B2.3 Cell specialization

Form and function—Cells

Standard level and higher level: 2 hours

Additional higher level: 1 hour

Guiding questions

• What are the roles of stem cells in multicellular organisms?

• How are differentiated cells adapted to their specialized functions?

SL and HL

B2.3.1—Production of unspecialized cells following fertilization and their development into specialized cells by differentiation
Students should understand the impact of gradients on gene expression within an early-stage embryo.

Cell differentiation is the process by which an unspecialized cell develops into a cell type with a specific form and function. This can be caused through extrinsic or intrinsic mechanisms.
Extrinsic mechanisms rely on external signalling molecules (**morphogens)** that alter the cell's gene expression, causing it to differentiate. Formation of tissues and organs during embryonic development (first 8 weeks after fertilization & zygote formation) is driven by the action of morphogens:
• **Source cells** secrete morphogens into nearby (undifferentiated) cells, establishing a **gradient**;
  • Cells closer to the source cell will be exposed to high concentrations of morphogens
  • Cells farther away from the source cell will be exposed to lower concentrations of morphogens
• Different morphogen concentrations lead to differential gene expression and thus the differentiation of cells into different types

B2.3.2—Properties of stem cells
Limit to the capacity of cells to divide endlessly and differentiate along different pathways.
Stem cells are undifferentiated or partially undifferentiated cells with unique properties: 1. **Self-renewal**: stem cells undergo multiple rounds of cell division whilst remaining undifferentiated. 2. **Potency**: the capacity to differentiate into specialized cells. 3. **Indefinite division**: unlike somatic (differentiated) cells that have a limited number of cell divisions before reaching senescence, stem cells can divide endlessly.

B2.3.3—Location and function of stem cell niches in adult humans

Limit to two example locations and the understanding that the stem cell niche can maintain the cells or promote their proliferation and differentiation. Bone marrow and hair follicles are suitable examples.

Stem cell niches are microenvironments that maintain and regulate stem cells via **paracrine** (short-range intercellular signalling) and **contact-dependent** signalling. Examples:

- **Bone marrow**: contains **hematopoietic multipotent stem cells** that differentiate into red and white blood cells.
- **Hair follicles**: contain **multipotent hair follicle stem cells** that give rise to new hair follicles.

B2.3.4—Differences between totipotent, pluripotent and multipotent stem cells

Students should appreciate that cells in early-stage animal embryos are totipotent but soon become pluripotent, whereas stem cells in adult tissue such as bone marrow are multipotent.

Stem cells are not all equally potent; some differentiate into more types of cells than others.

- **Totipotent**: give rise to embryonic and extraembryonic (e.g. placenta) tissue. The zygote is a totipotent stem cell but quickly becomes pluripotent after a few cellular divisions during early-stage embryonic development.
- **Pluripotent**: give rise to all embryonic (but not extraembryonic) tissue. They are only present during embryonic development (not in human adults).
- **Multipotent**: give rise to several cell types and are present throughout human life.
- **Unipotent**: give rise to only 1 cell type and exist throughout human life.

B2.3.5—Cell size as an aspect of specialization

Consider the range of cell size in humans including male and female gametes, red and white blood cells, neurons and striated muscle fibres.

Cell size is one way in which stem cells specialize into cell types with specific forms and function. Cell size in humans can range from around 5μm to 100μm, depending on the cell type. Some cells have a small diameter but great length, like sperms and neurons (axons), whilst others are small in diameter and length, like blood cells. The mature ovum in humans is large enough to be seen with the naked eye, whilst most other cells require microscopy techniques.

NOS: Students should recognize that models are simplified versions of complex systems. In this case, surface-area-to-volume relationship can be modelled using cubes of different side lengths. Although the cubes have a simpler shape than real organisms, scale factors operate in the same way.

The surface area and volume of a cube is commonly used to explain the concept of SA:V ratio. Although cell shape is more complex than a simple cube, it is still an effective model.

B2.3.6—Surface area-to-volume ratios and constraints on cell size
Students should understand the mathematical ratio between volume and surface area and that exchange of materials across a cell surface depends on its area whereas the need for exchange depends on cell volume.

Changes in cell size lead to changes in plasma membrane surface area and cell volume.
• **Surface area** affects the **exchange of materials** across a cell surface:
  • High surface area = high rate of material exchange
  • Low surface area = low rate of material exchange
• **Cell volume** affects the **demand of materials** for metabolism:
  • Larger cells require more materials to fulfil their functions of life
  • Smaller cells require less materials to fulfil their functions of life
Surface area-to-volume ratio mathematically describes the relationship between a cell's surface area and its volume. A high SA:V ratio indicates that the cell is efficient at balancing material exchange with metabolism rate (a low ratio indicates cellular inefficiency). The SA:V ratio also puts a limit on cell size; cells can only be so big before the ratio becomes too small to be viable.

Additional higher level

B2.3.7—Adaptations to increase surface area-to-volume ratios of cells
Include flattening of cells, microvilli and invagination. Use erythrocytes and proximal convoluted tubule cells in the nephron as examples.

High SA:V ratio is required when efficient transport of molecules is needed:
• **Erythrocytes**: biconcave disc-like shape increases SA:V ratio for efficient/maximal gas exchange
• **Proximal convoluted tubule cells**:
  • **Microvilli** on the luminal (apical) side of the tubule cells increases the SA:V ratio to maximize reabsorption of solutes from the filtrate
  • **Basal invaginations** (folding of the tube on the side facing blood vessels) increase the SA:V ratio of molecular transport into the blood

B2.3.8—Adaptations of type I and type II pneumocytes in alveoli

Limit to extreme thinness to reduce distances for diffusion in type I pneumocytes and the presence of many secretory vesicles (lamellar bodies) in the cytoplasm that discharge surfactant to the alveolar lumen in type II pneumocytes. Alveolar epithelium is an example of a tissue where more than one cell type is present, because different adaptations are required for the overall function of the tissue.

During respiration, air travels through the nose, bronchi, bronchioles, and finally reach the alveoli (functional unit of the respiratory system). **Alveoli** are air-filled sacs that are lined with a single-layer epithelium composed of 2 types of **pneumocytes**:

- **Type I pneumocytes** cover most of alveolar surface and carry out gas exchange
  - **Thin and flattened shape** increases SA:V ratio and decreases the distance oxygen requires to travel from the air to the blood vessels
- **Type II pneumocytes**: cover some of alveolar surface and produce pulmonary surfactant
  - **Pulmonary surfactant** is composed of lipids and proteins. It is found in the inner lining of alveoli to prevent their collapse by reducing surface tension
  - Type II have a **cuboid shape** to increase cytoplasmic volume (and thus production of lipids and proteins needed for the surfactant)
  - Type II contain many **secretory vesicles (lamellar bodies)** in the cytoplasm that store the surfactant components for secretion
  - Type II contain **microvilli** on their alveolar-facing side to increase the SA:V ratio for maximal surfactant secretion

B2.3.9—Adaptations of cardiac muscle cells and striated muscle fibres

Include the presence of contractile myofibrils in both muscle types and hypotheses for these differences: branching (branched or unbranched), and length and numbers of nuclei. Also include a discussion of whether a striated muscle fibre is a cell.

Muscle fibers can be classified into **striated** (skeletal and cardiac) or **non-striated** (smooth). Striated fibers are aligned in a way such that their different regions form visible stripes under a microscope.

	Skeletal	**Cardiac**
Fiber length	Long	Shorter than skeletal fibers
Branching	No	Yes (allows for synchronous and rapid contraction)
Striation	Yes	Yes
Nucleation	Multinucleate	Uninucleate
Connectivity	Fibers are not connected	Fibers are connected by **intercalated disks** and **gap junctions** to allow for synchronous and rapid contraction
Innervation	**Motor neurons** for voluntary control	**Autonomous nervous system** for involuntary control

It is debated whether skeletal muscle can be considered a cell because they do not share many characteristics of cells (i.e. they are much larger than most cells and are not uninucleate like most cells).

B2.3.10—Adaptations of sperm and egg cells
Limit to gametes in humans.

	Sperm	Ovum
Nucleus	Haploid	Haploid
Size	Very small (increases sperm speed)	Very large (to store all the nutrients necessary for zygote growth)
Motility	Yes (via **flagella**)	No
Shape	Streamlined head-tail shape for efficiency & speed	Spherical
Organelles	Minimal (increase sperm speed); **helical mitochondria** provide energy for motility	Most organelles are present
Specialized vesicles	**Acrosomal vesicles** aid in penetration of zona pellucida during fertilization	**Cortical granules** release their contents after fertilization to prevent polyspermy

Linking questions

• What are the advantages of small size and large size in biological systems?

• How do cells become differentiated?

Review questions

SL and HL

- State **two** stem cell niches found in the human body. [1]
- Define a stem cell niche. [1]
- State 1 similarity between bone marrow and hair follicle stem cells. [1]
- Outline the properties of stem cells. [2]
- Outline how morphogens drive cell differentiation in early embryonic development. [3]
- Explain how cell size is restricted. [4]
- Describe, using examples, the differences between stem cell potencies. [6]

Additional Higher Level

- Describe the adaptations of erythrocytes and the proximal convoluted tubule. [3]
- During differentiation, stem cells undergo changes to their structure. Outline **two** different structural changes bone marrow stem cells undergo as they specialize into erythrocytes. [4]
- Explain how alveoli are adapted to their function. [6]
- Compare the adaptations of human gametes. [6]
- Compare and contrast cardiac and skeletal muscle fibers. [6]
- Explain the advantages of small size and large size in biological systems. [7]
- Cells with completely different functions sometimes posses similar forms. Discuss how **three** structures are **each** present in at least **two** or more different types of cells. [8]

References

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