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Resonant Absorption of Microwaves by Macromolecules

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Abstract

The objective of the study is to detect the resonant absorption of an ultra-high-frequency electromagnetic field in the centimeter range by DNA molecules at a frequency corresponding to the natural frequency of torsional vibrations of the DNA helix. Instead of DNA solution, cultures of various bacteria containing DNA were used, for whose DNA spirals the resonant frequencies of torsional vibrations were calculated. The cultures were placed in test tubes or cuvette and irradiated by microwave generator. Theoretical analysis of the reaction of DNA to external ultrahigh-frequency radiation was carried out, including taking into account the environment and during replication with the formation of replicative forks, the resonant frequencies of DNA of three types of bacteria were determined. Peak absorption of microwave electromagnetic field by bacterial cultures was detected on calculated frequencies corresponding to the natural frequencies of torsional vibrations of DNA helices of these types of bacteria.

Subject Areas

Biophysics, Microbiology

Keywords

Torsional Oscillations, Power Flux Density, Electromagnetic Field, Microwaves

1. Introduction

In addition to the nuclear quadrupole resonance and nuclear magnetic resonance spectra, DNA spectra are located in the millimeter, teraherz, IR and UV ranges. These spectra are interpreted using covalent optical model, in an elastic rod model, in model of two elastic weakly interacting rods coiled into spiral, in model that takes into account that each of the DNA helices consists of sugars,

phosphates and nucleotides, as well as in the dynamic theory of the crystal lattice, in model of molecular dynamics, in quantum models (Frelich models, etc.).

The spectrum of centimeter range of DNA molecules is practically not studied.

In cellular organisms, in addition to DNA, there are no molecules that would correspond to the wavelength of microwave EMF, for example, torsional and rotational-vibrational movements of the molecule. Thus the rotational spectrum of trifluoriodomethane, CF3I, lies in the range of 6 - 18 GHz, for ammonia NH_3 (inversion splitting of energy levels) the spectrum is in the range of 3 - 1.33 GHz, for the ND3 molecule, 1.7 - 2 GHz. However, on the one hand, there are no ammonia-type molecules in living cells, and secondly, the rotational-vibrational spectra of cellular macromolecules are located outside the microwave range, in the UV and IR regions, the same spectra of the NH_4^+ cation or $H_2PO_4^-$, HPO_4^{2-}, HCO_3^-, NO_3^-, SO_4^{2-} anions contained in the cell are also in the terahertz and IR regions. Thus, the resonance of DNA torsional vibrations in the microwave range is distant from the spectra of other cell molecules and can be easily determined.

As is known, the excited DNA molecule of bacteria is capable of emitting microwaves in the ultrahigh frequency (microwave) range [1]. It is natural to assume that the DNA molecule absorbs electromagnetic waves in the same microwave range.

The effect of different frequencies and intensities of the microwave electromagnetic field (EMF) on bacteria has been studied only in terms of assessing survival, mitotic activity, cell division rate, stimulation, or in terms of the work of bacterial regulatory systems [2] [3] [4] [5] [6].

The direct effect on DNA in bacterial culture was studied in the millimeter range, some frequencies were identified by the authors as the natural (resonant) frequencies of various types of vibrations of the DNA molecule, for example, conformal, collective vibrations of large molecular groups in DNA, as well as the resonance of hydrogen bonds [7] [8] [9] [10].

The effect of the microwave centimeter range on DNA remained unexplored, it was only assumed that DNA has its own frequencies in this spectrum [11].

By exposure to microwave EMF on *M. Avium* 104, *Mycobacterium tuberculosis H37RV* (*Pasteur*) and *E. coli ATCC* 25618 strains, indirect evidence was obtained that certain frequencies excite resonant torsional vibrations in the helices of bacterial DNA molecules [12], and the magnitude of these frequencies was inversely proportional to the square root of the DNA lengths.

The purpose of this study is to conduct a direct experiment showing that DNA molecules are able to absorb electromagnetic radiation in the microwave range in a resonant manner.

2. The Theoretical Part

Let's evaluate whether it is possible to detect the absorption of DNA molecules not in DNA solution, but in tissue or in bacterial culture. In 1 cm^3, for example,

the liver, 200 million cells, 10^8. Plus 4 orders of magnitude, a unit of accuracy, say, a gas analyzer. If the number of nucleotide pairs is 10^6 - 10^7, then 8 + (6 − 7) + 4 = 18 − 19 orders of magnitude. For comparison, the Loshmidt number, *i.e.* the number of molecules in cm^3 is about 10^{19}. If we take, say, sensitive EPR spectrometers operating in the microwave range as a sample, their sensitivity is 10^{-12} - 10^{-14} (from the Avogadro number). Consequently, the sensitivity of conventional spectrum analyzers for tissue is sufficient in excess.

The number of bacterial colonies in 1 ml of suspension is about 10^{10}, that is, taking into account 6 orders of magnitude, which add millions of DNA nucleotides, a conventional microwave spectrum analyzer is quite capable of detecting absorption by DNA molecules.

The effect of microwave EMF on the dipoles of the DNA chain in view of its macroscopic length can only have classical character, the torsional vibrations of its spiral are described by classical laws.

If we consider a quantum oscillator, the equation for the wave function is written as:

$$\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}+\frac{mx^2\omega^2}{2}\psi=E\psi$$

Here $\hbar$ is Planck's constant, *m*, mass of oscillator, ω is circular frequency, ψ, wave function, *x*, coordinate, *E*, energy. The equation has solution expressed in terms of Hermite polynomials, while the expression for energy should look like this: $E_n=\hbar\omega\left(n+\frac{1}{2}\right)$, $n=0,1,2,3,\cdots$. In the case of torsional oscillations, the equation takes the form

$$\frac{2\hbar^2}{md^2}\frac{\partial^2\psi}{\partial\varphi^2}+\frac{Gd^2\varphi^2}{8}\psi=E\psi,$$

где G is the stiffness of the oscillator, *d*, is it' length, φ, the angle of rotation. Then

$$E_n=\frac{2\hbar}{m}\sqrt{\frac{G}{J}}\left(n+\frac{1}{2}\right)$$

Here *J*, the moment of inertia of an elementary oscillator on spiral, $J=md^2/4$. Suppose the moment of inertia increases due to an increase in length by ∂r. Then the equation will be written as:

$$\frac{\hbar}{2m}\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial\varphi^2}\right)\psi+\frac{Gr^2\varphi^2}{8}\psi=E\psi,$$

where *r* is the radius of the oscillator, a coordinate that is not initially discrete. But each energy level in the semi-classical approximation can be matched with a radius $r_n=an^2$, where $a=\hbar^2/kme^2$, Bohr radius ($k=1/4\pi\varepsilon_0$, ε_0, is the electric constant, *m* is the mass, *e* is the electron charge).

In the case of the Bohr atom, the orbit change occurs due to the absorption of a quantum of the electromagnetic field, in the case of a dipole oscillator in DNA

due to the pumping of energy by enzymes. In the classical case with natural frequency oscillations f_0 energy $E = G$, because $E = J\omega^2/2$, and an increase in the radius does not lead to a change in energy, but only to a decrease in frequency in accordance with the law of conservation of angular momentum. The classical torsional pendulum does not have spectrum of vibrational modes, there is only single natural frequency in the frequency spectrum, f_0. If the energy levels are discrete, it is obvious that the increase in the diameter of the oscillator and, accordingly, the decrease in frequency should also be discrete. For example, if we simply represent the energy as increasing $E_{n+1} = aE_n$, and by analogy with the Bohr atom, and imagine an increase of the radius $r_{n+1} = br_n$, where a and b, increasing integer functions from a natural series n and greater than one, then

$$\omega_{n+1} = \sqrt{\frac{a}{b}}\omega_n$$

Thus, the first two nearest frequencies differ from each other by about one and a half times, which is refuted by experiment, these frequency differences are not detected by one and a half times.

Thus, there is only one line in the centimeter spectrum of torsional vibrations of the DNA helix.

Therefore, instead of the Schrodinger equation, in order to obtain an expression for the natural frequency, we can use the Lagrange formalism [13], while DNA behaves like a rod when twisting [14] [15].

In the rod model, the resonant frequency of the EMF is inversely proportional to the square root of N:

$$f = kN^{-1/2} \tag{1}$$

where the coefficient $k = 21.75$ is determined using experimental data for different types of bacteria with different DNA lengths [6]. This is the general formula of torsional vibrations of any DNA [16] [17].

The DNA of bacteria is annular, the ring is compactified into an inflorescence. When torsional vibrations are excited in a molecule, the number of base pairs per turn of its spiral $\gamma = 10$ changes, and since the order of engagement $Lk = N/\gamma = const$ (Lk is the order of engagement, N is the number of base pairs in the molecule), a topological stress arises in the spiral, which leads to overspriralization. As a result, the natural frequency of torsional vibrations of the molecule changes, due to changes in stiffness.

The coefficient k integrally includes the inhomogeneity of the DNA helix, its bends, compactification, topological stresses and its environment.

Since the natural frequency of torsional vibrations of DNA depends on the length of the DNA helix, it differs in magnitude for different cells. For bacteria, it is about 10 GHz, for humans, from 1.91 GHz to 4.29 GHz. The external field, when the frequency of the field coincides with the natural frequency of DNA vibrations, excites torsional vibrations in the molecule, which prevent DNA replication, as a result of which, after several "unsuccessful" preparations for division

(six cell cycles), the cell dies [6]. Thus, the fact of resonant absorption of the electromagnetic field of the microwave range by DNA molecules is indirectly proved by the fact of a resonant decrease in the survival rate of bacterial cells at the calculated frequency.

When replicating, the oscillations are also classical. In this case, there are two types of oscillators in the helix of linear DNA: those fragments that are on the helix and replication forks, in addition, the resulting parts of DNA (Okazaki fragments) occur abruptly. The analysis shows that during replication, the torsional oscillations of the DNA helix with unwinding replication forks and, accordingly, with an increasing moment of inertia relative to the helix axis in the simplest case are modeled by the following dimensionless equation

$$\left(1+k\tau\right)\ddot{\varphi}+k\dot{\varphi}+\varphi=0$$

Here $\tau=\omega_0 t$, dimensionless time, φ, the angle of rotation of torsional oscillations. The second term of the equation is quasi-dissipative, the role of dissipation is performed by an increase in the moment of inertia (a decrease in the amplitude of oscillations). When $k\ll 1$ frequency decreases linearly [5].

In the presence of dissipation, the quadratic velocity term leads to the Riccati equation $\ddot{u}=\left(ax-b\right)u$: where *x*, *u* are the redefined time and angle. From here it can be seen that replication together with normal dissipation reduces the natural frequency of torsional vibrations of the DNA helix.

During replication, one of the strands of the DNA ring breaks, both strands of the DNA helix react to the electromagnetic field separately. To eliminate the effect of replication, E. coli cultures were placed in saline. Due to the fact that the diameter of the DNA helix is much smaller than the length of the helix, it does not matter whether the DNA is circular or linear, formula (1) will be valid.

The formula is valid for any number of base pairs, for example, for $N=400$, the calculation by formula (1) gives a frequency of the order of 1 THz, which coincides with [18].

3. The Experimental Part

In experiments, a culture was studied *E. coli M*17 with a CFU concentration (3 - 5) × 10^8 per 1 ml or, according to the method of culture preparation, about 10^8 DNA molecules, the optical density of the solution was 1.3%. Non-thermal level of the microwave radiation power flux density of 2.5 mW/sm^2 was used. The DNA length is 4483,110 bp, respectively, the frequency calculated according to the formula (1) is 10.272 GHz.

To exclude the effects of replication and overcoiling, cultures were prepared not in a nutrient medium, but in saline, studies were conducted at a temperature of 21 degrees. The schematic diagram of the installation is shown in **Figure 1**.

The radiation source was Agilent Technologies E82570 1 microwave generator, Agilent Technologies E82570 power amplifier was used to amplify the signal to 1 W. The density of the microwave power flux was approximately 2.5 mW/cm^2 (at this power, in accordance with the results of additional study, the

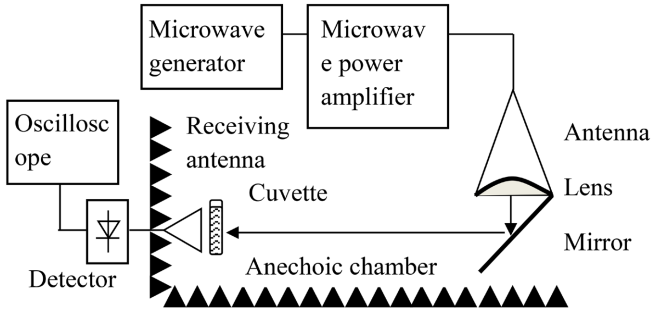

Figure 1. Schematic diagram of the installation.

microwave power flux was 2 mW/cm^2). Several experiments were conducted. In first experiments, the studied solutions were poured into battery of 5 glass tubes with an internal diameter of 13 mm, the height of the column of solutions was 38 mm. To determine the resonant frequency, the experiments were carried out according to the following method: digital oscilloscope measured the voltage at the detector output proportional to the power of microwave radiation (the detector worked on a quadratic section of the volt-ampere characteristic). The studies were conducted in the frequency range from 8.5 to 11.0 GHz. For a rough estimate, the frequency change step was 0.1 GHz, then, after determining the narrowed range, 0.01 GHz, and finally, near the resonant frequency, 0.001 GHz.

It was found that at the resonant frequency f_0 = 10.272 ± 0.001 GHz, the absorption coefficient of the bacterial culture was 2%. Such small absorption coefficient is explained by the low concentration of bacteria, respectively, the low concentration of DNA macromolecules in the saline solution and the small volume of the liquid under study. In following experiment with new culture of *E. coli M*17 with an optical density of culture in a test tube with saline solution of 7.3%, the absorption coefficient increased to 4% at the same frequency. As the battery of test tubes approached the receiving antenna, the absorption coefficient increased. According to the results of the experiment, it was concluded that the thickness of the tubes, equal to 14 mm, coincides in order of magnitude with the wavelength of microwave radiation in a free space of 3.2 cm, therefore, there is a diffraction effect on individual tubes and interference of secondary waves at the location of the receiving antenna.

To exclude the detected effects, the tubes were replaced with plane-parallel cell made of organic cuvette with cross-section size of 100 × 78 mm, which coincides with the size of the opening of the receiving antenna, and thickness of 14 mm, the solution of the third culture of *E. coli M*17 had density of 7.3%. The cuvette was installed at an optimal distance, close to the receiving antenna.

In order to exclude the spectrum of saline and cuvettes and obtain effective absorption, measurements were carried out twice: with a cuvette filled with 4% saline solution and with solution of the culture under study.

The coefficients of absorption of microwave radiation by tubes with saline solution and with solution of the culture under study are calculated.

In order to calculate let's precise: 1 ml of the solution contains about 10^{26} mo-

lecules (according to the well-known formula through the Avogadro number, the mass of 1 ml and the molar mass) of the saline solution, therefore, taking into account the low concentration of the *E. coli M*17 culture of 10^8 DNA molecules, the effects of overexposure of molecules cannot be taken into account and to calculate the absorption of parallel monochromatic radiation beam in an absorbing medium, use the Booger-Lambert law $I = I_0 \exp(kx)$, where I_0 and $I(x)$ are the intensity of incident and transmitted radiation to a depth of x, k is the absorption coefficient at the appropriate frequency.

Thus, in view of the Booger-Lambert law, the transmission coefficient was determined by the voltage ratio U:

$$K = U_{with\_bacteria} / U_{without}$$

(U_0 is normalized to one). The dependence of the transmission coefficient on the radiation frequency is shown in Figure 2.

Calculation of the absorption coefficient

1) Non-resonant absorption, medium level

$K_{not\_resonanse} = (0.823 + 0.838)/2 \approx 0.83$.

2) Resonant absorption at half power level $K_{res/2} = (0.83 + 0.772)/2 \approx 0.8$.

3) Resonant absorption at the resonance frequency

$K_{resf_0} = 0.83 - 0.772 = 0.59$.

Taking 0.83 as 100%, we get an absorption of 7.0%.

Calculation of measurement error associated with different levels of non-resonant absorption to the right and left of the resonant frequency:

$$K_{resf_0 left} = 0.823 - 0.772 = 0.051$$

$$0.823 - 100\%$$

$$0.051 - x\%$$

$$x = 0.051 \times 100\% / 0.838 = 6.197\% \approx 6.2\%$$

$$K_{resf_0 right} = 0.838 - 0.772 = 0.066$$

$$0.838 - 100\%$$

$$0.066 - x\%$$

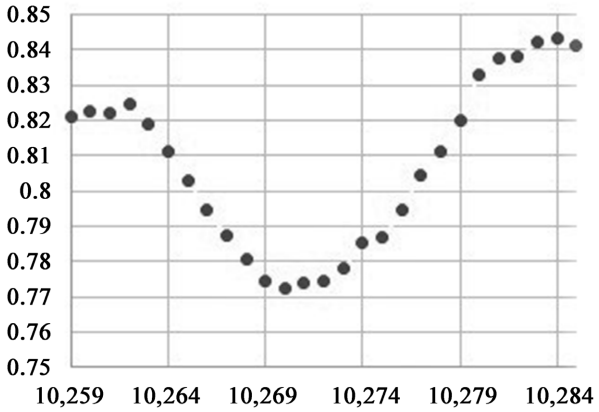

Figure 2. The dependence of the transmission coefficient on the frequency of radiation.

$$x = 0.066 \times 100\% / 0.838 = 7.876\% \approx 7.9\%$$

The average value $x = (6.2 + 7.0 + 7.9)/3 = 7.033 \approx 7.0\%$, as it was calculated earlier, but now an error of 0.8% down and 0.9% up is visible, we may take ± 0.9%.

Taking into account the thickness of the walls of the cuvette 3 mm, the thickness of the liquid layer x = 17 mm, while the coefficient of non-resonant absorption is $k_{non\_res} = (0.11 \pm 0.01)\,\mathrm{cm}^{-1}$, and resonant at frequency f_0 = 10.272 GHz and $k_{res} = (0.04 \pm 0.01)\,\mathrm{cm}^{-1}$. Thus, the total resonant and non-resonant absorption at the specified frequency is $k_{res} + k_{non\_res} = (0.15 \pm 0.01)\,\mathrm{cm}^{-1}$.

The Q-factor of the resonant system at the level of half resonant absorption, calculated by the formula $Q = f_0/(f_в - f_н) = 1030$, where f_{up} and f_{down} are the upper and lower boundaries of the resonant absorption band at the level of half power. This is large value, so the peak of resonant absorption is quite sharp.

Taking into account the concentration of bacterial culture $m = (3 \div 5) \times 10^8\ \mathrm{cm}^{-3}$, the layer of saline solution with cross section S = 1 cm^2 and length l = 1.7 cm contains $M = (5.1 \div 8.5) \times 10^8$ of bacteria, respectively, the same number of DNA molecules. This makes it possible to evaluate the microscopic cross section of the absorption of microwave radiation by a single DNA molecule at the resonant frequency:

$$\begin{aligned}\sigma_f &= \sigma_{non\_res} + \sigma_{res} = \frac{k_{non\_res}}{M} + \frac{k_{res}}{M} \\ &= \left(1.8 \pm 0.5 \times 10^{-10}\right)\mathrm{cm}^{-1} + \left(0.7 \pm 0.2 \times 10^{-10}\right)\mathrm{cm}^{-1} \\ &= \left(2.5 \pm 0.5 \times 10^{-10}\right)\mathrm{cm}^{-1}\end{aligned}$$

The macroscopic absorption cross-section allows calculations of absorption coefficients depending on the concentration of bacteria and the thickness of the bacterial solution layer.

4. Results

At the resonant frequency f_0 = 10.271 ± 0.001 GHz, an effective absorption of 7.0% ± 0.8% was obtained on an *E. coli M*17 culture. The certain resonant frequency in the error coincides with the results of previous experiments f_0 = 10.272 ± 0.001 GHz and is close to the calculated value of 10.26 GHz.

On *M. Avium* culture, the effective absorption was 7.3%, the resonant frequency f_0 = 10.317 ± 0.001 Hz and close to the calculated 10.31 GHz.

On *Mycobacterium tuberculosis culture* the effective absorption was 7.1%, f_0 = 10.356 ± 0.001 GHz and close to the calculated value of 10.36 GHz.

5. Discussion

Torsional vibrations of DNA molecules are poorly studied, their study is almost not presented in the literature.

This study is a direct proof of the resonant absorption of DNA molecules in the microwave spectrum. The absorption of the electromagnetic field by bacteri-

al cultures took place almost strictly at the frequency that corresponded to the calculated natural frequencies of torsional vibrations of the corresponding DNA molecules. Thus, it is proved that the effect of absorption by DNA molecules of the electromagnetic field of ultrahigh frequency exists, and this frequency is the natural frequency of torsional vibrations of DNA molecules.

The fact that the resonance absorption graph is not symmetrical near the resonance point is explained by the ratio $D \ll L$, where D is the diameter of the DNA helix, L is its length, in order to achieve symmetry, it is necessary to take a lot of measurements and average.

6. Conclusion

The study can be used as a basis for the identification of different types of bacteria and diagnosis of bacterial diseases.

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Conflicts of Interest

The author declares no conflicts of interest.

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