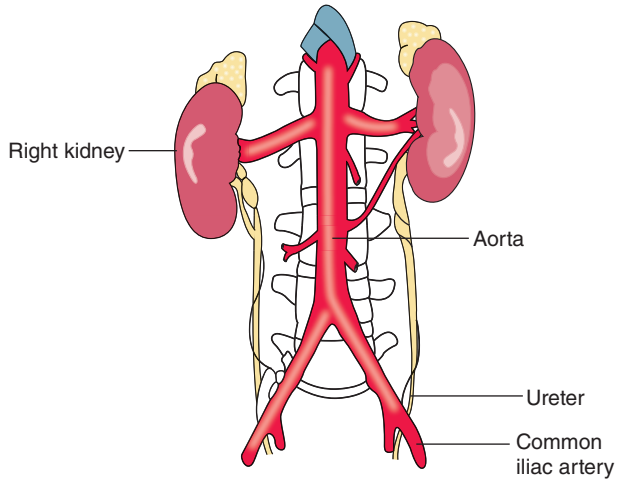


**FIGURE 1.8** Common iliac vessels and ureter. *Source*: Peate and Nair (2009). With permission of John Wiley & Sons.

## URETERS

The ureters are narrow, muscular tubes that transport urine from the renal pelvis of each kidney to the urinary bladder. Each ureter measures approximately 25–30 cm in length and about 5 mm in diameter. They descend from the kidneys and pass over the pelvic brim at the point where the common iliac arteries divide, before entering the posterolateral aspect of the bladder (see Figure 1.8). Importantly, the ureters penetrate the bladder wall at an oblique angle, which helps prevent backflow of urine.

Structurally, each ureter consists of three layers:

1. Inner layer: Lined with transitional epithelium, allowing for stretch and flexibility
2. Middle layer: Composed of smooth muscle that facilitates the movement of urine through peristalsis
3. Outer layer: Made up of fibrous connective tissue providing support and protection

Urine is propelled through the ureters by rhythmic peristaltic waves generated by the smooth muscle layer. These waves are triggered when urine collects in the renal pelvis, causing muscular contractions that push the fluid towards the bladder. The frequency of these contractions is influenced by the volume of urine present and can range from every few minutes to several times per minute. This coordinated movement ensures urine travels steadily in small spurts into the bladder for storage until micturition.

## THE URINARY BLADDER

The urinary bladder is a hollow, muscular organ that is situated within the pelvic cavity, positioned just behind the symphysis pubis. In males, the bladder lies in front of the rectum, while in females it is located anterior to the vagina and beneath the uterus (Hwekwete 2025). It functions as a smooth muscular reservoir that is used for storing urine. Although its resting shape is generally spherical, the bladder's shape can be altered by pressure from surrounding organs. When empty, the bladder's internal surface forms folds that are known as rugae, but as it fills with urine, these folds flatten and the bladder walls stretch, becoming smoother.

This expansion occurs with minimal increase in internal pressure. Typically, the bladder can comfortably store between 350 and 750 mL of urine. In females, it is slightly smaller due to the space occupied by the uterus, which is located above it.

The bladder's inner lining consists of transitional epithelium, a specialised mucous membrane that also lines the ureters. This epithelium is supported by a layer of connective tissue called the submucosa, which contains elastic fibres that enhance stretchability.

At the base of the bladder is a triangular area called the trigone, formed by three openings: two from the ureters (forming the base of the triangle) and one at the apex leading into the urethra (see Figure 1.9). Small flaps of mucosa act as valves over the ureteric openings, permitting urine to enter the bladder while preventing backflow. The urethral opening is surrounded by a ring of the detrusor muscle, which forms the internal urethral sphincter and controls the release of urine.

The bladder wall is made up of three layers:

1. Inner mucosal layer of transitional epithelium
2. Middle muscular layer (detrusor muscle)
3. Outer fibrous connective tissue layer

Blockages or obstructions in the urinary tract can occur due to various causes, such as kidney stones, tumours, an enlarged prostate gland or the growing uterus during pregnancy. Such obstructions can result in the build-up of urine, potentially leading to kidney damage or infection. While kidney stones often cause severe pain, other forms of obstruction may be asymptomatic and only discovered through abnormal test results or imaging (e.g. ultrasound or X-ray).

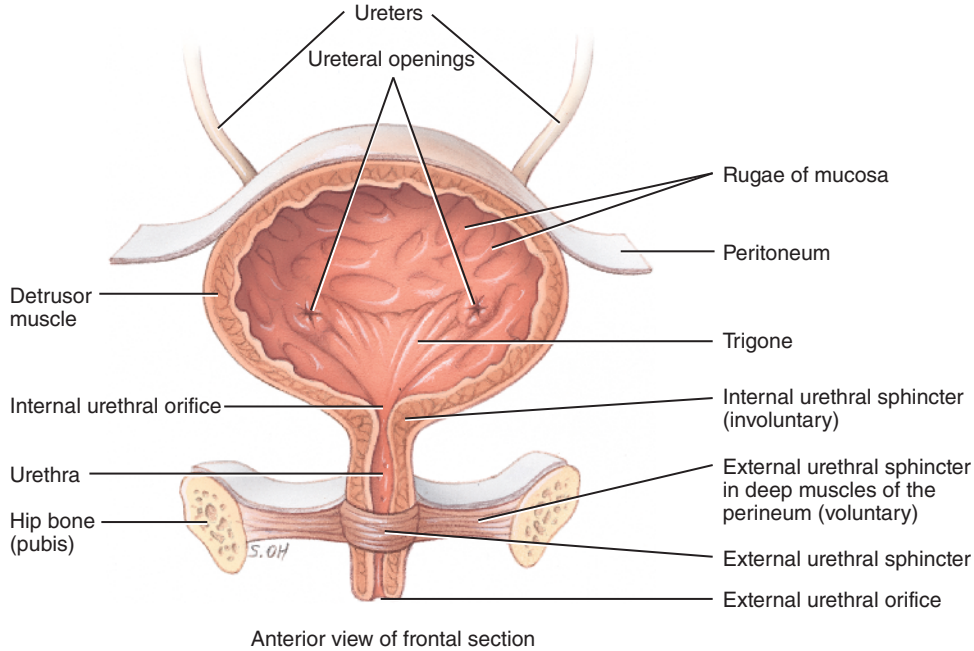


**FIGURE 1.9** The urinary bladder. *Source*: Tortora and Derrickson (2014). With permission of John Wiley & Sons.

Urinary tract infections, such as cystitis (bladder infection), can progress to more serious conditions if left untreated. Symptoms may include pyrexia, frequent and urgent need to urinate, painful urination (dysuria), and discomfort or pressure in the lower abdomen or back. Urine may appear cloudy, have a strong or unpleasant odour, or contain blood. If infection ascends to the kidneys, it can cause pyelonephritis, a serious infection of the kidney tissue. This usually occurs when cystitis spreads upwards, but it can also result from bloodstream infections originating elsewhere in the body, such as streptococcal infections, impetigo (a skin infection) or bacterial infections of the heart.

## URETHRA

The urethra is a muscular tube responsible for draining urine from the bladder and expelling it from the body. It is composed of three layers:

1. Muscular
2. Erectile
3. Mucous

The muscular layer is a direct continuation of the bladder's muscle. Surrounding the urethra are two distinct sphincter muscles. The internal urethral sphincter consists of involuntary smooth muscle fibres and is formed by the detrusor muscle at the junction between the bladder and urethra. In contrast, the external urethral sphincter is made up of voluntary skeletal muscles. The urethra is longer in males than in females. Both sphincters work to keep the urethra closed when urine is not being passed, with the internal sphincter controlled involuntarily and the external sphincter under voluntary control.

## MALE URETHRA

The male urethra passes through four distinct regions:

1. Prostatic region runs through the prostate gland.
2. Membranous portion passes through the pelvic diaphragm.
3. Bulbar urethra, located within the perineum and scrotum, extends from the external urethral sphincter to the peno-scrotal junction and is surrounded by the corpus spongiosum. This part contains the openings of the ducts from the Cowper's glands and varies in length among individuals.
4. Penile region extends along the length of the penis.

In males, the urethra serves a dual purpose: it expels urine and is also part of the reproductive system. Unlike the relatively straight female urethra, the male urethra follows an S-shaped curve along the penis and is approximately 20 cm long. It is divided into several sections: the spongy (or penile) urethra, the prostatic urethra and the membranous urethra. The spongy urethra is further subdivided into the fossa navicularis, pendulous urethra and bulbous (bulbar) urethra.

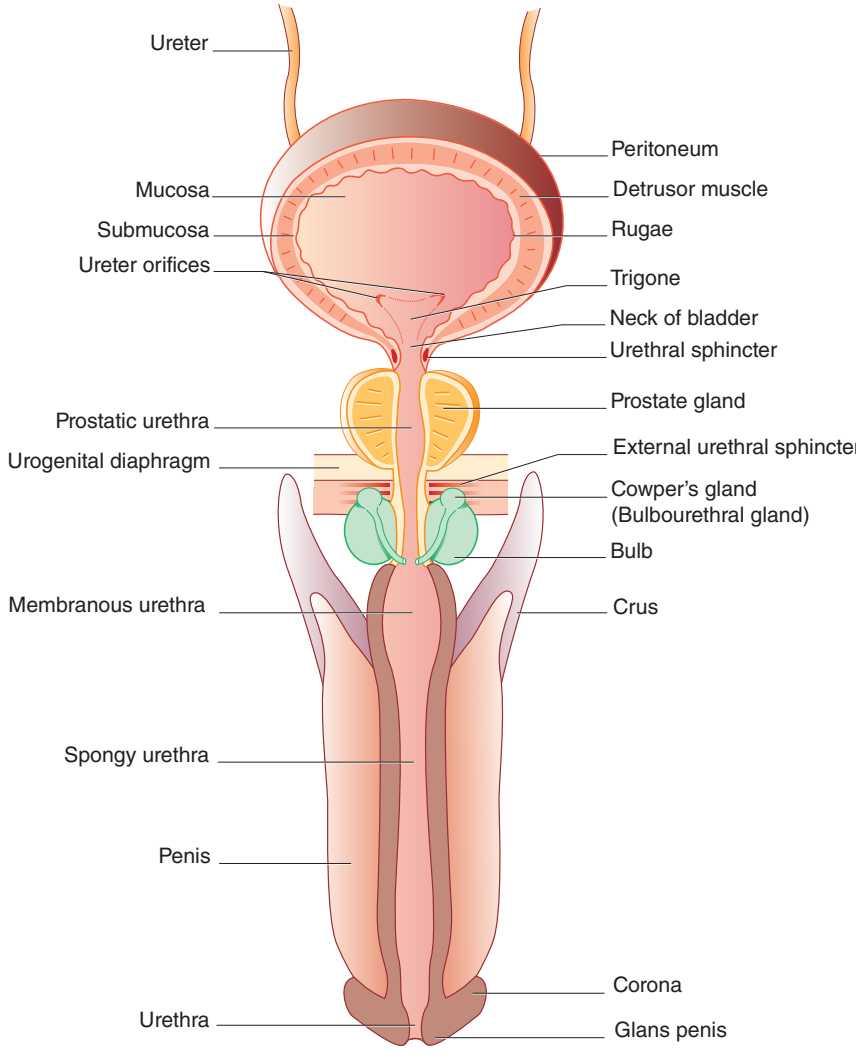


**FIGURE 1.10** The male urethra

The prostatic portion, which is the proximal segment of the urethra, measures about 2.5 cm in length. It runs from the neck of the urinary bladder through the prostate gland and is designed to receive drainage from small ducts within the prostate, including two ejaculatory ducts (see Figure 1.10).

## FEMALE URETHRA

In females, the urethra is closely attached to the anterior wall of the vagina. Its external opening, known as the urethral orifice, is situated just in front of the vaginal opening and behind the clitoris. The female urethra is relatively short, measuring about 4 cm in length, and serves solely to transport urine out of the body. The urethral orifice is located within the vestibule, nestled between the labia minora, specifically positioned between the clitoris and the vaginal opening (see Figure 1.11).

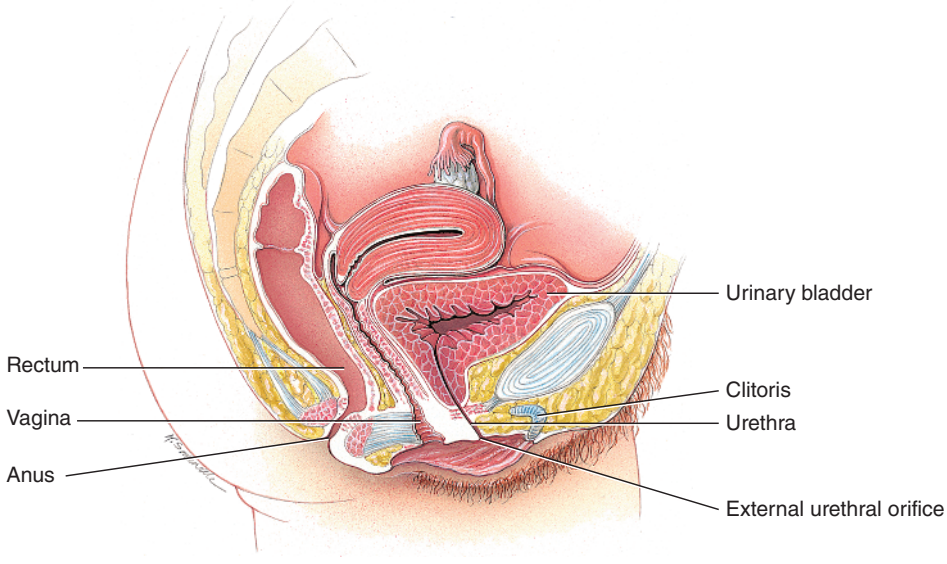


**FIGURE 1.11** The female urethra. *Source*: Nair and Peate (2013). With permission of John Wiley & Sons.

## MICTURITION

When the bladder fills with urine and reaches a volume of approximately 300 mL, stretch receptors located in the bladder walls are activated. These receptors send signals through sensory parasympathetic nerve fibres to the sacral region of the spinal cord. This sensory information is then processed within the spinal cord and relayed to two distinct groups of neurones that coordinate the act of urination (Walker 2024).

Firstly, parasympathetic motor neurones, located in the pons of the brainstem, are stimulated. These neurones trigger the contraction of the detrusor muscle, the muscular layer of the bladder wall, which increases the pressure inside the bladder. As the detrusor muscle contracts, the internal urethral sphincter, composed of smooth muscle and under involuntary control, relaxes and opens, allowing urine to pass into the urethra.

Simultaneously, somatic motor neurones that innervate the external urethral sphincter via the pudendal nerve are inhibited. This relaxation of the external sphincter, which is under voluntary control, permits urine to flow out of the bladder and through the urethra, aided by gravity.

Although micturition is fundamentally a reflex action, most individuals have considerable voluntary control over the process. They can consciously regulate the timing of urination, modulate the flow rate and stop or start urine passage at will, unless impaired by neurological or physiological conditions.

## CONCLUSION

The renal system is fundamental to maintaining homeostasis by regulating the body's fluid balance, electrolyte concentrations, acid–base balance and the removal of metabolic waste products. The kidneys, as the primary organs, are highly specialised in filtering blood through millions of nephrons, where processes such as glomerular filtration, tubular reabsorption and secretion occur with remarkable precision. These mechanisms allow the body to conserve essential nutrients and water while efficiently eliminating toxins and excess substances.

The structural complexity of the renal system, from the microscopic nephrons to the larger, microscopic anatomical components including the ureters, bladder and urethra, ensures the controlled transport, storage and elimination of urine. The interplay between the renal vasculature and tubular system underpins the kidneys' ability to finely regulate blood pressure, pH and electrolyte levels, aided by an intricate hormonal network involving aldosterone, ADH, angiotensin II and ANP.

Furthermore, the neural control mechanisms coordinating micturition demonstrate the sophisticated integration of the renal system with the nervous system, allowing voluntary control over urination while maintaining reflexive responses to bladder filling.

An understanding of the renal system's anatomy and physiology is essential for healthcare professionals, as it provides the basis for recognising normal function, diagnosing abnormalities and implementing effective treatments. The kidney's critical role extends beyond waste elimination to systemic effects that influence cardiovascular health, fluid homeostasis and metabolic balance, emphasising its importance in overall human health and disease.

## GLOSSARY OF TERMS

**Aldosterone:** A steroid hormone secreted by the adrenal glands that regulates sodium and water balance by increasing reabsorption in the kidneys.

**Angiotensin II:** A potent vasoconstrictor hormone involved in blood pressure regulation and stimulating aldosterone release.

**Antidiuretic hormone (ADH):** A hormone produced by the hypothalamus and stored in the posterior pituitary that increases water reabsorption in the kidneys, reducing urine volume.

**Bowman's capsule:** A cup-shaped structure surrounding the glomerulus where blood filtration begins in the nephron.

**Collecting duct:** The final part of the nephron that collects urine from multiple nephrons and transports it to the renal pelvis.

**Detrusor muscle:** The smooth muscle layer of the bladder wall responsible for contracting during urination to expel urine.

**Efferent arteriole:** The small artery that carries blood away from the glomerulus after filtration.

**Glomerulus:** A network of capillaries within Bowman's capsule where blood is filtered to form the initial filtrate.

**Juxtaglomerular apparatus:** A specialised structure near the glomerulus that regulates blood pressure and filtration rate by releasing renin.

**Loop of Henle:** A U-shaped section of the nephron responsible for concentrating urine by reabsorbing water and salts.

**Nephron:** The functional unit of the kidney, consisting of the glomerulus, renal tubules and collecting duct, responsible for urine formation.

**Peritubular capillaries:** Capillary networks surrounding the renal tubules where reabsorption and secretion occur between blood and tubular fluid.

**Proximal convoluted tubule:** The segment of the nephron immediately after Bowman's capsule where most reabsorption of water, ions and nutrients occurs.

**Renal cortex:** The outer region of the kidney where most nephrons are located.

**Renal medulla:** The inner region of the kidney composed of renal pyramids that contain the loops of Henle and collecting ducts.

**Renal pelvis:** The funnel-shaped structure that collects urine from the collecting ducts and directs it into the ureter.

**Renal tubule:** The portion of the nephron extending from Bowman's capsule that processes filtrate through reabsorption and secretion.

**Renin:** An enzyme secreted by juxtaglomerular cells that initiates the renin–angiotensin–aldosterone system (RAAS) to regulate blood pressure.

**Tubular reabsorption:** The process of reclaiming water and solutes from the filtrate back into the bloodstream.

**Tubular secretion:** The process by which substances such as hydrogen ions and drugs are actively transported from blood into the renal tubules.

**Ureter:** A muscular tube that transports urine from the renal pelvis to the urinary bladder.

**Urethra:** The tube that conveys urine from the bladder out of the body.

**Urinary bladder:** A hollow, muscular organ that stores urine until micturition.

## MULTIPLE CHOICE QUESTIONS

1. Which structure is the functional unit of the kidney?
   **a)** Nephron
   **b)** Glomerulus
   **c)** Ureter
   **d)** Renal pelvis

2. What is the primary function of the glomerulus?
   **a)** Reabsorption of nutrients
   **b)** Filtration of blood
   **c)** Storage of urine
   **d)** Transport of urine to the bladder

3. The hormone aldosterone primarily regulates:
   **a)** Potassium excretion
   **b)** Sodium and water balance
   **c)** Calcium absorption
   **d)** Glucose metabolism

4. Antidiuretic hormone (ADH) acts on which part of the nephron?
   **a)** Proximal convoluted tubule
   **b)** Loop of Henle
   **c)** Collecting duct
   **d)** Glomerulus

5. Which part of the kidney collects urine before it passes into the ureter?
   **a)** Renal cortex
   **b)** Renal medulla
   **c)** Renal pelvis
   **d)** Renal capsule

6. The ureters connect the kidneys to the:
   **a)** Urethra
   **b)** Urinary bladder
   **c)** Renal pelvis
   **d)** Prostate gland

7. What type of epithelium lines the urinary bladder?
   **a)** Squamous epithelium
   **b)** Transitional epithelium
   **c)** Columnar epithelium
   **d)** Cuboidal epithelium

8. The muscle responsible for bladder contraction during urination is the:
   **a)** Detrusor muscle
   **b)** External urethral sphincter
   **c)** Internal urethral sphincter
   **d)** Smooth muscle of the ureter

9. Which of the following substances is normally not found in urine?
   **a)** Urea
   **b)** Glucose
   **c)** Creatinine
   **d)** Electrolytes

10. Which layer of the kidney contains the glomeruli?
    **a)** Renal medulla
    **b)** Renal pelvis
    **c)** Renal cortex
    **d)** Renal capsule

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