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Cell membrane causes the lipid bilayers to behave as variable capacitors: A resonance with self-induction of helical proteins

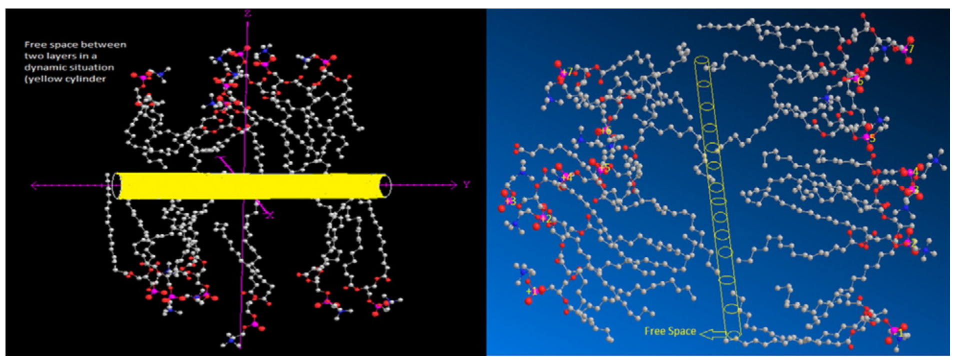
Majid Monajjemi

Department of Chemistry, Science and Research Branch, Islamic Azad University, Tehran, Iran

HIGHLIGHTS

- Cell membrane variable capacitor and self-induction of helical proteins
- The resonance of which is the main reason for biological pulses
- The quantum tunneling is allowed in some micro positions while it is forbidden in other forms.

GRAPHICAL ABSTRACT



"Free space between two layers in a dynamic situation"

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ABSTRACT

Cell membrane has a unique feature of storing biological energies in a physiologically relevant environment. This study illustrates a capacitor model of biological cell membrane including DPPC structures. The electron density profile models, electron localization function (ELF) and local information entropy have been applied to study the interaction of proteins with lipid bilayers in the cell membrane. The quantum and coulomb blockade effects of different thicknesses in the membrane have also been specifically investigated. It has been exhibited the quantum effects can appear in a small region of the free space within the membrane thickness due to the number and type of phospholipid layers. In addition, from the viewpoint of quantum effects by Heisenberg rule, it is shown the quantum tunneling is allowed in some micro positions while it is forbidden in other forms of membrane capacitor systems. Due to the dynamical behavior of the cell membrane, its capacitance is not fixed which results a variable capacitor. In presence of the external fields through protein trance membrane or ions, charges exert forces that can influence the state of the cell membrane. This causes to appear the charge capacitive susceptibility that can resonate with self-induction of helical coils; the resonance of which is the main reason for various biological pulses.

1. Introduction

All capacitors are formed with the same fundamental structure in both classical and quantum circumstances. When a voltage appears between two electrodes of a capacitor, an electric field is created in the dielectric which results in the storage of electrical energy in order to produce a mechanical force between the electrodes. In a variable capacitor, the capacitance can be intentionally and repeatedly changed, either mechanically or electronically. Variable capacitors are often used in L/C circuits to set the resonance frequency (e.g. to tune a radio) or as a variable reactance (e.g. for impedance matching in antenna tuners).

E-mail address: m_monajjemi@srbiau.ac.ir.

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The composition of a cell membrane can directly affect its function, including membrane permeability, cell signaling, and cell capacitance [1–3]. The lipid section of the membrane has various barrier functions such as preventing most of the molecules and ions from crossing in or out. The membrane is covered on both sides by collection of charged dissolved minerals with a similar function as a conducting metal plate.

The exterior cell membrane such as mitochondria in mammals and chloroplasts in plants has the capacity to accumulate and store charge in order to produce energy. Since the required energy for running any type of machinery is mechanical or biological, it seems reasonable for the nutrients that can enhance energy production and energy storage, to have profound biological effects.

Many studies on the lipid membrane have been carried out in order to explore properties such as cholesterol's impact, heat capacity changes due to increasing salt concentration and correlative lipid motion during diffusions, thickness fluctuations and bilayer undulations [1–4]. Local interactions of membrane proteins and lipids as well as the effect of fluorescent probes on bilayer properties have also been investigated by atomistic molecular dynamics (MD) simulations [5–9]. The lipid bilayer itself is mostly impenetrable to ions and molecules [10]. Therefore, charged molecules must cross through special channels within the lipid bilayers, called the ion channels. These channels are made of trans protein membrane molecules, containing aqueous pores which connect the inside of the cell to the extracellular space. These channels can open and close in response to various signals. The passage of charged molecules through these channels in the cell membrane endows the membrane with an electric conductive characteristic, allowing for inward and outward current flows [11]. This is an important factor that establishes electric circuits in biological tissues. Hence, the electrophysiology and dynamic behavior of phospholipids cause the membrane to act as a variable capacitor, while ion channel proteins are regarded as electrical resistors. The nerve pulse, for instance, is considered to be a propagating segment of charged capacitor loaded by currents through the channel proteins [12].

The cell membrane is an interface between the cell interior, other cells as well as the components of the extracellular material, which facilitates the allegiance and communication with these materials as well as other cells. In normal multicellular organisms, each cell communicates with the other cells in a suitable, coherent and coordinated manner. The natural properties of membrane structures enable the cell components as well as the whole cell to oscillate and interact resonantly with other cells.

It is suggested by Smith and Best that the cellular components in the cell possess the ability to function as electrical resonators [13]. Activating the receptor might have several outcome such as: increasing the transport of certain molecules or mineral ions from one side of the cell membrane to the other side, increasing or inhibiting the activity of enzymes involved in metabolic synthesis or degradation, activating genes to produce certain proteins, turning off the gene production of other proteins or causing the cytoskeletal proteins to change the shape or motility of the cell, etc. Upon switching back to its inactive conformation, the receptor protein will detach from the effector proteins/enzymes with releasing a signal [14]. The signaling mechanisms are either chemically or resonantly mediated. Chemical communication is facilitated by chemical soluble signals that travel through the blood stream.

The soluble signaling molecules might be produced in distant sites by endocrine cells or are concealed by embedded cells such as macrophages, T-cells and B-cells. When these soluble signaling molecules are presented to the organ cells, they can either activate or inhibit cellular metabolic reactions by activating cell membrane or cytoplasmic glycoprotein receptors [15].

Cell receptors can also be activated by electric field or vibrational resonance with particular frequencies and amplitudes via a process known as electro-conformational coupling [16]. The electrical charge distribution in cell receptors can be altered by electrical oscillations of the right frequency and amplitude, causing the cell receptors to undergo conformational changes as if the receptor was activated by a chemical signal.

It has been extensively elaborated by Ross Adey that applying weak electromagnetic fields of certain range of frequency and intensity could act as the first courier by activating glycoprotein receptors in the cell membrane. He has reported that one particular effect of applying the weak electromagnetic fields is the release of calcium ions inside the cell. He has also documented that cells respond constructively to a wide range of frequencies including those of extremely low frequencies (ELF) with the range of 1–10 Hz. This range of frequency is known as the Schumann resonance frequency that is naturally produced in the atmosphere [17]. It is also reported by Adey that certain frequency bands between 15 and 60 Hz have been found to alter the protein synthesis, mRNA functions, immune responses and intercellular communication which could lead towards promoting cancer [18].

It is shown here that the structure of phospholipids in a cell membrane can have a variable capacitor behavior in its dynamics and resonating with the self-induction of helical coils from ligand receptor, (even hormones, growth factors, and neurotransmitters) which would lead towards alteration/initiation of membrane regulation of internal cellular processes. It is known that as the current varies, the magnetic field also varies which causes an electromotive force of self-induction. This opposes any further change in the current, same as the coils in inductors. When a conductor is coiled, the magnetic field is produced by current flow expands across adjacent coil turning points. A small change in voltage can lead to a large uptake of charge and a large capacitive current. This current changes the induced magnetic field and also creates a force that opposes the changes in the current. This effect does not occur in static conditions of DC circuits when the current is steady. The effect only arises in a DC circuit when the current experiences a change in the value. Some membrane proteins as well as the DNA contain helical coils in their structure which might allow them to electronically function as inductor coils. The membrane proteins and DNA might enable the cell to transiently produce very high electrical voltage since they function as electrical inductors. The cell membrane acts as a leaky dielectric, meaning that any kind of illness or change in dietary intake that affects the composition of the cell membrane and its associated minerals can affect and alter cellular capacitance.

2. Membrane capacitor model

The membrane variable capacitance, $C_{mem}(t)$ defines the amount of charge (q) which is stored on two capacitor plates at a fixed membrane voltage as a function of time $V_{mem}(t)$. Clearly, due to the nano scale size in the cell membrane, quantum electrical characteristics should be taken into consideration. In case of thin-membrane configurations, this indicates that the geometric capacitanceC_{mem}^{geo} is related to the applied voltage, ΔV_{mem} as indicated in Eq. (1):

$$C_{mem}^{geo} = \frac{\sigma}{\Delta V_{mem(t)}} = \frac{\varepsilon_r \varepsilon_0}{d_{mem(t)}} \quad (1)$$

where σ is the surface charge density of membrane, ε_0 is the permittivity of free space i.e. ~8.85×10^{-12} $F.m^{-1,}$ and $d_{mem(t)}$ is the thickness expectation filling by the alkyl chain as a dielectric of the membrane phospholipids. It is also a function of time because of dynamic behavior.

In this study, a small cell membrane capacitor is made by creating an insulating layer of alkyl between two phosphate groups. Assuming that the capacitor electrodes carry ±Q charges from one electrode towards the opposite side, the initial energy stored in the electrostatic field between the capacitor plates is given by $E_i = \frac{Q^2}{2C}$.