ISSN:3030-332X
Impact factor: 9,493
International journal of scientific researchers

STRUCTURAL AND BIOPHYSICAL PROPERTIES OF BIOLOGICAL MEMBRANES AND THEIR PHYSIOLOGICAL MECHANISMS IN MAINTAINING CELLULAR HOMEOSTASIS

Doliyev Ahmadjon Ulugbek ugli
Student, Faculty of Medicine,
Asia International University
E-mail: ahmadjondoliyev@gmail.com

Narzullayeva Malika Shuxratovna
Scientific supervisor:
Assistant, Department of Fundamental Medicine,
Asia International University
E-mail: mnarzullayeva1@icloud.com
https://doi.org/10.5281/zenodo.23799129

ABSTRACT

This article analyzes the structural and biophysical properties of biological membranes and their role in maintaining cellular homeostasis. The aim of the study is to describe the homeostatic functions of the lipid bilayer, the fluid mosaic model, membrane fluidity, permeability, and ion transport mechanisms. A systematic literature review was conducted using international scientific databases (PubMed, NCBI Bookshelf, ScienceDirect) and classical works (Singer and Nicolson, 1972; Alberts et al.). The main findings indicate that membrane lipid composition, asymmetry, and biophysical parameters (fluidity, thickness, and dielectric properties) directly regulate the activity of ion channels, Na^+/K^+-ATPase, and other transporters. These mechanisms maintain ion gradients, osmotic balance, calcium homeostasis, and signaling. In conclusion, biological membranes are not passive barriers but dynamic homeostatic systems, and their dysfunction may lead to various pathologies. The findings provide a theoretical basis for the fields of membranology, physiology, and biomedicine.

Keywords: biological membrane, lipid bilayer, fluid mosaic model, membrane fluidity, ion channels, Na^+/K^+-ATPase, cellular homeostasis, selective permeability

INTRODUCTION

The cell is the basic structural and functional unit of living organisms. Its interaction with the external environment, the stability of its internal environment (homeostasis), and the coordination of metabolic processes are directly mediated by biological membranes. The plasma membrane and organelle membranes separate the cell from the external environment while ensuring the selective transport of ions, nutrients, signaling molecules, and metabolites. In the second half of the twentieth century, views on membrane structure changed fundamentally. The fluid mosaic model proposed by Singer and Nicolson in 1972 remains a major theoretical framework today. According to this model, the membrane consists of a lipid bilayer in which proteins move freely. Subsequent studies revealed lipid rafts (domains), lipid asymmetry, interactions with cytoplasmic proteins, and mechanisms of active membrane remodeling. Cellular homeostasis is the process of maintaining stable concentrations of ions, pH, osmotic pressure, metabolite levels, and other parameters. Membranes play a central role in this process. Through ion channels, pumps (especially Na^+/K^+-ATPase), transporters, and receptors, the membrane protects the internal environment from external influences. Membrane biophysics—fluidity, thickness, elasticity, and dielectric properties—

determines the efficiency of these processes. The relevance of this study lies in the association between impaired membrane properties and many diseases, including neurodegenerative, cardiovascular, and metabolic disorders. The aim of this article is to analyze the structural and biophysical properties of biological membranes and describe their physiological mechanisms for maintaining cellular homeostasis. The research question is: how do membrane structure and biophysics regulate homeostatic processes? The literature review was based on classical and contemporary sources.

METHODS

The object of the study is the structural and biophysical properties of biological membranes and their homeostatic functions. The subject is the relationship between the lipid bilayer, proteins, ion transport mechanisms, and homeostasis.

Methods: systematic literature review. Data were collected from the following sources:

- PubMed, NCBI Bookshelf, ScienceDirect, Google Scholar; - Classical works: Singer and Nicolson (1972), Alberts et al. (Molecular Biology of the Cell, 6th edition, 2014); - Contemporary reviews: Ernst et al. (2018), Levental et al. (2020–2022), Watson (2015). Search keywords: “biological membranes structure,” “fluid mosaic model,” “membrane fluidity,” “ion transport homeostasis,” “Na/K ATPase,” and “membrane biophysics.” Inclusion criteria: peer-reviewed articles, works published between 1972 and 2024, and sources in English and Russian. Exclusion criteria: reviews devoted solely to clinical practice and lacking experimental data. Analysis method: qualitative content analysis, comparison and synthesis of key concepts. Results were presented using tables and schematic explanations. RESULTS 1. Structural organization. Biological membranes consist mainly of lipids (40–50%), proteins (40–50%), and carbohydrates (5–10%). Phospholipids (phosphatidylcholine, phosphatidylethanolamine, phosphatidylserine, and sphingomyelin), glycolipids, and cholesterol are the main lipid components. Phospholipids are amphiphilic, with a hydrophilic “head” and a hydrophobic “tail.” In an aqueous environment, they spontaneously form a bilayer (approximately 4–5 nm thick). According to the model of Singer and Nicolson (1972), the membrane is a “fluid mosaic”: lipids move like a two-dimensional fluid, integral proteins are embedded in the bilayer, and peripheral proteins are attached to its surface. Lipid asymmetry is important: phosphatidylcholine and sphingomyelin predominate in the outer layer, while phosphatidylethanolamine and phosphatidylserine predominate in the inner layer. This asymmetry is maintained by flippases, floppases, and scramblases. Current evidence indicates that membranes have a “mosaic” structure containing lipid rafts (domains rich in cholesterol and sphingolipids). 2. Biophysical properties. - Fluidity: Lipids undergo lateral diffusion (coefficient approximately 10^{-8}–10^{-7} cm^2/s). Flip-flop movement is slow. Fluidity depends on temperature, fatty acid saturation, and cholesterol content. Unsaturated fatty acids increase fluidity, while cholesterol acts as a “buffer.” - Permeability: Permeability is high for hydrophobic molecules (O_2, CO_2, steroids) and low for ions and polar molecules. - Phase transitions: Transition from the gel (Lβ) state to the liquid-crystalline (Lα) state. - Electrical properties: Membrane capacitance is approximately 1 $\mu F/cm^2$; the potential is usually −40 to −90 mV. 3. Homeostatic mechanisms. Passive transport: simple and facilitated diffusion (through ion channels). Active transport: Na^+/K^+-ATPase (3 Na^+ out, 2 K^+ in), Ca^{2+}-ATPase, and H^+-ATPase. Secondary active transport: symport and antiport. Calcium homeostasis: approximately 100 nM in the cytoplasm and approximately 1 mM outside the cell; maintained by SERCA and plasma membrane pumps. Volume and osmotic balance: maintained through aquaporins and ion pumps. Signaling: involves membrane receptors and lipid rafts. The results show that membrane biophysics and transport mechanisms interact to maintain homeostasis. DISCUSSION The findings support the classical fluid mosaic model while substantially expanding it. Whereas the Singer and Nicolson (1972) model viewed lipids as a passive “solvent,” contemporary studies

(Ernst et al., 2018; Levental et al.) consider the membrane an active homeostatic system. Lipid rafts and asymmetry localize signaling and transport processes.

Na^+/K^+-ATPase maintains not only ion gradients but also cell volume and osmotic balance. Disruption of calcium homeostasis triggers apoptotic and necrotic processes. Changes in membrane fluidity (for example, an increase in unsaturated fatty acids) affect protein conformation and alter the activity of channels and pumps. Compared with earlier studies, homeoviscous adaptation (adaptation to temperature) is also present in eukaryotes, although it is more complex and occurs through lipidome remodeling. Altered membrane properties are observed in Alzheimer's disease, Parkinson's disease, diabetes, and heart disease. This highlights the potential of lipid-based therapies and ion-channel modulators. The discussion indicates that membrane homeostasis is a multilevel process involving molecular (lipid–protein interactions), ultrastructural (domains), and cellular (transport and signaling) levels.

CONCLUSION

Biological membranes are a central element of cellular homeostasis. Their structural organization (lipid bilayer, proteins, and asymmetry) and biophysical properties (fluidity, permeability, and electrical parameters) determine the activity of ion channels, pumps, and transporters. Ion gradients, osmotic balance, and signaling are maintained through Na^+/K^+-ATPase, calcium pumps, and selective channels. The findings show that the membrane is not a passive barrier but a dynamic, adaptable homeostatic system. Practical implications: targeted modification of membrane properties (regulation of lipid composition and use of ion-channel modulators) may open up new approaches in biomedicine. Future directions include further investigation of membrane homeostasis using lipidomics, green fluorescence microscopy, and computer modeling.

REFERENCES

1. Singer S.J., Nicolson G.L. The fluid mosaic model of the structure of cell membranes // Science. – 1972. – Vol. 175, No. 4023. – pp. 720–731.
2. Alberts B., Johnson A., Lewis J., Morgan D., Raff M., Roberts K., Walter P. Molecular Biology of the Cell. 6th ed. – New York: Garland Science, 2014. – 1464 pp.
3. Cooper G.M. The Cell: A Molecular Approach. 2nd ed. – Sunderland: Sinauer Associates, 2000 (NCBI Bookshelf).
4. Ernst R., Ballweg S., Levental I. Cellular mechanisms of physicochemical membrane homeostasis // Current Opinion in Cell Biology. – 2018. – Vol. 53. – pp. 44–51.
5. Watson H. Biological membranes // Essays in Biochemistry. – 2015. – Vol. 59. – pp. 43–69.
6. Levental K.R., Levental I. et al. Lipidomic and biophysical homeostasis of mammalian membranes // Nature Reviews Molecular Cell Biology (related works, 2020–2022).
7. Keener J., Sneyd J. Mathematical Physiology. I: Cellular Physiology. – Springer, 2009. – Chapter 2.
8. Gennis R.B. Biomembranes: Molecular Structure and Function. – New York: Springer-Verlag, 1989 (Russian translation: Gennis R. Biomembranes. – Moscow: Mir, 1997).
9. Rubin A.B. Biophysics. 3rd ed. – Moscow: Moscow State University, 2004.
10. Shaw T.R., Ghosh S., Veatch S.L. Critical Phenomena in Plasma Membrane Organization and Function // Annual Review of Physical Chemistry. – 2020. – Vol. 72. – pp. 51–72.
11. StatPearls. Physiology, Membrane. – Treasure Island: StatPearls Publishing, 2023 (NCBI Bookshelf).
12. OpenStax. Anatomy and Physiology / Biology. – Houston: OpenStax, 2013–2024.