B2.2 Organelles and compartmentalization

Form and function—Cells

Standard level and higher level: 1 hour

Additional higher level: 2 hours

Guiding questions

• How are organelles in cells adapted to their functions?

• What are the advantages of compartmentalization in cells?

SL and HL

B2.2.1—Organelles as discrete subunits of cells that are adapted to perform specific functions

Students should understand that the cell wall, cytoskeleton and cytoplasm are not considered organelles, and that nuclei, vesicles, ribosomes and the plasma membrane are.

Organelles ('little organs') are discrete subunits of cells that are adapted to perform specific functions.

The following are not considered organelles:

(1) **Cell wall**; it is located on the *external* surface and thus is not ***sub*unit**
(2) **Cytoskeleton**; it is a network of dispersed (not **discrete**) protein filaments
(3) **Cytoplasm**: it does not perform **specific functions**

Double-membraned	Single-membraned	No membrane
• Nuclei • Mitochondria • Chloroplasts	• Smooth endoplasmic reticulum • Rough endoplasmic reticulum • Golgi apparatus • Vesicles • Lysosomes • Vacuoles • Peroxisomes	• Nucleoli • Ribosomes

NOS: Students should recognize that progress in science often follows development of new techniques. For example, study of the function of individual organelles became possible when ultracentrifuges had been invented and methods of using them for cell fractionation had been developed.

Cell fractionation is the process by which cellular compartments (organelles) are separated using **centrifugal (spinning) force** whilst preserving their structure via 2 main steps:

(1) **Homogenization**: disruption of tissue and release of cellular compartments to form a **homogenate**:
  (a) **Formation of the homogenous medium**:
    i. Adding sucrose at hypotonic or isotonic conditions to preserve morphological integrity
    ii. Adding extra chemicals in cells with structures like cell walls to further homogenize
  (b) **Tissue disruption**: can be done by either physical disruption (mortar and pestle, blender) or chemical disruption (organic solvents)
(2) **Centrifugation**: separating cell compartments by density, size, and shape;
  (a) **Differential centrifugation**: increasing the relative centrifugal force to separate components with significantly different sedimentation rates (heavier organelles sediment first)
  (b) **Rate-zonal centrifugation**: applying a thin layer of the homogenate as a single band to a pre-centrifuged solution with a density gradient of a particular chemical (usually sucrose) and then centrifuging again to create several bands of varying density corresponding to cell parts

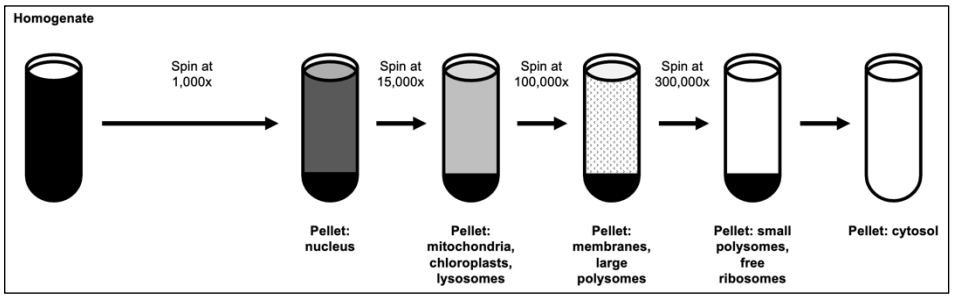

Figure 1: differential centrifugation.

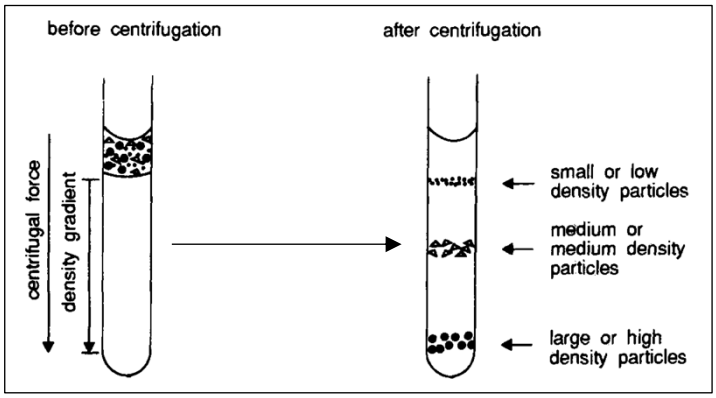

Figure 2: rate-zonal centrifugation (Libretexts).

B2.2.2—Advantage of the separation of the nucleus and cytoplasm into separate compartments

Limit to separation of the activities of gene transcription and translation—post-transcriptional modification of mRNA can happen before the mRNA meets ribosomes in the cytoplasm. In prokaryotes this is not possible—mRNA may immediately meet ribosomes.

Advantages of the separation of the nucleus and cytoplasm into separate compartments:

(1) **Complex gene regulation**: enables post-transcriptional modification to occur in the nucleus before the mRNA meets ribosomes in the cytoplasm, increasing proteinic diversity

(2) **Genome protection**: enclosing DNA within the nucleus protects it from damage

Since prokaryotes lack compartmentalization, transcription and translation are coupled, leading to **faster gene expression**.

B2.2.3—Advantages of compartmentalization in the cytoplasm of cells

Include concentration of metabolites and enzymes and the separation of incompatible biochemical processes. Include lysosomes and phagocytic vacuoles as examples

Advantages of compartmentalization in the cytoplasm of cells:

(1) **Rate of reactions**: organelles provide a concentrated environment for specific biochemical reactions to occur, increasing metabolic efficiency.

(2) **Separation of incompatible biochemical processes**: for example,

(a) lysosomes contain hydrolytic enzymes that would harm the cell if released but are crucial for its survival

(b) food vacuoles have a different pH than the cytoplasm in order for digestive enzymes to function

Additional higher level

B2.2.4—Adaptations of the mitochondrion for production of ATP by aerobic cell respiration

Include these adaptations: a double membrane with a small volume of intermembrane space, large surface area of cristae and compartmentalization of enzymes and substrates of the Krebs cycle in the matrix.

The mitochondrion is adapted for production of ATP by aerobic cell respiration:

- **Double membrane**: the **outer membrane** is permeable to many ions, molecules, and even small proteins, but the **inner membrane** is much more selective and impermeable to most substances in order to prioritize proton pumping.
- **Intermembrane space**: very narrow gap between the outer and inner membranes to allow for rapid accumulation of protons and thus quick establishment of a proton gradient to fuel chemiosmosis.
- **Cristae**: the inner folding allows for a large surface area for protein channels involved in the ETC.
- **Matrix**: serves as a medium with high concentrations of enzymes and substances needed for aerobic respiration.

B2.2.5—Adaptations of the chloroplast for photosynthesis

Include these adaptations: the large surface area of thylakoid membranes with photosystems, small volumes of fluid inside thylakoids, and compartmentalization of enzymes and substrates of the Calvin cycle in the stroma.

The chloroplast is adapted for photosynthesis:

- **Thylakoid membranes**: thin, flattened, disced shape provides large surface area for the accommodation of more photosystems for photosynthesis.
- **Thylakoid lumen**: small volume enables rapid accumulation of protons and quick establishment of a proton gradient to facilitate chemiosmosis.
- **Stroma**: serves to compartmentalize enzymes and substrates needed for the Calvin cycle to ensure proximity and high concentrations necessary for efficient photosynthesis.

B2.2.6—Functional benefits of the double membrane of the nucleus

Include the need for pores in the nuclear membrane and for the nucleus membrane to break into vesicles during mitosis and meiosis.

Functional benefits of the double membrane of the nucleus:

(1) **Nuclear pores**: the nucleus needs to import histones, transcription factors, and splicing factors whilst exporting ribosomal subunits, mRNA, and tRNA. Controlled, regulated transport of such large substances is not possible through a single phospholipid bilayer, so a double membrane is necessary. Nuclear pores are composed of dozens of different proteins (**nucleoporins**), which connect the interior of the nucleus (**nucleoplasm**) to the cytosol through pores channels (pores).

(2) **Vesicles**: when the nuclear envelope disintegrates during cell division, vesicle fusion helps to reform it, which would only be possible if it was a double membranous structure.

B2.2.7—Structure and function of free ribosomes and of the rough endoplasmic reticulum

Contrast the synthesis by free ribosomes of proteins for retention in the cell with synthesis by membrane-bound ribosomes on the rough endoplasmic reticulum of proteins for transport within the cell and secretion.

A **ribosome** is a large complex made of several different **ribosomal proteins** and **ribosomal RNA (rRNA)** molecules. It is composed of one **large ribosomal subunit** containing 3 rRNA molecules and one **small ribosomal subunit** containing 1 rRNA molecule. *Both* subunits are involved in the formation of the 3 **tRNA binding sites**; **A (aminoacyl) site**, **P (peptidyl) site**, **E (exit) site**. The main function of ribosomes is protein synthesis.

There are 2 spatially separate populations of ribosomes; **free ribosomes** and **membrane-bound ribosomes**. Both are structurally and functionally identical, differing only in the proteins they are synthesizing at any given time. When a ribosome happens to be translating a protein with an **ER signal sequence**, the signal directs it to the ER membrane, and it becomes membrane-bound for the time being.

Proteins synthesized by membrane-bound ribosomes are destined for secretion out of the cell or incorporation into the plasma membrane, while other proteins for use within the cell are synthesized by free ribosomes.

The **endoplasmic reticulum (ER)** is a continuous (connected) membrane system of convoluted, flattened, uniform sacs (**cisternae**) that are contiguous with the nuclear membrane. There are two types of ER which differ in structure and function:

- **Rough endoplasmic reticulum (RER)**: contains membrane-bound ribosomes and enriched with integral proteins involved in translocation and processing of newly synthesized polypeptides because it is mainly adapted for **protein synthesis / folding / quality control**.
- **Smooth endoplasmic reticulum (SER)**: often more convoluted than the RER and does not contain membrane-bound ribosomes because it is mainly adapted for **lipid synthesis and metabolism**.

B2.2.8—Structure and function of the Golgi apparatus

Limit to the roles of the Golgi apparatus in processing and secretion of protein.

The **Golgi apparatus** is composed of a collection of fused cisternae (less tubule-like than the ER) that form two major networks; the **Cis Golgi network** (first cisternal structure facing the nucleus) and the **Trans Golgi network** (final cisternal structure facing the cell plasma membrane). Unlike the ER, the Golgi cisternae are not contiguous and their widths are not uniform.

The cis and trans networks/sides differ in their integral protein and enzyme composition, because the cis face receives newly synthesized proteins from the ER whilst the trans face exports finalized proteins through budding vesicles. These adaptations allow for the Golgi apparatus to perform its function of **transport, sorting, and modification of both proteins and lipids**.

There are two main models as to how the Golgi apparatus performs its functions:

1. **Cisternal Maturation Model**: cisternae mature over time, moving from the cis side to the trans side as their enzyme composition changes over time to account for their change in position, while the proteins remain inside as ‘passengers’.
2. **Vesicular Transport Model**: each cisterna is a stable compartment made of an unchanging, specific enzyme composition which proteins move through via vesicles.

The Cisternal Maturation Model best fits current data, but many questions remain.

B2.2.9—Structure and function of vesicles in cells
Include the role of clathrin in the formation of vesicles.
Vesicles are small sacs surrounded by a single lipid bilayer that constantly and naturally form via exocytosis and endocytosis with **transport** as the main function. They can either contain material for transport or themselves be the material to be moved (i.e. their bilayer, when fused with the cell's plasma membrane, helps the cell increase its surface area during interphase). **Clathrin-coated vesicles (CCVs)** are the most studied type of vesicles, and are simply vesicles coated by the protein **clathrin**. Clathrin forms a basket-like network on the cytosolic surface of the membrane, which: 1. Provides **mechanical support** for vesicles to facilitate the formation of their spherical structure 2. Captures and recruits target molecules for onwards transport

Linking questions

• What are examples of structure–function correlations at each level of biological organization?

• What separation techniques are used by biologists?

Review questions

SL and HL

- Define the term organelles. [1]
- List **three** membrane-bound organelles. [1]
- Explain why the nucleus is the first sediment formed during differential centrifugation. [1]
- Suggest why hypertonic conditions are not used for cell fractionation. [1]
- Outline the advantages of the separation of the nucleus and cytoplasm in eukaryotes. [2]
- Outline the advantages of the separation of organelles and the cytoplasm in eukaryotes. [3]
- Outline the reasons for why some cellular components are not considered organelles. [3]
- When yeast cells go dormant because of a lack of food availability, their cytoplasm assumes a solid state. Predict the effect this would have on cellular processes, justifying your answer. [3]
- Explain how you would determine whether a newly discovered cellular structure is an organelle or not, giving named examples for your criteria. [4]
- Describe how cell fractionation works. [5]

Additional Higher Level

- Compare and contrast the models used in explaining how the Golgi apparatus functions. [2]
- Outline the role of clathrin. [2]
- Outline the structure and function of vesicles. [3]
- Explain how the nuclear envelope is coevolved with its function(s). [3]
- Explain the benefits of the structure of the nuclear envelope. [3]
- Describe the structure and function of the Golgi apparatus. [4]
- Describe the structure and function of ribosomes. [4]
- Compare and contrast the adaptations of mitochondria and chloroplasts to their functions. [4]
- Describe the structure and function of the endoplasmic reticulum. [4]
- Explain how mitochondria are adapted to their function. [5]
- Explain how the organelles involved in protein synthesis are adapted to their functions. [8]

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