D3.3 Homeostasis

Continuity and change—Organisms

Standard level and higher level: 2 hours

Additional higher level: 2 hours

Guiding questions

• How are constant internal conditions maintained in humans?

• What are the benefits to organisms of maintaining constant internal conditions?

SL and HL

D3.3.1—Homeostasis as maintenance of the internal environment of an organism
Variables are kept within preset limits, despite fluctuations in external environment. Include body temperature, blood pH, blood glucose concentration and blood osmotic concentration as homeostatic variables in humans.
Homeostasis is the maintenance of a dynamic equilibrium within the internal environment of an organism. In humans, it involves constantly adjusting variables like temperature, pH, blood glucose concentration and blood osmotic concentration in response to internal and external changes, keeping them close to the set point. A **set point** is a physiological value or range of values in which the body functions optimally within (i.e. the set point for body temperature is 36-37°C). Set points can change due to age or disease, like increased blood pressure in elderly people or fever during illness.

D3.3.2—Negative feedback loops in homeostasis

Students should understand the reason for use of negative rather than positive feedback control in homeostasis and also that negative feedback returns homeostatic variables to the set point from values above and below the set point.

Feedback loops are the systems that control the levels of a variable for which a receptor, control center, and effector exist. When a change occurs in the human body, receptors sense the change as stimulus and send signals to the brain, which generates a response that is sent to an effector (i.e. muscle or gland).

Negative feedback loops change the direction of the stimulus by increasing or decreasing it. Either way, the stimulus is not allowed to continue as it did before the receptor sensed it. All homeostatic mechanisms exist in negative feedback loops.

Positive feedback loops maintain the direction of the stimulus, intensifying it. Since they do not cause the body to return back to the set point, they are ***not*** a homeostatic mechanism, but sometimes necessary, like oxytocin and uterine contraction during childbirth.

Feedback loops are composed of a(n):

(1) **Stimulus (or initiation event)**: causes deviations away from the set point of a variable
(2) **Variable**: parameters that are monitored, controlled, and affected by the control center
(3) **Receptor**: senses changes in the variable's value and communicates it to the control center via electrical impulses or hormones
(4) **Control center (integrator)**: compares the variable value with the set point and signals to effectors accordingly
(5) **Effector**: executes changes necessary to adjust the variable

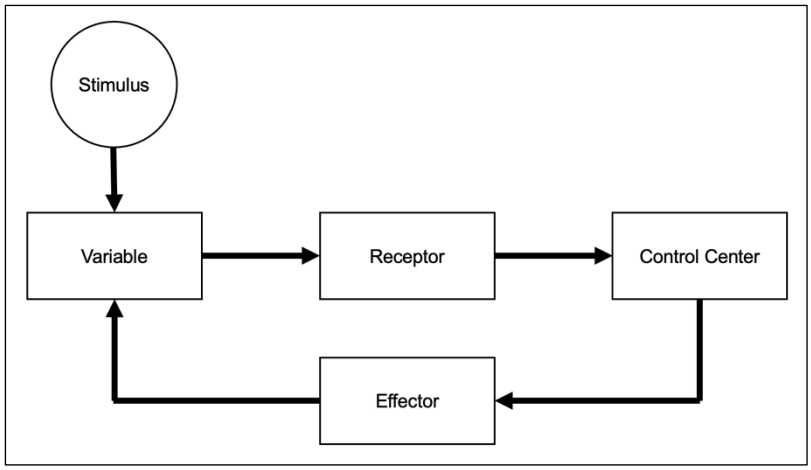

Figure 1: feedback loops diagram (adapted from Anatomy and Physiology I).

D3.3.3—Regulation of blood glucose as an example of the role of hormones in homeostasis

Include control of secretion of insulin and glucagon by pancreatic endocrine cells, transport in blood and the effects on target cells.

- **High** glucose levels are sensed by endocrine **pancreatic β-cells**, which secrete insulin that signals to muscle fibers, liver cells, and adipose tissue to take up the excess glucose.
- **Low** glucose levels are sensed by endocrine **pancreatic α-cells**, which secrete glucagon that signals to liver cells to break down glycogen and release more glucose into the blood.

This example shows how sometimes the same structure (in this case the pancreas) can act both as a receptor and control center.

D3.3.4—Physiological changes that form the basis of type 1 and type 2 diabetes

Students should understand the physiological changes, together with risk factors and methods of prevention and treatment.

Diabetes mellitus refers to a group of diseases that affect how blood sugar (glucose) is used by the body. Regardless of the type of diabetes, it leads to excess sugar in the blood, which disrupts blood osmolarity and normal homeostatic functioning.

Aspect	Diabetes I	Diabetes II
Type of disease	Autoimmune	Chronic metabolic disorder
% of population affected	1%	8.5%
Cause	Destruction of insulin-producing pancreatic β-cells	Insulin resistance due to mainly obesity or aging
Risk factors	• Family history • Young age (usually develops in children and young adults)	• Obesity • Sedentary lifestyle • Non-alcoholic fatty liver • Family history
Physiological effects / symptoms	• High glucose blood levels • High glucose levels in urine • Increased/frequent urination • Extreme thirst • Frequent infections • Slow-healing sores • Fatigue	
Prevention	• Physical activity • Healthy diet • Maintaining a healthy weight	
Treatment	Insulin supplements	Dietary and lifestyle changes

D3.3.5—Thermoregulation as an example of negative feedback control

Include the roles of peripheral thermoreceptors, the hypothalamus and pituitary gland, thyroxin and also examples of muscle and adipose tissue that act as effectors of temperature change.

Thermoregulation is an example of a negative feedback homeostatic mechanism; when temperature increases, the body works to bring it down, and if temperature drops, the body works to bring it up.

(1) **Thermoreceptors** located in the core of the body and skin sense changes in temperature and send a signal to the hypothalamus. **Peripheral thermoreceptors** are located in the skin are most influenced by temperature changes as the skin is most exposed to the external environment.

(2) The hypothalamus processes the stimulus from these receptors and sends signals to effectors of temperature change, for example (**STAMB**):

- **S**weat glands secrete fluid at high temperatures and stop at low temperatures
- **T**hyroxin secretion is increased in the thyroid gland when temperatures drop in order to boost metabolic rate, which generates heat
- **A**dipose tissue breaks down fat to generate heat
- **M**uscle contraction generates heat
- **B**lood vessels **c**onstrict to **c**onserve heat and dilate to lose heat

D3.3.6—Thermoregulation mechanisms in humans
Students should appreciate that birds and mammals regulate their body temperature by physiological and behavioural means. Students are only required to understand the details of thermoregulation for humans. Include vasodilation, vasoconstriction, shivering, sweating, uncoupled respiration in brown adipose tissue and hair erection.

Thermoregulation mechanisms are of 2 broad types:

- **Physiological**: involuntary action of effectors that produce or dissipate heat.
- **Behavioral**: voluntary actions to regulate body temperature, i.e. making nests or seeking shade.

Response to warmth	Response to cold
• Vasodilation to lose heat • Fluid secretion by sweat glands	• Vasoconstriction to conserve heat • Sweat glands stop fluid secretion • Hair erection, which evolved to trap heat and insulate but is no longer effective • Uncoupled respiration in brown adipose tissue is a form of cell respiration that generates heat without ATP to raise body temperature

Additional higher level

D3.3.7—Role of the kidney in osmoregulation and excretion
Students should understand the distinction between excretion and osmoregulation. Osmoregulation is regulation of osmotic concentration. The units for osmotic concentration are osmoles per litre (osmol L^{-1}).

Osmoregulation is the homeostatic regulation of osmotic concentrations in bodily fluids and is measured in osmoles per litre (osmolL^{-1}). For example, 1 mole of NaCl dissolved in a litre of water equals 2 osmolL^{-1}, since each NaCl molecule dissociates into 2 ions.

Excretion is the removal of metabolic waste.

The **kidney** carries out *both* osmoregulation and excretion in the human body through the **nephron**, which is the functional unit of the kidney. Each kidney contains over 1 million nephrons.

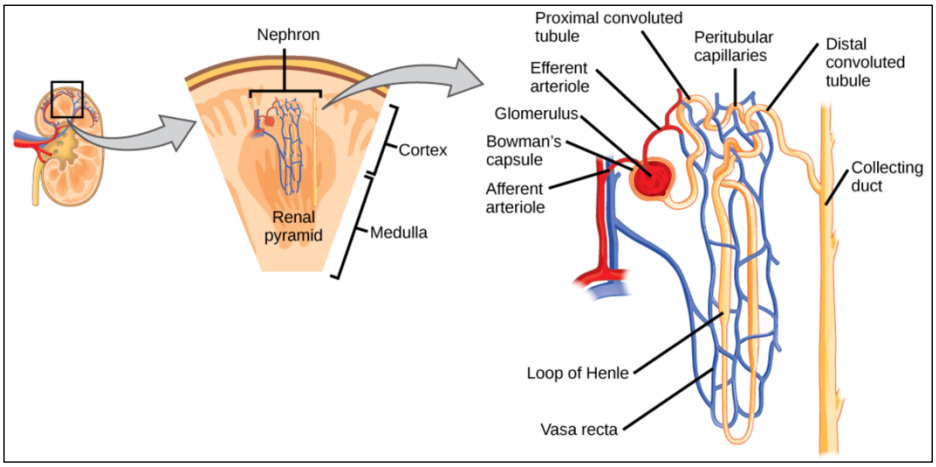

Figure 2: anatomy of a nephron (Ann Clarks).

D3.3.8—Role of the glomerulus, Bowman's capsule and proximal convoluted tubule in excretion

Students should appreciate how ultrafiltration remove solutes from blood plasma and how useful substances are then reabsorbed, to leave toxins and other unwanted solutes in the filtrate, which are excreted in urine.

Ultrafiltration, the removal of solutes from blood plasma, is the first step in urine production:

- **Afferent arteriole**: delivers unfiltered blood from the renal artery to the glomerular capillary network.
- **Efferent arteriole**: carries blood from the glomerular capillaries to the peritubular capillaries. It is narrower than the afferent arteriole, which creates high resistance and helps maintain a high hydrostatic pressure in the glomerular capillaries, enabling substances to be pushed out (filtered).
- **Glomerular capillary network**: a network of tightly packed, convoluted, and fenestrated blood capillaries surrounded by Bowman's capsule. High blood pressure ***and*** concentration gradients (mainly) drive small molecules out of its capillaries, through the GBM, and into the glomerular capsule.
- **Glomerular Basement Membrane (GBM)**: a negatively charged glycoprotein matrix between the glomerular epithelial cells and podocytes that prevents the filtration of proteins and large anionic molecules.
- **Podocytes**: the visceral (inner) epithelial layer of Bowman's capsule, which feature finger-like projections called **pedicels** or **foot processes**. These pedicels interdigitate (interlock), which creates small **filtration slits** that are covered by cell-surface proteins forming the **slit diaphragm**, further preventing the passage of proteins.
- **Bowman's (glomerular) capsule**: cup-shaped sac that performs the first step in ultrafiltration by collecting the filtered fluids (now called **tubular fluid**) from the blood. Its impermeable **parietal** (outer) **cells** prevent the glomerular filtrate from leaving and they eventually become the renal tubule's lining as they leave the glomerulus.

Tubular reabsorption, the selective reabsorption of useful substances into the bloodstream, is the second step in urine formation and occurs mostly in the PCT.

Proximal convoluted tubule (PCT): twisted (convoluted) tubule with ample surface area for transporting materials, which is achieved by:

(a) **microvilli** lining the inner (**apical**; facing lumen of renal tubule) membrane of the parietal cells, creating a **brush border**
(b) infoldings of the outer (**basal**; facing interstitial space) membrane
(c) **tight junctions** between the parietal cells

Reabsorbing materials into the bloodstream requires transporting them from the lumen of the renal tubule through the apical membrane of epithelial cells, across the cytoplasm, through the basal membrane into the interstitial space and finally into the **peritubular capillaries**, which are small and fenestrated. Although most of the substances are reabsorbed in the PCT, this process continues throughout the entire remainder of the renal tubule. The amount of water leaving in the PCT is proportional to the amount of solutes leaving in order to ensure that the filtrate in the PCT is isotonic with blood and the interstitial space.

Substance reabsorbed	PCT	Loop of Henle	DCT	CD
Glucose	Secondary active transport with Na+ (~100%)	-	-	-
Amino acids / Short polypeptides	Symport with Na+ (~100%)	-	-	-
Sodium	Active transport via ATPase (~65%)	Active transport (~25%)	Active transport (~5%)	Active transport (~5%)
Chloride	Diffusion	Diffusion	Diffusion	Secondary active transport
Water	~65% via osmosis	~15% via osmosis in descending limb	Osmosis (amount controlled by ADH)	

D3.3.9—Role of the loop of Henle

Limit to active transport of sodium ions in the ascending limb to maintain high osmotic concentrations in the medulla, facilitating water reabsorption in the collecting ducts.

The **Loop of Henle** is a U-shaped tubule with a **thin descending limb** and **thick ascending limb**, and sometimes extends from the cortex into the medulla of the kidney. It is responsible for water and sodium/chloride ion reabsorption, in addition to creating a salty medulla environment.

- The epithelial cells of the descending limb contain permanent aquaporins that allow water to diffuse into the interstitial space unrestricted, but *not* sodium.
- The epithelial cells of the ascending limb do not contain aquaporins (impermeable to water) because they mainly contain symporters for active transport of Na^+/Cl^- into the interstitial space.
- Surrounding the Loop of Henle is the **vasa recta**; a network of narrow, long blood vessels that run parallel to the Loop of Henle and are part of the **countercurrent multiplier system**. The blood in the vasa recta flows in the direction opposite to the filtrate (counter), which along with the selective reabsorption of the Loop of Henle, increase (multiply) the concentration of solutes deep in the medulla.

This results in a hypotonic filtrate that enters the DCT and a hypertonic environment in the kidney's medulla, which establishes the conditions needed for reabsorption and facilitates the role of the CD.

D3.3.10—Osmoregulation by water reabsorption in the collecting ducts

Include the roles of osmoreceptors in the hypothalamus, changes to the rate of antidiuretic hormone secretion by the pituitary gland and the resultant switches in location of aquaporins between cell membranes and intracellular vesicles in cells of the collecting ducts.

The **Distal convoluted tubule (DCT)** carries out any remaining reabsorption of water and sodium (actively); its epithelial cells do not contain a brush border but they have the greatest mitochondrial density and ATPase activity of any nephron segment to carry out further reabsorption of Na^+/Cl^-.

The **Collecting Duct (CD)** is the final portion of the nephron tubule system which 'collects' urea and transports it to the renal pelvis and then ureters for excretion. It is responsible for **osmoregulation**, the process of maintaining salt and osmotic (fluid) balance across membranes within the body, which occurs as follows:

(1) **Osmoreceptors** in the **hypothalamus** sense the slightest change in blood osmolarity and result in the secretion of **vasopressin**, or **antidiuretic hormone (ADH)** from the posterior pituitary gland in the hypothalamus.

(2) ADH then binds to receptors in the **principal cells** of the CD, activating a second messenger (cAMP) and causing the phosphorylation of intracellular vesicles storing aquaporins, which promotes their movement and insertion into the apical membrane.

(3) This promotes the passive movement of water out of the CD as it descends into the hypertonic environment of the medulla, which helps the body regulate blood osmolarity and conserve water during dehydration.

D3.3.11—Changes in blood supply to organs in response to changes in activity

As examples, use the pattern of blood supply to the skeletal muscles, gut, brain and kidneys during sleep, vigorous physical activity and wakeful rest.

Due to the limited amount of blood, patterns of supply need to be well-regulated to ensure that the right organ is being supplied with the right amount of blood at the right time. Blood supply can be increased by **vasodilation** and decreased via **vasoconstriction**.

Organs	Physical state		
	Sleep	Wakeful rest	Vigorous activity
Skeletal muscles	Low blood supply	Moderate blood supply	High blood supply
Gut	Depends on amount of food	Depends on amount of food	Low blood supply
Brain	High blood supply	Moderate blood supply	High blood supply
Kidneys	Low blood supply	**Maximum blood supply** (kidneys receive ~25% of cardiac output)	Low blood supply

Linking questions

• For what reasons do organisms need to distribute materials and energy?

• What biological systems are sensitive to temperature changes?

Review questions

SL and HL

- Define homeostasis. [1]
- Distinguish between feedback loops, giving an example for each in the human body. [2]
- Distinguish between physiological and behavioral thermoregulation, giving examples. [2]
- Outline the benefits to organisms of maintaining constant internal conditions. [3]
- Explain how homeostasis is disrupted in diabetes. [3]
- Explain how glucose levels are kept within a narrow range in human blood. [4]
- Outline the causes, effects, and possible treatments for diabetes. [6]
- Explain thermoregulation in humans. [7]

Additional Higher Level

- State the function(s) of the nephron. [1]
- Explain the role of the countercurrent multiplier system in the Loop of Henle. [4]
- Explain how selectivity in the nephron is achieved. [4]
- Compare and contrast the ascending and descending limbs of the Loop of Henle. [4]
- Explain the differential permeability of the proximal convoluted tubule in urine formation. [4]
- Outline the changes in blood supply to organs in response to changes in activity. [5]
- Compare and contrast the proximal and distal convoluted tubules. [6]
- Describe osmoregulation in the human nephron. [6]
- Discuss how epithelial cells are adapted to the nephron's function. [7]
- Explain how the structure of the nephron's blood supply is adapted to its function. [7]
- Proteinuria is a disease in which large amounts of protein are found in urine. Discuss the possible structures affected by this illness. [7]
- Describe the process of tubular reabsorption in the kidneys. [7]
- Describe the structure of the nephron. [7]
- Describe the journey of a group of sodium ions, starting in the afferent arteriole of a nephron. [8]

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