MDCAT Biology Unit 15: Homeostasis, study guide with practice MCQs

What MDCAT asks

Unit 15 covers how the body keeps its internal conditions steady: the kidney and osmoregulation (B15.1), and thermoregulation with nitrogenous excretion and the urea cycle (B15.2). The two subtopics carry equal weight and together account for roughly 2 to 3 of the 81 Biology questions, about one from each.

B15.1 Osmoregulation and the kidney

B15.1.1 Describe the structure of the kidney and nephron

Homeostasis is the maintenance of a steady internal environment despite changes outside the body. **Osmoregulation** keeps the water and solute content of the blood within narrow limits. **Excretion** is the removal of the waste products of metabolism, such as urea and carbon dioxide.

The two bean-shaped kidneys lie against the back wall of the abdomen on either side of the vertebral column. Each is supplied by a **renal artery** and drained by a **renal vein**; urine leaves through the **ureter**, is stored in the **bladder** and passes out through the **urethra**. A kidney cut lengthways shows three regions: the outer, darker **cortex**, holding the Bowman's capsules and convoluted tubules; the inner, paler **medulla**, made of cone-shaped **renal pyramids** that hold the loops of Henle and collecting ducts, whose tips open into cups called calyces; and the funnel-shaped **pelvis**, where the calyces join to feed the ureter.

The working unit is the **nephron**; each kidney holds about one million.

1. **Bowman's capsule**: a cup-shaped, double-walled blind end in the cortex, enclosing a knot of capillaries, the **glomerulus**. Together they form the **renal corpuscle**.
2. **Proximal convoluted tubule (PCT)**: the first coiled part, in the cortex, with microvilli and many mitochondria because most reabsorption happens here.
3. **Loop of Henle**: a hairpin that runs down into the medulla (descending limb) and back up (ascending limb).
4. **Distal convoluted tubule (DCT)**: the second coiled part, in the cortex, for fine adjustment of salt, water and pH.
5. **Collecting duct**: shared by several nephrons; runs down through the medulla and empties at the papilla into the pelvis.

Blood supply. An **afferent arteriole** enters each capsule and splits into the glomerulus; the capillaries rejoin as a narrower **efferent arteriole**, which then forms the **peritubular capillaries** around the tubules.

Part of nephron	Where it lies	Main job

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Bowman's capsule and glomerulus	Cortex	Ultrafiltration of blood
Proximal convoluted tubule	Cortex	Reabsorbs all glucose and amino acids, most water and salts
Loop of Henle	Medulla	Counter-current multiplier: makes the medulla salty
Distal convoluted tubule	Cortex	Salt reabsorption (aldosterone), secretion of K+ and H+
Collecting duct	Medulla	Water reabsorption under ADH

B15.1.2 Explain ultrafiltration, selective reabsorption and the role of ADH; describe kidney disorders and dialysis

Ultrafiltration (pressure filtration) takes place in the renal corpuscle. Because the afferent arteriole is wider than the efferent arteriole, blood in the glomerulus is under high pressure, about 55 to 60 mm Hg. This forces water and small solutes through the capillary wall and basement membrane into the capsule. Blood cells and plasma proteins such as albumin are too large and stay in the blood. The **glomerular filtrate** therefore contains water, glucose, amino acids, salts, urea, uric acid and creatinine at the same concentrations as plasma.

This push is opposed by the osmotic pressure of the plasma proteins left in the blood (about 30 mm Hg) and the pressure of fluid already in the capsule (about 15 mm Hg). The difference is the **net filtration pressure**, about 10 mm Hg. Both kidneys form about 125 cm^3 of filtrate per minute, roughly 180 litres a day. Only 1 to 2 litres of urine leave daily, so about 99 per cent of the filtered water is taken back.

Selective reabsorption returns useful substances to the blood.

- **PCT**: reabsorbs all the glucose and amino acids by active transport (using ATP), about two thirds of the sodium ions actively with chloride following, and about two thirds of the water by osmosis.
- **Loop of Henle**: makes the medulla salty. The **descending limb** is permeable to water but not salt, so water leaves by osmosis and the filtrate becomes concentrated. The **ascending limb** is impermeable to water and pumps sodium and chloride ions out by active transport, so the filtrate becomes dilute as it rises. The opposite flow in the two limbs multiplies the effect (the **counter-current multiplier**), so tissue fluid gets saltier towards the tip of the medulla.
- **DCT**: reabsorbs more sodium under **aldosterone** (adrenal cortex) and secretes potassium and hydrogen ions into the filtrate (**tubular secretion**), which helps to keep blood pH steady.
- **Collecting duct**: passes down through the salty medulla, so water leaves by osmosis if the wall is permeable, and that depends on ADH.

The role of ADH. Antidiuretic hormone (vasopressin) is a peptide made by neurosecretory cells of the **hypothalamus** and released from the **posterior pituitary**. Osmoreceptors in the hypothalamus monitor the water content of the blood:

- **Blood too concentrated** (sweating, salty food, little drinking): more ADH, the walls of the DCT and collecting duct become more permeable to water, more water is reabsorbed, and a **small volume of concentrated urine** is produced.
- **Blood too dilute** (after drinking a lot): less ADH, the duct walls become less permeable, little

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water is reabsorbed, and a **large volume of dilute urine** is passed.

Kidney disorders.

- **Kidney stones**: hard deposits formed when salts, mostly calcium oxalate, crystallise out of concentrated urine in the pelvis. A stone moving into the ureter causes severe pain and blood in the urine. Small stones pass out with plenty of fluid; larger ones are broken by **lithotripsy**, focused shock waves applied from outside the body.
- **Diabetes insipidus**: too little ADH. The collecting ducts stay impermeable, so the person passes very large volumes of dilute urine with no glucose. In diabetes mellitus, by contrast, blood glucose exceeds what the PCT can reabsorb and glucose appears in the urine.
- **Kidney failure**: the kidneys stop filtering (high blood pressure, diabetes mellitus, infection); urea, potassium and water build up in the blood, fatal if untreated. The treatments are dialysis and transplant.

Dialysis is the separation of small molecules from large ones by diffusion across a partially permeable membrane. In **haemodialysis** blood flows through thin tubes of partially permeable membrane bathed in **dialysis fluid**, which holds glucose and salts at the same concentrations as healthy plasma but no urea. Urea, excess salts and other wastes diffuse out down their gradients, while glucose has no gradient and stays. Blood and fluid flow in opposite directions to keep the gradient, heparin stops clotting, and the cleaned blood returns to a vein, for several hours about three times a week. A **kidney transplant** is the lasting cure but needs a matched donor and lifelong immunosuppressant drugs.

MDCAT trap: ADH changes reabsorption, not filtration. Students write that ADH "increases the filtrate" or "acts on the glomerulus". It does neither: the filtrate volume is fixed by the pressures in the renal corpuscle, where ADH has no receptors. ADH acts on the distal convoluted tubule and collecting duct, making them more permeable to water so that more of the filtrate's water is reabsorbed: the filtrate volume is unchanged, the urine volume falls and its concentration rises. Linked rules: more ADH means less urine, not more; ADH is released from the posterior pituitary but made in the hypothalamus; too little ADH gives diabetes insipidus (dilute urine, no glucose), whereas glucose in the urine points to diabetes mellitus.

Worked example. A healthy adult forms 180 litres of glomerular filtrate a day and passes 1.5 litres of urine. (a) What percentage of the filtered water is reabsorbed? (b) On a hot day the same person, drinking the same amount, passes only 0.6 litres. Explain the change.

(a) Water reabsorbed = 180 - 1.5 = 178.5 litres. Percentage = 178.5 ÷ 180 × 100 = 99.2 per cent, most of it in the PCT.

(b) Sweating concentrates the blood; the hypothalamic osmoreceptors detect this and the posterior pituitary releases more ADH. The DCT and collecting duct become more permeable, more water is reabsorbed into the blood, and the urine falls to 0.6 litres while its concentration rises. The filtrate volume is unchanged, because ADH does not act on the glomerulus.

B15.2 Thermoregulation and excretion

B15.2.1 Explain thermoregulation in humans

Thermoregulation is the maintenance of a steady body temperature. Enzymes work best near 37 °C:

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higher and they begin to denature, lower and reactions slow. **Ectotherms** (fishes, amphibians, reptiles) gain most of their heat from the surroundings; **endotherms** (birds and mammals) generate heat by their own metabolism and keep the core temperature nearly constant.

Heat is **gained** from metabolism (mainly liver and muscle) and from hot surroundings; it is **lost** from the skin by radiation, conduction, convection and the evaporation of sweat. Evaporation works even when the air is hotter than the body, but sweat that drips off removes little heat, which is why humid heat is so uncomfortable.

The body's thermostat is the **hypothalamus**. Its own thermoreceptors measure the temperature of the blood flowing through it, and it receives impulses from cold and warm receptors in the skin. The set point is about 37 °C; any change triggers responses that reverse it, which switch off once the temperature is back to normal. This is **negative feedback**.

Too hot: skin arterioles widen (**vasodilation**), so more warm blood flows near the surface and more heat is radiated; sweat is produced and its evaporation cools the skin; the hairs lie flat; the person rests and seeks shade.

Too cold: skin arterioles narrow (**vasoconstriction**), keeping blood deep in the body, so the skin turns pale and loses less heat; sweating stops; skeletal muscles contract involuntarily (**shivering**), releasing heat from respiration; the hair erector muscles raise the hairs ("goose bumps"), trapping insulating air in furry mammals; adrenaline (quickly) and thyroxine (over days) raise the metabolic rate; the person curls up or adds clothing.

Fever is a reset of the thermostat, not a failure of it. **Pyrogens**, released by white blood cells in response to bacterial toxins, raise the hypothalamic set point, say to 39 °C. The body now treats 37 °C as too cold, so the patient shivers and feels chilled while the temperature climbs; when the set point returns to 37 °C the patient sweats and flushes as the extra heat is lost. Above about 41 °C enzymes and brain cells are damaged.

Response	Too hot	Too cold
Skin arterioles	Vasodilation: skin flushed, more heat radiated	Vasoconstriction: skin pale, less heat radiated
Sweat glands	Active: evaporation cools the skin	Inactive
Hair erector muscles	Relaxed: hairs flat	Contracted: hairs raised, air trapped
Skeletal muscles	Relaxed, activity reduced	Shivering: heat from respiration
Hormones	No extra	Adrenaline (fast) and thyroxine (slow) raise metabolic rate
Behaviour	Seek shade, rest, drink	Curl up, add clothing, move about

B15.2.2 Compare nitrogenous wastes (ammonia, urea, uric acid) and describe the urea cycle in the liver

The body cannot store excess amino acids. Those not needed are broken down in the liver by **deamination**: the amino group ($-NH_2$) is removed as **ammonia** (NH_3), leaving a keto acid that is respired or converted into glucose or fat. Ammonia is highly toxic, so it must either be flushed out at once in a great deal of water or converted into something safer. The choice depends on how much

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water the animal can spare and where its embryo develops.

- **Ammonia**: very soluble and very toxic, needs the most water, but costs no energy to make. **Ammonotelic** animals: most aquatic invertebrates, bony fishes and tadpoles.
- **Urea**, $CO(NH_2)_2$: far less toxic, soluble, needs moderate water, costs ATP to make. **Ureotelic** animals: mammals, adult amphibians and cartilaginous fishes.
- **Uric acid**: least toxic and almost insoluble, so it is passed as a semi-solid white paste with almost no water, but it is the most expensive to make. **Uricotelic** animals: birds, reptiles, insects and land snails, which must save water or lay shelled eggs in which the waste is stored as harmless crystals.

Feature	Ammonia	Urea	Uric acid
Toxicity	Very high	Low	Very low
Solubility in water	Very high	High	Almost insoluble
Water needed for excretion	Most	Moderate	Least (paste)
Energy cost to make	None	Moderate	Highest
Where made	All cells, mainly liver	Liver (urea cycle)	Liver
Typical animals	Bony fishes, aquatic invertebrates, tadpoles	Mammals, adult amphibians, sharks	Birds, reptiles, insects, land snails
Term	Ammonotelic	Ureotelic	Uricotelic

The urea cycle (ornithine cycle, Krebs-Henseleit cycle) runs in **liver** cells. It joins two molecules of ammonia with one of carbon dioxide to make one of urea and one of water, at the cost of ATP:

$2NH_3 + CO_2 \rightarrow CO(NH_2)_2 + H_2O$

The amino acid **ornithine** is used up and regenerated each turn. In the form taught at FSc level:

1. Ammonia and carbon dioxide (as carbamoyl phosphate, made with ATP) combine with **ornithine** to form **citrulline**.
2. Citrulline takes up a second amino group (from aspartate in the full pathway) to form **arginine**.
3. The enzyme **arginase** splits arginine with water into **urea** and **ornithine**; ornithine returns to step 1 and urea passes into the blood.

Recite: ornithine → citrulline → arginine → urea + ornithine. The blood carries urea to the kidneys, which excrete it in urine. Other excretory organs are the lungs (carbon dioxide), the skin (water, salts, a little urea) and the liver (bile pigments from haemoglobin).

> **MDCAT trap: urea is made in the liver, not the kidney.** Because urea is "the kidney's waste", many students answer that the kidney makes it. It makes none. Deamination and the urea cycle both happen in liver cells; the liver releases urea into the blood and the kidneys merely filter it out. Check: in kidney failure the blood urea rises, which shows urea is still being made elsewhere while the kidney has stopped removing it. The liver is the chief organ of nitrogen metabolism, the kidney of nitrogen excretion.

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Worked example. A chick develops for three weeks sealed inside a shelled egg with a fixed supply of water. Explain why birds excrete uric acid rather than ammonia or urea.

Step 1: Inside a shelled egg wastes cannot be removed; they must be stored until hatching. Step 2: Ammonia is far too toxic to store and would need water the egg does not have. Step 3: Urea is less toxic but soluble, so over three weeks it would build up to a harmful concentration and draw water osmotically. Step 4: Uric acid is almost insoluble, so it precipitates as harmless crystals in a membrane sac, with no osmotic effect and almost no water. Answer: uric acid is non-toxic, insoluble and water-saving, the only arrangement that works inside a closed egg; the price is the extra ATP needed to make it.

Practice MCQs

1. Which part of the nephron extends down into the renal medulla?
   A. Bowman's capsule
   B. Loop of Henle
   C. Proximal convoluted tubule
   D. Distal convoluted tubule
2. Which substance is present in blood plasma but absent from the glomerular filtrate of a healthy person?
   A. Glucose
   B. Urea
   C. Amino acids
   D. Albumin
3. A person drinks two litres of water in a short time. Which change follows?
   A. Less ADH is released and the collecting ducts become less permeable to water
   B. More ADH is released and the collecting ducts become more permeable to water
   C. Less ADH is released and the glomerular filtration rate falls
   D. More ADH is released and a large volume of dilute urine is formed
4. In haemodialysis the dialysis fluid contains glucose and salts at the same concentrations as healthy plasma but no urea. Glucose is added to the fluid in order to
   A. supply energy to the patient during the session
   B. draw water out of the blood by osmosis
   C. prevent the loss of glucose from the blood by diffusion
   D. speed up the diffusion of urea out of the blood
5. In a glomerulus the blood pressure is 60 mm Hg, the osmotic pressure of the plasma is 32 mm Hg and the pressure of fluid in Bowman's capsule is 18 mm Hg. The efferent arteriole then constricts so that glomerular blood pressure rises by 5 mm Hg. The new net filtration pressure is
   A. 15 mm Hg
   B. 10 mm Hg
   C. 5 mm Hg
   D. 23 mm Hg
6. On a cold morning, which response is brought about by the hypothalamus?
   A. Vasodilation of the arterioles in the skin
   B. Increased production of sweat

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C. Reduced secretion of thyroxine
D. Shivering of the skeletal muscles

7. A patient with a bacterial infection has a body temperature of 39.5 °C, yet feels cold and is shivering. The best explanation is that
   A. the hypothalamus has stopped responding to temperature
   B. pyrogens have raised the hypothalamic set point above the present body temperature
   C. thyroxine secretion has fallen sharply
   D. the sweat glands have become blocked
8. Which group of animals excretes its nitrogenous waste mainly as uric acid?
   A. Bony fishes
   B. Mammals
   C. Birds
   D. Adult amphibians
9. A desert lizard excretes uric acid rather than urea. The main advantage of uric acid to this animal is that it
   A. is less toxic than ammonia but more soluble than urea
   B. can be made without using any ATP
   C. is produced in the kidney rather than the liver
   D. can be passed out as a semi-solid paste with very little water
10. Each molecule of urea carries two nitrogen atoms. If the amino groups removed from 10 molecules of amino acid are all converted into urea in the liver, the number of urea molecules formed is
    A. 5
    B. 10
    C. 20
    D. 2

1. B. Only the loop of Henle and the collecting duct enter the medulla; the capsule and both convoluted tubules lie in the cortex.

2. D. Albumin is a plasma protein, too large to be filtered; glucose, urea and amino acids are small and enter the filtrate.

3. A. Dilute blood is detected by the hypothalamus, ADH release falls, the collecting ducts become less permeable and a large volume of dilute urine is passed.

4. C. Equal glucose concentrations give no gradient, so glucose stays in the blood, while urea, absent from the fluid, diffuses out.

5. A. Net filtration pressure = 60 - (32 + 18) = 10 mm Hg; raising the blood pressure by 5 mm Hg gives 65 - 50 = 15 mm Hg.

6. D. In the cold the hypothalamus causes vasoconstriction, stops sweating, raises thyroxine and triggers shivering, which releases heat from muscle respiration.

7. B. Pyrogens raise the set point, so the hypothalamus reads 39.5 °C as too cold and switches on heat-gain responses.

8. C. Birds, reptiles and insects are uricotelic; bony fishes excrete ammonia, mammals and adult amphibians excrete urea.

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9. D. Uric acid is insoluble and non-toxic, so it leaves as a paste with minimal water loss; it costs more ATP than urea, and like urea it is made in the liver.

10. A. Ten amino groups give ten nitrogen atoms as ammonia, and each urea takes two, so five urea molecules form.

Before the test: 12 facts to recite

1. Kidney regions from outside in: cortex, medulla (pyramids), pelvis; then ureter, bladder, urethra.
2. Nephron in order: Bowman's capsule with glomerulus, proximal convoluted tubule, loop of Henle, distal convoluted tubule, collecting duct.
3. The afferent arteriole is wider than the efferent arteriole, giving the high glomerular pressure needed for ultrafiltration.
4. Glomerular filtrate holds water, glucose, amino acids, salts and urea; no blood cells and no plasma proteins.
5. Net filtration pressure = glomerular blood pressure minus (plasma osmotic pressure plus capsular pressure), about 10 mm Hg.
6. The PCT reabsorbs all glucose and amino acids by active transport and most of the water and salts; about 99 per cent of filtered water is reabsorbed overall.
7. Loop of Henle: descending limb lets water out, ascending limb pumps salt out and is impermeable to water; this makes the medulla salty.
8. ADH is made in the hypothalamus, released from the posterior pituitary, and acts on the DCT and collecting duct: more ADH gives less, more concentrated urine.
9. Diabetes insipidus is a lack of ADH (dilute urine, no glucose); kidney stones are mostly calcium oxalate; dialysis removes urea by diffusion across a partially permeable membrane.
10. The hypothalamus controls temperature by negative feedback: too hot gives vasodilation and sweating; too cold gives vasoconstriction, shivering and more thyroxine and adrenaline.
11. Ammonia: most toxic, most water (bony fishes, ammonotelic); urea: intermediate (mammals, adult amphibians, ureotelic); uric acid: least toxic, insoluble, water-saving (birds, reptiles, insects, uricotelic).
12. The urea cycle runs in the liver: ornithine → citrulline → arginine, then arginase gives urea plus ornithine; overall $2NH_3 + CO_2 \rightarrow CO(NH_2)_2 + H_2O$.

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