Cell membrane structure and functions biology essay

A cell is a dynamic and a complex structure surrounded by a membrane known as the plasma membrane. This acts like a barrier between the inside of the cell and the outside resulting in different chemical environments on the two sides. The cell membrane is not restricted to the outer surface but is also present inside surrounding the organelles. These biological membranes have played a crucial role in the evolution from prokaryotes to multicellular eukaryotes. In prokaryotes, there is only one type of membrane present i. e. the plasma membrane but the unicellular eukaryotes have intracellular membranes compartmentalizing its contents into different functional chambers known as organelles. Each organelle though performs its own specific function, they cross-talk with each other via these membranes in order to work as a unit. Further, different cells in multicellular eukaryotes communicate with each other through these membranes.

The membrane, therefore serves a dual purpose of both protecting the interior of the cell from its external environment and also provides a communication interface between the cell and its surroundings or other cells. The diverse functions performed by biological membranes can be attributed to the molecular composition and structure of these membranes.

Models for Cell Membrane Structure

It took almost a century to develop the present accepted model of a cell membrane based on various physiological and biophysical studies. Physiological experiments involving the transport of molecules and ions across the membrane by Overton in 1899 suggested that the membrane is composed of lipid molecules. Later, Langmuir (1917) showed that lipids when spread on water using Langmuir trough form a monomolecular layer on the surface of the water by calculating the area per lipid molecule. The hydrophobic tails of these lipids were bent and protruding out from the surface of the water. When this method for measuring the area per lipid molecule was applied to the lipids extracted from the known amount of erythrocyte membranes, Gorter and Grendel (1925) concluded that the lipids exist as a bilayer and not a monolayer in a membrane giving birth to the lipid- bilayer membrane model.

In 1935, Danielli and Davson elaborated on the model based on the studies measuring the surface tension that membranes are made up of phospholipid bilayer sandwiched between two protein layers. Based on optical imaging of membrane morphology using electron microscopy, Robertson argued that the basic structure of all the membranes is same and proposed the ‘ Unit Membrane Model’ in 1959 []. Several other studies [review or book] suggested that the lipid bilayer has fluid-like properties with lipids and proteins floating in it. Studies of proteins present in erythrocytes membrane and that extracted from other membranes led Singer and Nicolson to classify membrane proteins as peripheral and integral proteins; and finally proposing the ‘ Fluid Mosaic Model’ in 1972 []. This is the most accepted model describing the structure of a cell membrane. According to this model, mosaic of protein molecules is embedded within the fluid of lipid bilayer which is supported by the freeze-fracture studies of the plasma membrane (Figure).

Composition of Membranes

Membrane Lipids

The lipid bilayer is only 5 to 10nm thick organized in distinct regions primarily attributed to the hydrophobic effect caused due to the amphipathic nature of these molecules with both polar and the non-polar regions (Figure). The interactions of these regions with the aqueous environment have been studied with various techniques like x-ray reflectometry,[1] neutron scattering[2] and nuclear magnetic resonance.

In order to exclude the non-polar regions from the aqueous environment, lipid molecules arrange in such a manner so that the hydrophobic tails point inwardly towards each other and the polar head groups are exposed on the outside facing the water. The outermost region on either side of the bilayer is completely hydrated and is typically around 8-9Å thick. The hydrophobic core of the bilayer is typically 3-4 nm thick. The intermediate region is partially hydrated and is approximately 3 Å thick.

These lipid molecules arrange spontaneously naturally or artificially in solution to form structures like micelles and liposomes (Figure). Micelles are monolayer spherical structures formed by lipid molecules in aqueous environment. On the other hand, liposomes are concentric bilayer of fluid-filled vesicles surrounding the water compartment on both the surfaces.

The membrane of the animal cells is composed primarily of three major types of lipids: phospholipids, glycolipids and cholesterol with phospholipids being the most abundant (Figure). The polar head groups of these phospholipids contain a phosphate group and either a glycerol (known as phosphoglycerides) or sphingosine. There are four major phospholipids present in the animal cells, three are phosphoglycerides namely phosphatidylcholine, phosphatidylethanolamine and phosphatidylserine; and the fourth sphingomyelin is the only sphingolipid. The heads of glycolipids contain a sphingosine with one (known as cerebroside) or more sugars (known as ganglioside) attached to it. Cholesterol is a sterol molecule with a small hydrophilic hydroxyl group and a rigid ring structure that stabilizes the bilayer.

Membrane Proteins

The membrane consists of different types of proteins accounting for 25-75% of the mass of the membrane and are categorized based on their interactions with the lipid bilayer (Figure). Moreover, the manner in which a protein is associated with the membrane is indicative of its function. Integral or intrinsic proteins are embedded with in the lipid bilayer. These could be transmembrane proteins spanning the entire length of the bilayer and possess hydrophobic domains which are anchored to hydrophobic lipids and hydrophilic domain interacting with external molecules. They could have only one membrane-spanning (single pass transmembrane proteins, e. g. glycophorin) or multispanning (multi-pass transmembrane proteins, e. g. band3 protein of erythrocyte) segments. The transmembrane segments have helical e. g. bacteriorhodopsin or Î²- barrel structures. These proteins can be extracted from the phospholipid bilayer only by disrupting the hydrophobic interactions by using detergents like SDS or Triton-X 100.

Peripheral or the extrinsic proteins, on the other hand, are loosely bound to the hydrophilic lipid and protein groups on the surface of the membrane by weak ionic interactions. These can be easily removed with high salt or extreme pH without disrupting the phospholipid bilayer. Lipid-anchored proteins are covalently bound to lipid molecule which in turn anchors the protein in the cell membrane. The lipid can be phosphatidylinositol, a fatty acid or a prenyl group.

Membrane Carbohydrates

Carbohydrate moieties are present on the non-cytoplasmic surface of the membrane covalently attached to either protein or lipid molecules forming glycoproteins or glycolipids. These carbohydrates help in orientation of protein molecules on the cell surface and sorting in cellular compartments. The glycocalyx or the cell coat is the layer of carbohydrates on the cell surface that protects it and participates in the cell-cell interaction. The carbohydrates of the glycolipids of the erythrocytes membrane determine the ABO blood groups in human.

Fluidity of Membranes

Under physiological conditions, phospholipid molecules in the membrane are in the liquid crystalline state and the molecules are not physically attached to each other so, they can move within the bilayer. These movements could be within a monolayer i. e. rotational and lateral or between two layers i. e. flip-flop. Flip-flop movements are rare and slower compared to the other two as it requires energy for a lipid molecule to traverse from one layer to the other. Besides, some proteins also move in the membrane as concluded from studies based on human-mouse cell hybrids produced by fusion of human and mouse cells [Frye and Michael Edidin in 1970] and FRAP (fluorescence recovery after photobleaching) experiments (Figure).

Fluidity in the cell membrane is attributed to its lipid composition. The cis-unsaturated fatty acids with kinks in their hydrocarbon tails and shorter lengths of the tails increase the fluidity by preventing the ordered packing of phospholipids in the bilayer. Cholesterol molecules present in the bilayer affects its fluidity differently at different temperatures because of its rigid ring structure. It reduces the fluidity by decreasing the movement of adjacent phospholipids but at low temperatures, it increases the fluidity by preventing solidification [Alberts].

Fluidity of the membrane allows different molecules like proteins to interact with each other to perform various processes like transport of molecules and cell signalling. Moreover, membrane fluidity is required for various cellular processes like cell movement and cell division.

Asymmetry of Membranes

The two leaflets, that is, the inner and the outer monolayer portions of the lipid bilayer differ in their physical and chemical properties. This is due to the asymmetric organization of the various components of the membrane. For example, glycolipids and glycoproteins are always present on the non-cytoplasmic surface of the plasma membrane. Membrane regions differ in their lipid composition. The outer leaflet contains predominantly phosphatidylcholine and sphingomyelin whereas, the inner leaflet contains phosphatidylethanolamine and phosphatidylserine. The inner leaflet also consists of phosphatidylinositol which play a key role in the transfer of stimuli from the plasma membrane to the cytoplasm [Cooper]. The membrane proteins also differ in their distribution in the two leaflets. For example, spectrin and ankyrin are present on the inner surface of the erythrocytes membrane forming a fibrillar membrane skeleton. GPI-anchored proteins ar present on the external surface of the membrane. The asymmetry of the membrane suggested different roles played by the components of the membrane present on the two surfaces (Figure eg intestinal epithelial cell membrane: Tight junction , lateral movements).

Lipid Rafts

The plasma membrane of eukaryotic cells have specialized regions known as lipid rafts which differ in their composition from the rest of the membrane. These detergent-resistant and heterogeneous microdomains are rich in cholesterol, sphingolipids and certain proteins. Lipids in these rafts are more highly ordered and tightly packed as compared to the rest of the lipid bilayer. Various studies have attributed diverse roles like in transport of cholesterol, endocytosis, signal transduction, intracellular trafficking and neural development and function to these lipid rafts. Caveolae is an example of lipid rafts which are the invaginated domains in the plasma membrane. In caveolae, a protein caveolin is associated with the cholesterol in the lipid raft. It plays roles in membrane internalization and cell signaling. [Pike et al, 2002; Wary et al, 1998; Huang et al, 1999; Rothberg et al, 1992] (Review: Razani & Lisanti, 2001. Exp. Cell Research 271: 36-44).

Might not in endocytosis [Thompsen et al, 2002] see lipid rafts 4 references

Functions of membranes:

Membranes act as boundaries between the cell and its environment and are essential for maintaining the integrity of the cell and the various membrane-bound organelles within the cell, regulating the transport of materials into and out of the cell, responding to external and internal stimuli, and cell-to-cell recognition.

The proteins present on the inner surface of the plasma membrane provides shape and maintains the integrity of the cell by anchoring the cytoskeleton found underlying the cell membrane in the cytoplasm. The major component of the cytoskeleton of the most well studied erythrocyte membrane is the fibrous protein spectrin. This protein interacts with other peripheral proteins like ankyrin, actin and tropomyosin. Dystophin, a member of the spectrin family is found in the membrane skeleton of muscle cells. The importance of these proteins is suggested by the fact that mutations in dystrophin leads to muscular dystrophy.

Regulated transport of materials across the membrane is due to the amphipathic nature of the lipid bilayer. Therefore, the membranes are selectively permeable and the ability of a molecule or ion to traverse the bilayer depends majorly on its polarity and also on the size. Non-polar molecules like O2, N2 and benzene and small polar molecules like H2O, glycerol, urea and CO2 can pass the membrane but large uncharged (e. g. glucose), polar molecules (e. g. sucrose) and ions (e. g. H+, Na+, HCO3, Clâ€‘) are not able to diffuse easily across membranes. Hence, various mechanisms are required for transport of materials across the membrane, including simple diffusion, facilitated diffusion and active transport for micromolecules and exocytosis and endocytosis for macromolecules.

In simple diffusion, substances diffuse down their concentration gradient. In facilitated diffusion, movement of molecules down the concentration gradient is facilitated by channel and carrier proteins (e. g. glucose transporter). On the other hand, active transport requires energy to move solutes against their gradients and can be classified into primary or secondary active transport depending on the source of energy. The primary active transport depends on the hydrolysis of ATP and is of different types: P (e. g. Na+ – K+ ATPase, Figure), F and V types and the ATP-binding cassette or ABC transporters. In secondary active transport, specific solute indirectly drives the active transport of another solute and does not involve the hydrolysis of ATP. Secondary active transport may include either symport (e. g. Na+/Glucose transporter) or antiport (Cl-/HCO3 exchanger). The macromolecules such as proteins and polysaccharides are transported by endocytosis (from inside the cell to the outside) and exocytosis (from outside into the cell) (Figure).

Cell membrane is also involved in cell-cell communication. Specialized membrane structures like gap junctions in animals and plasmodesmata in plants provide the cytoplasmic continuity between cells. Tight junctions and desmosomes help in attachment of a cell to other cells or the extracellular matrix forming tissues.

Membrane also maintains cell potential by creating chemical and electrical gradient.

Cell signaling: Signals through chemical messengers (chemical or electrical stimuli) acting on the membrane receptors most of them being proteins. These signals are then transduced in the cell leading to a cascade of events in the cell. Specific for different cells like Gprotein, Tyrosine-kinase receptors

Peripheral proteins act as enzymes e. g. and receptors

In summary, biological membranes are the complex and dynamic structures composed of variety of proteins embedded in the fluid of the lipid bilayer. The amphipathic nature of the lipid bilayer and the diversity of membrane proteins are responsible for the involvement of biological membranes in large number of cellular processes.

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