On the similarity of polynucleosomal structures with metamaterials

Nelli Zyryanova [L,B],

Elena Erdyneeva [L,B],

Oksana Polesskaya[L,U],

Max Myakishev-Rempel [L,B]

L - Localized Therapeutics LLC, San Diego CA, USA

B - Biophysics Research Institute, San Diego, CA, USA

U - University of California -San Diego, San Diego, CA, USA

Corresponding author: MMR max@localizedtherapeutics.com

ABSTRACT

It is well-established that DNA behaves similar to an insulated electric wire. Previously, it has been suggested by the authors that DNA wrapped around the nucleosome behaves like electric induction coil. It had also been hypothesized by the authors that similar nucleosomal structures would resonate with each other. Here, it is further hypothesized that natural polynucleosomal structures have similar electromagnetic property as metamaterials because polynucleosomes and metamaterials have induction coils positioned at nearly perpendicular angles to each other. Based on that, it is predicted here that polynucleosomal structures in the cell would exhibit some of the properties of metamaterials. That is when an incident wave of specific frequency excites the polynucleosomal structure, it would create an electromagnetic field which would spread outside of the polynucleosomal structure and interfere with the incident wave, creating complex patterns of electromagnetic field as it is happening in metamaterials. It is also hypothesized here that such secondary electromagnetic field structures produced outside of polynucleosomes can be dynamic and can be used by the nature to regulate chromatin structure, catalyze reactions in the nucleus and the cytoplasm and collectively produce the morphogenetic field of the organism. Therefore, understanding of electromagnetic resonance in polynucleosomes should lead to better understanding of electromagnetic nature of morphogenesis and morphostasis.

We noticed that tetranucleosomes resemble nanomaterial, more specifically Negative-Refraction Metamaterial.

We suggest that tetranucleosomes may produce external patterns of electromagnetic fields which could be utilized by nature for 1. Gene regulation, 2. Control of cellular processes 3. Control of morphogenesis and morphostasis.

INTRODUCTION

In spite of extensive research, gene regulation is still not fully understood. Although all major transcription factors, gene promoter sequences and regulatory elements have been thoroughly characterized, our ability to predict transcription levels of genes is very limited. Even Genomatix [1], the leader in gene promoter analysis for the last 16 years, still has limited ability to predict the transcription of genes based on their regulatory sequences and the presence of

transcription factors. It is hypothesized by us and others that this uncertainty regarding gene transcription is caused not by the complexity of gene regulation but by an incomplete understanding of the mechanisms of gene regulation. In other words, gene promoters may contain yet undeciphered signals which are regulated neither by transcription factors nor by any other chemical means but via another principle discussed below.

Comparative genomics also suggests that additional yet unknown regulatory mechanisms are in place. Specifically, in addition to 1.5% protein coding sequences in the genome, there are 6% of sequences which, though they do not code for proteins, are also conserved and therefore would have an important biological function [2]. This strongly suggests that there are yet unknown mechanisms by which untranscribed sequences exert their function.

There are many strongly charged macromolecules: DNA, histones and many of the cell's proteins. When charged molecules move, they produce an electromagnetic field and affect surrounding charged molecules. Spinning of charged molecules also produces a magnetic field. In addition to the conductance of the cell's milieu, electricity is conducted by DNA and microtubules [3,4].

Charge transfer takes place in the DNA core via the overlapping π-electron system of stacked base pairs [6]. Both positive and negative charges, which are electron holes and excess electrons, respectively, could be transported through the DNA chain [7]. Depending on the DNA sequence, charge transfer occurs via multistep hopping or coherent superexchange (tunneling) mechanisms [8]. Charge transfer is robust in DNA wrapped around nucleosomes [9]. Packaging of DNA around the nucleosome does not inhibit charge transfer [10].

There is a body of research substantiating specific positive effects of low-power electromagnetic radiation on biological function, reviewed in [11]. These include light, microwave and other parts of electromagnetic spectrum. There is also a substantial body of experimental evidence where developmental patterning of the embryo was controlled experimentally in model biological systems via electricity, reviewed in [12].

Chromatin is highly polarized: DNA is strongly negative due to phosphate groups and histone proteins of the nucleosome are strongly positive due to lysine and arginine residues. Chromatin is very dynamic: cell cycle stages, transcription, protein synthesis and replication involve well coordinated and vast chromatin reorganization. Since chromatin is strongly polarized and dynamic, strong electrodynamic phenomena must occur [5] and these phenomena should be important for chromatin's function. Although the molecular side of chromatin function is well researched, its electrodynamic side is not sufficiently characterized.

Since DNA is structured with high periodicity and conducts electricity, it has been hypothesized that EM resonances play a role in genome function and gene regulation [13,14]. For DNA to engage in functionally important resonance, it should be able to support lasting oscillations. Which DNA structures could be electronic oscillators?

DNA is organized into several structures on different levels. Because of its simplicity and order, the double helix is the best understood among DNA structures.. The double helical DNA is wrapped on nucleosomes, forming the "beads on a string structure". The nucleosomal structure of DNA is very dynamic, and its movements are involved in the regulation of gene expression. The individual nucleosomes either stay in one place or roll along the DNA. The nucleosomes are further packed into di- and tetranucleosomes and further into irregular polynucleosomal structures [15–17].

Nucleosomes as oscillators

In technology, a basic electronic oscillator consists of a capacitor and an induction coil. Such oscillators are used in radios, computers and nearly every electronic device. Recently we suggested that among possible candidates for resonating structures in DNA, adjacent pairs of nucleosomes could work as natural electronic oscillators [18].

In this model, oscillation occurs by alternation of charges between the two nucleosomes. The united π-orbital electron cloud of the base stack of the DNA oscillates back and forth between the two nucleosomes. In this model, each nucleosome works both as a capacitor and as an induction coil. The inductance here is provided by DNA coils around nucleosomes. The electric

capacitance of the nucleosome is enhanced due to its polar nature: the negative charge accumulated in the DNA core is retained by the attraction of the positive charge of the histones. The positive charge accumulated in the DNA core is retained by the attraction of the negative charge of the DNA backbone.

Note that such an oscillation mode may occur in healthy physiological conditions via partial shifting of the united electron cloud and should not require ionization of individual DNA bases.

Initially, a number of polynucleosomal structures have been observed in reconstituted chromatin, including the variants of two-start zigzag and solenoid [19–21]. Yet, recent studies in live cells suggest that among polynucleosomal structures, the most abundant are the di- and tetra-nucleosomes and the orderliness of the structures fades as the structure's size increases [15–17]. Specifically, it is observed that unlike reconstituted chromatin on a periodic DNA template, in live cells, bigger structures are likely to be non-periodic because the linker lengths between the nucleosomes are irregular [15–17]. Therefore, a tetranucleosome emerges as the largest regular DNA structure that is abundant in live cells, and bigger structures are either irregular or rare in the cell. Here we suggest a possible synergistic arrangement of the dinucleosomal oscillators in a tetranucleosome, Fig. [TETRANUCLEOSOME]. Although the stacked nucleosomes would repel each other due to induced charge during oscillations, they would still be attached to each other due to their acidic patches.

Fig. [TETRANUCLEOSOME]. suggested charge oscillations in a tetranucleosome. *One of the two phases of the oscillation cycle is shown. In the other phase, the charges are reversed, not shown.*

In metamaterials nanohelices and nanorods is used as an element for modification of magnetic and dielectric permittivity. Researches change magnetic and electric characteristics of materials by using helices of different sizes and spatial orientation relative to each other [22,23]. The helix is small LC-circuit with its own oscillation frequency. Oscillation frequency may coincide or not with frequency of external electromagnetic field.

LC-circuit field is inertial so it can counteract to the external electromagnetic field. Oscillations form if external electromagnetic field frequency is close to resonance frequency of individual helix. Exited wave may be oriented contrarily and may enhance incident wave. Pendry [24] showed that a layer of material with $\varepsilon < 0$ and $\mu < 0$ may transfer image from one area of space to another without loss of quality because such material is a resonator for damped oscillations.

Nucleosomal spatial orientation in cell is non-random. DNA loops around nucleosome may compare to nanohelices of metamaterials. Probably, there are resonance frequencies for intensification or attenuation of nucleosomal helices own oscillation. It can also be assumed that whole nucleosomal tetramere is capable to extract energy from external electromagnetic fields.

Plasmon-resonance technology demonstrates that incident electromagnetic wave after refraction in dielectric material generates plasmon-polariton wave near the surface of material with negative dielectric permittivity. The plasmon-polariton wave emerges over a distance from localization of refraction due tunnel effect [25].

That methodology uses for biosensors and near-field microscopy. In metamaterials negative dielectric permittivity forms by using of metallic nanorods. Graphens can create plasmon-

polariton like metallic structures [26] Theoretically graphen-like carbogenium structures can form material with negative refraction index [27, 28].

Author contributions

NZ conceived the idea. All authors contributed to literature search and development of the idea.

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