Chapter 3
Cells
Cellular Form and Function

• Concepts of cellular structure
• Cell surface
• Membrane transport
• Cytoplasm
Development of the Cell Theory

- Hooke (1665) named the cell
- Schwann (1800’s) states: all animals are made of cells
- Pasteur (1859) disproved idea of spontaneous generation
  - living things arise from nonliving matter
- Modern cell theory emerged
Modern Cell Theory

• All organisms composed of cells and cell products.
• Cell is the simplest structural and functional unit of life.
• Organism’s structure and functions are due to the activities of its cells.
• Cells come only from preexisting cells.
• Cells of all species have many fundamental similarities.
Cell Size

• Human cell size
  – most from 10 - 15 µm in diameter
    • egg cells (very large) 100 µm diameter
    • nerve cell (very long) at 1 meter long

• Limitations on cell size
  – cell growth increases volume faster than surface area
    • nutrient absorption and waste removal utilize surface
Cell Surface Area and Volume

Large cell
- Diameter = 20 µm
- Surface area = 20 µm x 20 µm x 6 = 2,400 µm²
- Volume = 20 µm x 20 µm x 20 µm = 8,000 µm³

Small cell
- Diameter = 10 µm
- Surface area = 10 µm x 10 µm x 6 = 600 µm²
- Volume = 10 µm x 10 µm x 10 µm = 1,000 µm³

Effect of cell growth:
- Diameter (D) increased by a factor of 2
- Surface area increased by a factor of 4 (= D²)
- Volume increased by a factor of 8 (= D³)
General Cell Structure

- Light microscope reveals plasma membrane, nucleus and cytoplasm
- Resolution of electron microscopes reveals ultrastructure
  - organelles, cytoskeleton and cytosol
Major Constituents of Cell
Plasma Membrane

- Pair of dark parallel lines around cell (viewed with the electron microscope)
- Defines cell boundaries
- Controls interactions with other cells
- Controls passage of materials in and out of cell
Plasma Membrane

- Oily film of lipids with diverse proteins embedded in it
Membrane Lipids

- Plasma membrane = 98% lipids
- Phospholipid bilayer
  - 75% of the lipids
  - hydrophilic heads and hydrophobic tails
  - molecular motion creates membrane fluidity
- Cholesterol
  - 20% of the lipids
  - affects membrane fluidity (low concentration more rigid, high concentration more fluid)
- Glycolipids
  - 5% of the lipids
  - contribute to glycocalyx (carbohydrate coating on cell surface)
Membrane Proteins

- **Membrane proteins**
  - 2% of the molecules in plasma membrane
  - 50% of its weight

- **Transmembrane proteins**
  - pass completely through membrane
  - most are glycoproteins

- **Peripheral proteins**
  - adhere to membrane surface
  - anchored to cytoskeleton
Membrane Protein Functions

- Receptors, enzymes, channel proteins (gates), cell-identity markers, cell-adhesion molecules
Membrane Receptors

- Cell communication via chemical signals
  - receptors bind these chemicals (hormones, neurotransmitters)
  - receptor specificity
- Receptor activation produces a second messenger (chemical) inside of the cell
Second Messenger System

1. A messenger such as epinephrine (red triangle) binds to a receptor in the plasma membrane.
2. The receptor releases a G protein, which then travels freely in the cytoplasm and can go on to step 3 or have various other effects on the cell.
3. ATP binds to adenylate cyclase in the plasma membrane. Adenylate cyclase converts ATP to cyclic AMP (cAMP), the second messenger.
4. cAMP activates a cytoplasmic enzyme called a kinase.
5. Kinases add phosphate groups (P) to other cytoplasmic enzymes. This activates some enzymes and deactivates others, leading to varied metabolic effects in the cell.
Second Messenger System

- Chemical messenger (epinephrine) binds to a surface receptor
- Receptor activates G protein
- G protein binds to adenylate cyclase which converts ATP to cAMP (2nd messenger)
- cAMP activates a kinase in the cytosol
- Kinases phosphorylate (activate) proteins triggering physiological changes in cell
Membrane Enzymes

- Break down chemical messengers to stop their signaling effects
- Final stages of starch and protein digestion in small intestine
- Produce second messengers (cAMP)
Membrane Channel Proteins

• Transmembrane proteins with pores
  – some constantly open
  – gated-channels open and close in response to stimuli
    • ligand (chemically)-regulated gates
    • voltage-regulated gates
    • mechanically regulated gates (stretch and pressure)

• Important in nerve signal and muscle contraction
Membrane Carriers or Pumps

• Transmembrane proteins bind to solutes and transfer them across membrane

• Pumps = carriers that consume ATP
Membrane Cell-Adhesion Molecules

- Hold cells together in tissues
- Normal development
- Fertilization
- Growth of nervous system
- Immune response
Membrane Cell-Identity Markers

- Glycoproteins form the glycocalyx
  - surface coating
  - acts as a cell’s identity tag
- Enables body to identify “self” from foreign invaders
Glycocalyx

• Unique fuzzy cell surface
  – carbohydrate portions of membrane glycoproteins and glycolipids
  – unique in everyone but identical twins

• Functions (see Table 3.2)
  – cell recognition, adhesion and protection
Microvilli

• Extensions of membrane (1-2μm)
• Some contain actin
• Function
  – increase surface area for absorption
    • brush border
  – milking action of actin
    • actin filaments shorten microvilli
      – pushing absorbed contents down into cell
Cross Section of a Microvillus

Note: actin microfilaments are found in center of each microvilli.
Cilia

- **Hairlike processes 7-10µm long**
  - single, nonmotile cilium found on nearly every cell
  - Sensory in inner ear, retina and nasal cavity

- **Motile cilia**
  - beat in waves
  - power strokes followed by recovery strokes

Chloride pumps produce saline layer at cell surface. Floating mucus pushed along by cilia.
Cross Section of a Cilium

- Axoneme has 9 + 2 structure of microtubules
  - 9 pairs form basal body inside the cell membrane
  - dynein arms “crawls” up adjacent microtubule bending the cilia
Cystic Fibrosis

- Hereditary disease
  - chloride pumps fail to create adequate saline layer under mucus
- Thick mucus plugs pancreatic ducts and respiratory tract
  - inadequate absorption of nutrients and oxygen
  - lung infections
  - life expectancy of 30
Flagella

• Whiplike structure with axoneme identical to cilium
  – much longer than cilium

• Tail of the sperm = only functional flagellum
Membrane Transport

• Plasma membrane selectively permeable
  – controls what enters or leaves cell

• Passive transport requires no ATP
  – movement down concentration gradient
  – filtration and simple diffusion

• Active transport requires ATP
  – movement against concentration gradient
  – carrier mediated (facilitated diffusion and active transport)
  – vesicular transport
Filtration

• Movement of particles through a selectively permeable membrane by hydrostatic pressure

• Examples
  – filtration of nutrients from blood capillaries into tissue fluids
  – filtration of wastes from the blood in the kidneys
Simple Diffusion

• Net movement of particles from area of high concentration to area of low concentration
  – due to their constant, random motion

• Also known as movement down the concentration gradient
Diffusion Rates

• Factors affecting diffusion rate through a membrane
  – temperature - ↑ temp., ↑ motion of particles
  – molecular weight - larger molecules move slower
  – steepness of concentrated gradient - ↑ difference, ↑ rate
  – membrane surface area - ↑ area, ↑ rate
  – membrane permeability - ↑ permeability, ↑ rate
Membrane Permeability

• Diffusion through lipid bilayer
  – Nonpolar, hydrophobic substances diffuse through lipid layer

• Diffusion through channel proteins
  – Water and charged hydrophilic solutes diffuse through channel proteins

• Cells control permeability by regulating number of channel proteins
Osmosis

- Diffusion of water through a membrane
  - from area of more water to area of less water
- Aquaporins = channel proteins specialized for osmosis
Osmotic Pressure

- Amount of hydrostatic pressure required to stop osmosis
- Osmosis slows due to filtration of water back across membrane due to ↑ hydrostatic pressure
Osmolarity

• One osmole = 1 mole of dissolved particles
  – 1M NaCl (1 mole Na\(^+\) ions + 1 mole Cl\(^-\) ions) thus 1M NaCl = 2 osm/L
• Osmolarity = # osmoles/liter of solution
• Physiological solutions are expressed in milliosmoles per liter (mOsm/L)
  – blood plasma = 300 mOsm/L
  – osmolality similar to osmolarity at concentration of body fluids
Tonicity

- Tonicity - ability of a solution to affect fluid volume and pressure within a cell
  - depends on concentration and permeability of solute
- Hypotonic solution
  - low concentration of nonpermeating solutes (high water concentration)
  - cells absorb water, swell and may burst (lyse)
- Hypertonic solution
  - has high concentration of nonpermeating solutes (low water concentration)
  - cells lose water + shrivel (crenate)
- Isotonic solution = normal saline
Effects of Tonicity on RBCs

Hypotonic, isotonic and hypertonic solutions affect the fluid volume of a red blood cell. Notice the crenated and swollen cells.
Carrier Mediated Transport

• Proteins carry solutes across cell membrane

• Specificity
  – solute binds to a specific receptor site on carrier protein
  – differs from membrane enzymes because solutes are unchanged

• Types of carrier mediated transport
  – facilitated diffusion and active transport
Membrane Carrier Saturation

- **Transport maximum = transport rate when all carriers are occupied**
Membrane Carriers

• Uniporter
  – carries only one solute at a time

• Symporter
  – carries 2 or more solutes simultaneously in same direction (cotransport)

• Antiporter
  – carries 2 or more solutes in opposite directions (countertransport)
    • sodium-potassium pump brings in K\(^+\) and removes Na\(^+\) from cell

• Any carrier type can use either facilitated diffusion or active transport
Facilitated Diffusion

- Transport of solute across membrane down its concentration gradient
- No ATP used
- Solute binds to carrier, it changes shape then releases solute on other side of membrane
Active Transport

- Transport of solute across membrane up (against) its concentration gradient
- ATP energy required to change carrier
- Examples:
  - sodium-potassium pump
  - bring amino acids into cell
  - pump $\text{Ca}^{2+}$ out of cell
Sodium-Potassium Pump

- Needed because Na\(^+\) and K\(^+\) constantly leak through membrane
  - half of daily calories utilized for pump
- One ATP utilized to exchange three Na\(^+\) pushed out for two K\(^+\) brought in to cell
Functions of Na\(^+\) -K\(^+\) Pump

- Regulation of cell volume
  - “fixed anions” attract cations causing osmosis
  - cell swelling stimulates the Na\(^+\)-K\(^+\) pump to ↓ ion concentration, ↓ osmolarity and cell swelling

- Heat production (thyroid hormone increase # of pumps; heat a by-product)

- Maintenance of a membrane potential in all cells
  - pump keeps inside negative, outside positive

- Secondary active transport (No ATP used)
  - steep concentration gradient of Na\(^+\) and K\(^+\) maintained across the cell membrane
  - carriers move Na\(^+\) with 2\(^{nd}\) solute easily into cell
    - SGLT saves glucose in kidney
Vesicular Transport

- Transport large particles or fluid droplets through membrane in vesicles
  - uses ATP
- Exocytosis – transport out of cell
- Endocytosis – transport into cell
  - phagocytosis – engulfing large particles
  - pinocytosis – taking in fluid droplets
  - receptor mediated endocytosis – taking in specific molecules bound to receptors
Phagocytosis or “Cell-Eating”

Keeps tissues free of debris and infectious microorganisms.
Pinocytosis or “Cell-Drinking”

• Taking in droplets of ECF
  – occurs in all human cells
• Membrane caves in, then pinches off into the cytoplasm as pinocytotic vesicle
Transcytosis

- Transport of a substance across a cell
- Receptor mediated endocytosis moves it into cell and exocytosis moves it out the other side
  - insulin
Receptor Mediated Endocytosis

1. Extracellular molecules bind to receptors on plasma membrane; receptors cluster together.
2. Plasma membrane sinks inward, forms clathrin-coated pit.
3. Pit separates from plasma membrane, forms clathrin-coated vesicle containing concentrated molecules from ECF.
Receptor Mediated Endocytosis

- Selective endocytosis
- Receptor specificity
- Clathrin-coated vesicle in cytoplasm
  - uptake of LDL from bloodstream
Exocytosis

- Secreting material or replacement of plasma membrane

1. A secretory vesicle approaches the plasma membrane and docks on it by means of linking proteins. The plasma membrane caves in at that point to meet the vesicle.

2. The plasma membrane and vesicle unite to form a fusion pore through which the vesicle contents are released.
The Cytoplasm

• Organelles = specialized tasks
  – bordered by membrane
    • nucleus, mitochondria, lysosome, peroxisome, endoplasmic reticulum, and Golgi complex
  – not bordered by membrane
    • ribosome, centrosome, centriole, basal bodies

• Cytoskeleton
  – microfilaments and microtubules

• Inclusions
  – stored products
Nucleus

• Largest organelle (5 \( \mu \text{m} \) in diameter)
  – some anuclear or multinucleate

• Nuclear envelope
  – two unit membranes held together at nuclear pores

• Nucleoplasm
  – chromatin (thread-like matter) = DNA and protein
  – nucleoli = dark masses where ribosomes produced
Micrograph of The Nucleus

(a) Interior of nucleus
2 μm

(b) Surface of nucleus
1.5 μm

Nucleolus
Nucleoplasm
Nuclear envelope
Nuclear pores
Rough Endoplasmic Reticulum

- Parallel, flattened membranous sacs covered with ribosomes
- Continuous with nuclear envelope and smooth ER
- Synthesis of packaged proteins (digestive glands) and phospholipids and proteins of plasma membrane
Smooth Endoplasmic Reticulum

- Lack ribosomes
- Cisternae more tubular and branching
- Synthesis of membranes, steroids (ovary and testes) and lipids, detoxification (liver and kidney), and calcium storage (skeletal and cardiac muscle)
Smooth and Rough ER
Endoplasmic Reticulum

- Cisternae of rough ER
- Nucleus
- Ribosomes of rough ER
- Oil droplet (inclusion)
- Smooth endoplasmic reticulum
Ribosomes

• Granules of protein and RNA
  – found in nucleoli, free in cytosol and on rough ER

• Uses directions in messenger RNA to assemble amino acids into proteins specified by the genetic code (DNA)
Golgi Complex

- System of flattened sacs (cisternae)
- Synthesizes carbohydrates, packages proteins and glycoproteins
- Forms vesicles
  - lysosomes
  - secretory vesicles
  - new plasma membrane
Golgi Complex
Lysosomes

• Package of enzymes in a single unit membrane, variable in shape

• Functions
  – intracellular digestion of large molecules
  – autophagy - digestion of worn out organelles
  – autolysis - programmed cell death
  – breakdown stored glycogen in liver to release glucose
Lysosomes and Peroxisomes

(a) Lysosomes

(b) Peroxisomes

Mitochondria
Lysosomes
Golgi complex

Peroxisomes
Smooth ER

1 μm
0.3 μm
Peroxisomes

- Resemble lysosomes but contain different enzymes
- In all cells but abundant in liver and kidney
- Functions
  - neutralize free radicals, detoxify alcohol, other drugs and toxins
  - uses $O_2$, $H_2O_2$ and catalase enzyme to oxidize organic molecules
  - breakdown fatty acids into acetyl groups for mitochondrial use
Mitochondrion

- Double unit membrane
  - inner membrane folds called cristae
    - ATP synthesized by enzymes on cristae from energy extracted from organic compounds
- Space between cristae called matrix
  - contains ribosomes and small, circular DNA molecule (mtDNA)
EM of Mitochondrion
Evolution of Mitochondrion

• Evolved from bacteria that invaded primitive cell but was not destroyed
• Double membrane formed from bacterial membrane and phagosome
• Has its own mtDNA
  – mutates readily causing degenerative diseases
    • mitochondrial myopathy and encephalomyopathy
• Only maternal mitochondria inherited (from the egg)
  – sperm mitochondria usually destroyed inside egg
Centrioles

• Short cylindrical assembly of microtubules (nine groups of three)

• Two perpendicular centrioles near nucleus form an area called the centrosome
  – role in cell division

• Cilia formation
  – single centriole migrates to plasma membrane to form basal body of cilia or flagella
  – two microtubules of each triplet elongate to form the nine pairs of the axoneme
  – cilium reaches full length rapidly
Centrioles
Cytoskeleton

- Collection of filaments and tubules
  - provide support, organization and movement
- Composed of
  - microfilaments = actin
    - form network on cytoplasmic side of plasma membrane called the membrane skeleton
      - supports phospholipids and microvilli and produces cell movement
  - intermediate fibers
    - help hold epithelial cells together; resist stresses on cells; line nuclear envelope; toughens hair and nails
  - microtubules
Microtubules

• Cylinder of 13 parallel strands called protofilaments
  – (a long chain of globular protein called tubulin)
• Hold organelles in place; maintain cell shape; guide organelles inside cell
• Form axonemes of cilia and flagella, centrioles, basal bodies and mitotic spindle
• Can be disassembled and reassembled
Cytoskeleton
EM and Fluorescent Antibodies demonstrate Cytoskeleton
Inclusions

• No unit membrane
• Stored cellular products
  – glycogen granules, pigments and fat droplets
• Foreign bodies
  – dust particles, viruses and intracellular bacteria
Table 3.4

• Summary of organelles: their appearance and function

<table>
<thead>
<tr>
<th>Structure</th>
<th>Appearance to TEM</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma membrane</td>
<td>Two dark lines at cell surface, separated by narrow light space</td>
<td>Prevents escape of cell contents; regulates exchange of materials between cytoplasm and extracellular fluid; involved in intercellular communication</td>
</tr>
<tr>
<td>Microvilli (fig. 3.10)</td>
<td>Short, densely-spaced, hairlike processes or scattered bumps on cell surface; interior featureless or with bundle of microfilaments</td>
<td>Increase absorptive surface area; some sensory roles (hearing, equilibrium, taste)</td>
</tr>
<tr>
<td>Cilia (fig. 3.1)</td>
<td>Long hairlike projections of apical cell surface, awneme with 9 + 2 array of microtubules</td>
<td>Move substances along cell surface; some sensory roles (hearing, equilibrium, smell, vision)</td>
</tr>
<tr>
<td>Flagellum</td>
<td>Long, single, whiplike process with awneme</td>
<td>Sperm motility</td>
</tr>
<tr>
<td>Nucleus (figs. 3.3 and 3.21)</td>
<td>Largest organelle in most cells, surrounded by double unit membrane with nuclear pores</td>
<td>Genetic control center of cell directs protein synthesis</td>
</tr>
<tr>
<td>Rough ER (fig. 3.26a)</td>
<td>Extensive sheets of parallel unit membranes with ribosomes on outer surface</td>
<td>Protein synthesis and manufacture of cellular membranes</td>
</tr>
<tr>
<td>Smooth ER (fig. 3.26b)</td>
<td>Branching network of tubules with smooth surface (no ribosomes); usually broken into numerous small segments in TEM photos</td>
<td>Lipid synthesis, detoxification, calcium storage</td>
</tr>
<tr>
<td>Ribosomes (fig. 3.26a)</td>
<td>Small dark granules free in cytoplasm or on surface of rough ER</td>
<td>Interpret the genetic code and synthesize polypeptides</td>
</tr>
<tr>
<td>Golgi complex (fig. 3.27)</td>
<td>Several closely-spaced, parallel cisternae with thick edges, usually near nucleus, often with many Golgi vesicles nearby</td>
<td>Resolves and modifies newly synthesized polypeptides, synthesizes carbohydrates, adds carbohydrates to glycoproteins; packages cell products into Golgi vesicles</td>
</tr>
<tr>
<td>Golgi vesicles (fig. 3.27)</td>
<td>Round to irregular sacs near Golgi complex, usually with slight, texturally content</td>
<td>Become secretory vesicles and carry cell products to apical surface for exocytosis, or become lysosomes</td>
</tr>
<tr>
<td>Lysosomes (fig. 3.28a)</td>
<td>Round to ovoid sacs with single unit membrane, often a dark featureless interior but sometimes with protein layers or crystals</td>
<td>Contain enzymes for intracellular digestion, autophagy, programmed cell death, and glucose mobilization</td>
</tr>
<tr>
<td>Peroxisomes (fig. 3.28b)</td>
<td>Similar to lysosomes, often lighter in color</td>
<td>Contain enzymes for detoxification of free radicals, alcohol, and other drugs; oxidize fatty acids</td>
</tr>
<tr>
<td>Mitochondria (fig. 3.29)</td>
<td>Round, rod-shaped, bean-shaped, or threadlike structures with double unit membrane and shelflike infoldings called cristae</td>
<td>ATP synthesis</td>
</tr>
<tr>
<td>Centrioles (fig. 3.33)</td>
<td>Short cylindrical bodies, each composed of a circle of nine triplets of microtubules</td>
<td>Form mitotic spindle during cell division; unpaired centrioles form basal bodies of cilia and flagella</td>
</tr>
<tr>
<td>Centrosome (fig. 3.3)</td>
<td>Clear area near nucleus containing a pair of centrioles</td>
<td>Organizing center for formation of microtubules of cytoskeleton and mitotic spindle</td>
</tr>
<tr>
<td>Basal body (fig. 3.7b)</td>
<td>Unpaired centriole at the base of a cilium or flagellum</td>
<td>Point of origin, growth, and anchorage of a cilium or flagellum; produces axoneme</td>
</tr>
<tr>
<td>Microfilaments (figs. 3.31 and 3.32)</td>
<td>Thin protein filaments (6 nm diameter), often in parallel bundles or dense networks in cytoplasm</td>
<td>Support microvilli; involved in muscle contraction and other cell motility activities, and cell division</td>
</tr>
<tr>
<td>Intermediate filaments (fig. 3.3a)</td>
<td>Thicker protein filaments (8-10 nm diameter), extending throughout cytoplasm or concentrated at cell-to-cell junctions</td>
<td>Give shape and physical support to cell; anchor cells to each other and to extracellular matrix; compartmentalize cell contents</td>
</tr>
<tr>
<td>Microtubules (figs. 3.31 and 3.32)</td>
<td>Hollow protein cylinders (25 nm diameter)</td>
<td>Form axonemes of cilia and flagella, centrioles; basal bodies, and mitotic spindles; enable mobility of cell parts; direct organelles and macromolecules to their destinations within a cell</td>
</tr>
<tr>
<td>Inclusions (fig. 3.26b)</td>
<td>Highly variable—fat droplets, glycoprotein granules, protein crystals, dist, bacteria, viruses, never enclosed in unit membranes</td>
<td>Storage products or other products of cellular metabolism, or foreign matter retained in cytoplasm</td>
</tr>
</tbody>
</table>