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Electromagnetism - Properties of Erythrocytes

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Abstract

At the onset of blood flow, red blood cells (RBCs) align along the central plane of the vessels. In capillaries, RBCs transform from a biconcave disk into a parachute shape. As blood transitions from the arterial to the venous end, the hemoglobin in erythrocytes alters its magnetic susceptibility. Within approximately 0.6-0.8 seconds, oxygen is displaced from RBCs through diffusion. This study explores the fundamentals and interconnections of these processes.

Blood samples from 35 different healthy individuals were analyzed. The research examined magnetic field induction in ferromagnetic toroids, formed by the alternative electric field with a square wave signal, and studied the AC in the secondary coil - a tube filled with blood. This study discusses the impact of RBC geometry and hemoglobin allosteric transitions on electric signal generation and its relevance to cellular metabolic activity in the body.

The findings suggest that the AC field, originating from the heart's rotational dipole, can generate a magnetic field in RBCs, facilitating the allosteric transformations of hemoglobin. Hemoglobin's thermoelastic expansion and magnetostriction cause biconcave membrane oscillations at ultrasound frequencies. The resulting electroacoustic wave rotates charges at the cell's z-potential area, aids RBC migration into the flow plane, and enhances trans capillary diffusion of substances.

An electroacoustic standing wave emerges between the oscillating RBCs, coinciding with the wavenumber of externally penetrating infrared light. The synergic influence on hemoglobin in capillaries causes the RBC membrane to create a temporally frequency-modulated wave, carrying resonance molecular frequencies. This wave regulates biochemical processes within and outside body cells.

Keywords: Electroacoustic wave, erythrocyte, frequency modulation, hemoglobin, magnetostriction

1. Introduction

Microcirculation is a cornerstone of life, as it is the ultimate organ for which the cardiovascular system was designed. It is the sole location where body cells have direct access to blood (Fung & Zweifach, 1971). The study of blood flow in capillaries is therefore of paramount importance.

The total length of capillaries, the smallest of the blood vessels, in the human body is estimated to be 96,000 km, constituting about 80% of the total vessel length. Blood flow is expressed as the pressure gradient over resistance. By the time blood exits the capillaries and enters the venules, the pressure is significantly reduced. Resistance, determining the pressure drop, can be expressed as either viscous or inertial. Blood viscous resistance depends on various factors: hematocrit, plasma viscosity, RBC deformability under flow, and RBC aggregation-disaggregation properties. Blood viscosity varies in large arteries, veins, and microcirculation, where the shear rate can range from a few s^{-1} to more than $1000s^{-1}$ (Nader et al., 2019; Guyton & Hall, 2011).

Viscosity becomes significant as vessel diameter decreases, and blood flow is slowest in the capillaries. The diameter of capillaries is smaller than that of RBCs. In microcirculation, where the flow can be assumed to be almost inertia-less, RBCs are subjected to high viscous shear stress, resulting in parachute or slipper shapes (Takeishi et al., 2021).

The Fahraeus–Lindqvist effect, an increase in apparent viscosity with increasing tube diameter in vivo, is attributed to a cross-stream migration of RBCs in tube flow. This leads to the formation of two phases: a flow core

consisting mainly of RBCs and a cell-free layer (CFL) next to the tube wall. The CFL, having lower viscosity compared to the RBC core, acts as a lubrication layer, reducing effective blood viscosity. The cross-stream migration of RBCs in tube flow is governed by cell-wall hydrodynamic interactions, driving the cells away from the wall, and by cell–cell hydrodynamic interactions, dispersing RBCs. However, blood flow resistance in micro-vessels in vivo is markedly higher than that in microtubes in vitro. Micro-vessels, in contrast to glass tubes, are elastic, lined with endothelium, relatively short, and may be irregular in shape (Fedosov et al., 2010).

According to the hydroelectric analogy, due to the high cross-sectional area of parallel-filled capillaries, their mean resistance should be low. However, due to the increasing shear surface area (the resistance-area paradox), in arterioles and capillaries, the increasing splitting ratio of large vessels increases the total resistance to flow. Thus, blood flow in capillaries exhibits multisystem dependence.

In capillary microcirculation, substances exit and re-enter the blood through diffusion, hydrostatic, and osmotic pressure. However, the blood's stay time in the capillary functional areas is relatively short, about 0.6-0.8 second.

Until now, blood flow has been viewed predominantly as a hydro/mechanical process, with erythrocytes passively following the plasma. While this study explores the potential role of RBC structure/geometry and hemoglobin allosteric transitions in generating electric signals, as promotion devices.

2. Material and Methods

Blood samples from 35 different healthy individuals were collected. A ferromagnetic ring encircled the blood-filled tube, which contained venous blood.

This research examined the induction of AC in the blood secondary coil, formed by an alternating electric field with a square wave input signal in the primary coil, (also, the electric plates in opposite surfaces of the toroid) (Figure 1A).

Frequencies in the primary coil ranged from 100-65000Hz and 1-8MHz. In the secondary coil, an oscillating electromagnetic field forms, causing ionic and dipolar polarization of the substance, and voltage can be measured. Here, the AC electric field induces RBC membrane oscillation due to the thermoelastic expansion and magnetostriction of the hemoglobin. Induced signals were observed as RC oscillations (Figure 1B). Significant frequency differences were noted between the primary and secondary (blood) coils. (Table 1).

Table 1. Frequencies in the primary and secondary coils in the blood study.

Signal frequency on the primary coil	Signal frequency on the secondary coil
100-200 Hz.	100-200 Hz.
500-1000 Hz.	400-700 Hz.
3000-5000 Hz.	2000-3300 Hz.
6000-8000 Hz.	4000-5000 Hz.
10000-20000 Hz.	6400-10300 Hz.
40000-65000 Hz.	17300-20300 Hz.
1-2MHz.	520-860KHz.
4-8MHz.	1.1-2.0MHz.

The table shows the influence of the broad range of AC frequencies on blood. It's an indirect indication of the existing built-in mechanisms for magnetic fields with different frequency sensing.

Electric signals with an ECG rate of 1.1-1.25 Hz (65-75 beats/min) cannot induce signals in the secondary coil. Phase delay up to 90^0 in the secondary (blood) coil is noted in signals from the 1 KHz.

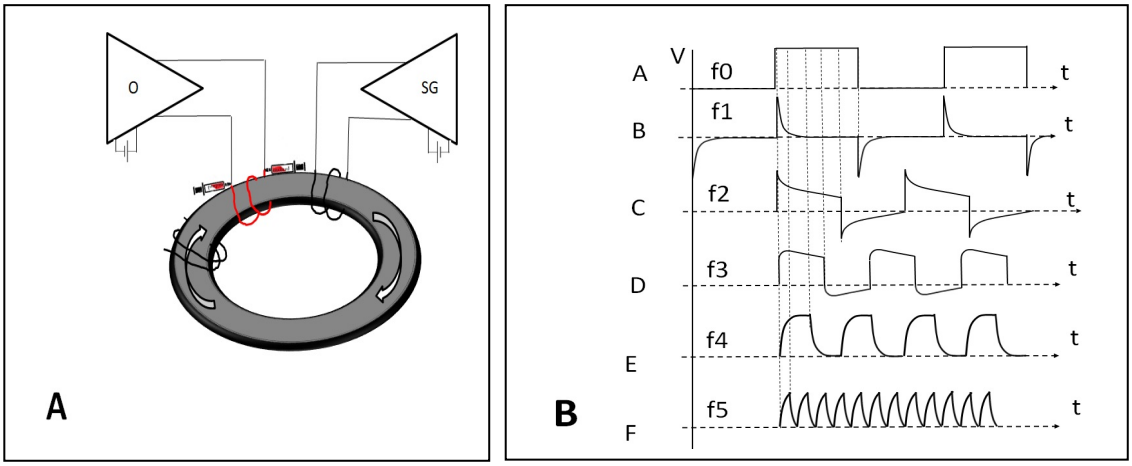

Figure 1. **A**. The signal generator (SG) sends the signals to the high-frequency transformer (or to the electrical plates in opposite surfaces of toroid-not shown) and induces signals in the secondary coil, registered by the oscilloscope (O); **B**. Signals in the primary coil are square form (**B**.A.). Inducting in the secondary coil at the low frequencies (f), it has a spike form (**B**.B). Wave uptakes square form f0-f4=100-65000Hz. (**B**.C to B.E). At the higher frequency f5. 4-8mHz (B.F), wave takes the triangle form. V-signal voltage, t-time, f0-rectangular signal in primary coil

Main hemodynamic factors (pressure, volumetric flow rate, shear stress, resistance, compliance, inductance, viscoelasticity, vessel wall structure) are different in the arterial, venous, and capillary systems, so the comparison between them becomes impossible, especially, with the presence of AC, flowing according to the charged substances of the human body. Changes in the signal frequency in the secondary coil may be caused by the modified impedance (as an RLC filter) according to the frequencies. This can be highly presented in the blood cell elements too. For the detailed analysis of the data, a more profoundly equipped experimental laboratory is necessary.

Below are the theoretical basics for the electromagnetic blood flow in the blood vessels, confirmed experimentally. We are open to the cooperation.

3. Results and Discussion

Before blood flow, myocardial depolarization initiates an alternating electric field in the heart chambers. Consequently, erythrocytes form ultrasound oscillations, displacing the surface positive charges in the Z potential region on nearby RBCs, thereby propagating the electroacoustic wave in the arterial and venous blood.

Ultrasound waves reflect and refract in surrounding substances, rotating charged particles and generating a magnetic repulsion field relative to the RBC. This results in vessel wall tension. Subsequently, the sum of forces - the pulse pressure (initiated by heart contraction) and the wall tension - forms the arterial blood flow (M. Beraia & G. Beraia, 2021).

In electroacoustics, the positive charge transmits distally in the human body as observed in the ECG. It is linked with the rotating negative charge motion in the dipole. The current direction is regulated by oxygen, fixed at the inner mitochondrial membrane of all biological cells. Oxygen, being a highly electronegative element, forms electron attraction at the end of the cell electron transport chain.

However, the flow of current is characterized by the flow of electrons. Any "flow" of positive charge is a mathematical convenience. On the cell membrane level, the rotational dipole field, at reflection, changes the phase and propagates as the negative (Q, S waves in ECG). It equals the forming displacement current between the body cell's double membranes and is transmitted through dielectric polarization (Figure 2).

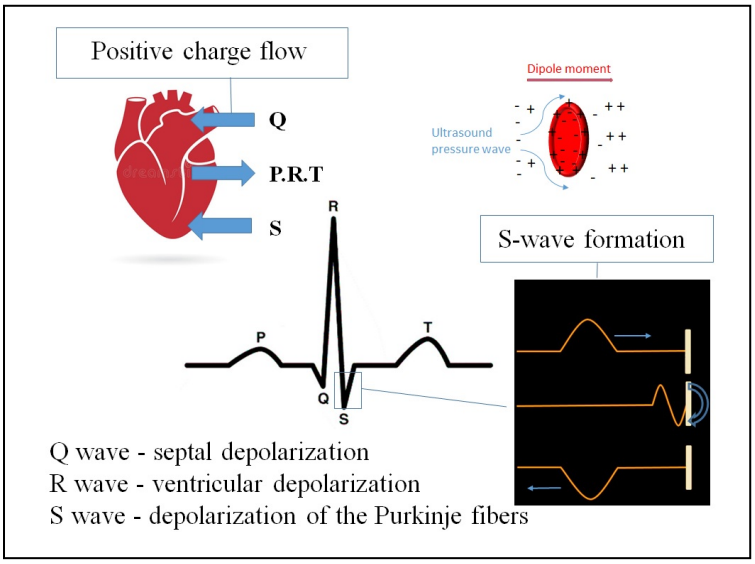

Figure 2. On ECG- P, R, and T waves are expressed as the positive deflection, while the Q and S waves are negative. In the human body cells, the signal propagates by the rotational dipole. Q, S signals are equal to the wave reflection, on the cell membrane. The rotational dipole changes phase in 180^0, forming a displacement current

Electroacoustic (photoacoustic) waves can also be generated by light. RBCs, containing large amounts of hemoglobin, which bind oxygen and absorb visible light significantly, rapidly increase in temperature and pressure upon absorbing light energy. This results in thermoelastic expansion and emission of a photoacoustic wave. These waves, detectable using conventional ultrasound transducers, have been used in vivo for functional imaging and photoacoustic tomography (Strohm, Berndl, & Kolios, 2013).

Magnetostriction - the change in shape/dimension of magneto conductors during magnetization due to magneto anisotropy - is another mechanism for membrane oscillation. Magnetostriction is extensively used to generate ultrasound and hypersound (Bychkov et al., 2016).

When an external alternating electric field penetrates the RBC (Purnell & Ramsey, 2019), it creates an oscillating magnetic field in the ring form, following any changes in an electric field inside and outside the torus. The principal advantage of toroidal coils, compared to non-toroidal, is magnetic field containment - the magnetic field outside of a toroidal coil is negligibly small, which reduces interactions with other fields and structures in the vicinity. The magnetic field inside the toroidal coil does not depend on the coil's cross-sectional shape (Griffiths, 1989).

Under normal physiological circumstances, over 95% of hemoglobin in arterial blood is in the oxyhemoglobin form, with venous oxygen saturation above 75%. Oxyhemoglobin is diamagnetic (repelled by the magnetic field - negative susceptibility), whereas deoxyhemoglobin is paramagnetic (attracted by the magnetic field - positive susceptibility). Deoxyhemoglobin is strongly paramagnetic due to four unpaired electrons at each iron center per heme group. Oxyhemoglobin, with no unpaired electrons due to its covalent bonds, is diamagnetic (Bren, Eisenberg, & Gray, 2015).

The binding between iron in hemoglobin and the oxygen molecule is a coordinate/dative bond, where both electrons in the bond are "donated" by the same atom. The binding of oxygen to iron(II) heme pulls the iron into the porphyrin ring plane, inducing a slight conformational shift. This shift encourages oxygen binding to the three remaining heme units within hemoglobin - a cooperative process. Hemoglobin, an allosteric protein, undergoes a conformational change during tense (deoxygenated) to relaxed (oxygenated) transitions and vice versa (Yonetani & Laberge, 2008).

Raman difference spectroscopy measurements revealed frequency differences in the oxidation state marker lines between native and chemically modified human deoxyhemoglobins stabilized in either the R or the T quaternary structure. These differences suggest an increase in electron density of the antibonding p orbitals of the porphyrin rings in the R structure, explained by a charge transfer interaction between donor orbitals and the p orbitals of the porphyrins (Shelnutt et al., 1979).

The diamagnetism of oxyhemoglobin should be explained by the inverse magnetostrictive (Villari) effect, which is the change in magnetic susceptibility of a material due to structural rearrangement according to mechanical stress.

The investigation's results show that the main quaternary rearrangement connected with the R-T transition in hemoglobin occurs at physiological pH and room temperature on a timescale of about 2μs. The high rate of structural change is of unmistakable physiological importance. The hemoglobin molecule would not have achieved such a high level of organization if these structural changes did not occur faster than its reaction with oxygen. Photolysis of carbon monoxide and oxygen derivatives of hemoglobin by a short laser pulse produces a transient species that rapidly decays to normal deoxyhemoglobin. The decay of the transient species follows first-order kinetics with constants ranging from 0.8-1.8 x 10^{-7} sec (Alpert, Banerjee, & Lindqvist, 1974).

The magnetic field affects moving charges and thus the allosteric transformation of hemoglobin, which involves shifts of populations rather than a unidirectional conversion of one quaternary structure to another. The functional properties of hemoglobin, such as O2 binding, the Bohr effect, and cooperativity, are explained based on magnetic correlations. Analysis suggests that magnetism could be involved in the functioning of hemoglobin (Mayda et al., 2020).

The magnetic field, initiated by the electroacoustic and photoacoustic waves in toroid RBC, should manage the charged particles' motions inside the ring during conformational displacement in hemoglobin. Consequently, the RBC membrane will vibrate according to the directional motion of the charged particles. Thus, the membrane oscillation frequency can reflect the features of the electroacoustic, photoacoustic waves, and the vibration of the hemoglobin subunits (Figure 3).

The action of the magnetic field was demonstrated to increase the oxygen capacity of hemoglobin by 20% (Zhernovoĭ et al., 1999). During deoxygenation, hemoglobin releases electrons, forming the displacement current. Considering the charge of a single electron (1.6 x 10^{-19} coulomb), the stroke volume (and in the systemic open capillary flow) contains about 75.4 x 10^{6} erythrocytes; a typical erythrocyte contains about 2.7 x 10^{8} hemoglobin molecules, each carrying 4 heme groups, and can release 4 electrons upon oxygenation. Thus, the maximal displacement charge in the stroke volume is approximately 1.58 x 10^{-2} coulomb, and the current is about 20mA (5mA in binding/unbinding only the final oxygen molecules).

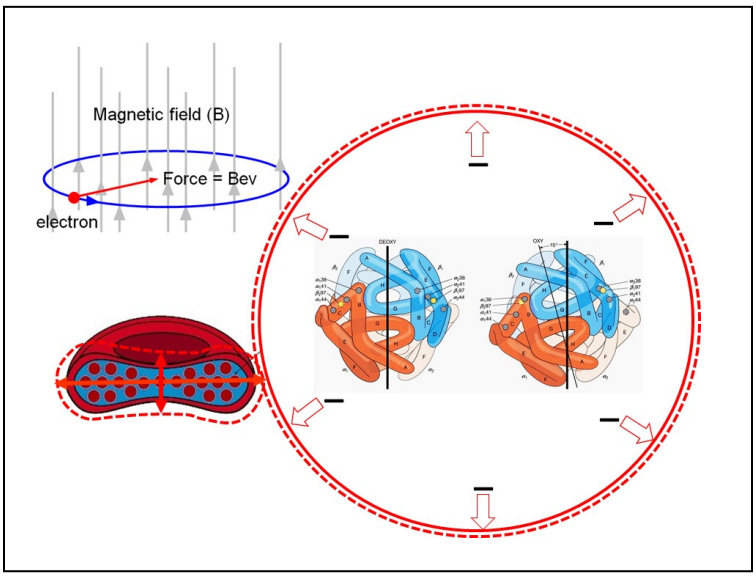

Figure 3. By the electromagnetic field, with the thermoelastic and magnetostriction effects of hemoglobin, RBC changes its shape, and the cell membrane oscillates. The magnetic field inside the erythrocytes affects the charged particles' direction

At the arterial and venous ends of the capillary, the current flow, magnetic field rotation in RBC, and the oxygen flow to the hemoglobin molecules are oppositely directed. Due to the capillary's low diameter, RBCs assume a parachute/jellyfish form. This enlarged surface of the RBC oscillates as a surface wave (characteristics of both transversal and longitudinal waves, with phase delay for the longitudinal). This provides pressure in both

directions. In the arterial and venous ends of the capillary, the vector of the ultrasound pressure wave facilitates the forced transport of substances through the vessel wall, in addition to the RBC displacement (Figure 4). In the shear flow, due to the asymmetry of the jellyfish surfaces, the tank-tread motion is formed.

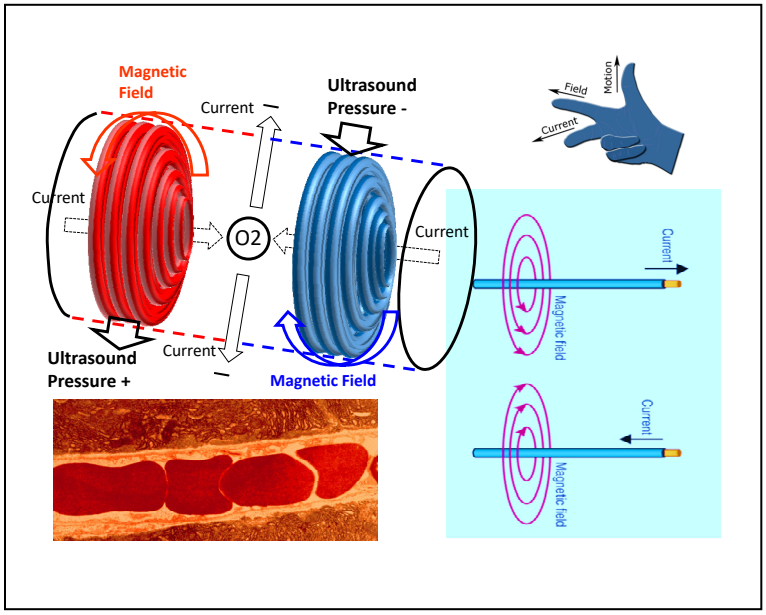

Figure 4. RBC in (systemic here) capillaries uptake parachute/jellyfish form. The acoustic waves, in assistance with the electromagnetic forces, facilitate the RBC motion and powered displacement of the substances through the vessel wall. Correlation is shown between the current direction, magnetic field, and the force affecting the charged particle

As oscillations are formed by cooperation with neighboring RBCs, a standing wave associated with resonance is formed. Evidence of resonance can be found in the ECG curve. Otherwise, the chaotic motion of the charges would form noise or signal damping.

The length of the standing wave in the blood can be calculated using the RBC's concavational radius and the distance between cell surfaces. Wave propagation is also accompanied by wave reverberation and overtones.

Two erythrocytes suspended in isotonic saline water cannot approach each other closer than 50-100 Å. The distance between RBCs is an important factor in RBC agglutination and depends on electronegative surface charges and the ionic cloud that normally surrounds them. A typical human red blood cell has a disk diameter of approximately 6.2–8.2 µm, a thickness at the thickest point of 2–2.5 µm, and a minimum thickness in the center of 0.8–1 µm (Kinnunen et al., 2011).

Considering the volume of blood in all open systemic capillaries (75 ml), the RBC quantity (by the volume of RBC - 90fL) can be found. Taking into account the volumetric ratios RBC+plasma (45-55%), the length of all open capillaries with a radius of 8µm, and the mean distance between cells flowing alone, can be found to be 6-7µm (Figure 3). Under microscopic study of capillary blood flow, the distance between RBCs is 2-8 µm ($2\text{-}8.10^{-4}$ cm).

Considering the biconcave form of the RBC and the capabilities of laser light reflection (Strohm, Berndl, & Kolios, 2013), the focal length for acoustic wave reflection must be 7.0- 7.3µm. At this distance, the reflected ultrasound waves from the RBC surfaces should form wave nodes (Figure 5). As the distance between cells and the form of the RBC oscillates, the above-mentioned distance will change.

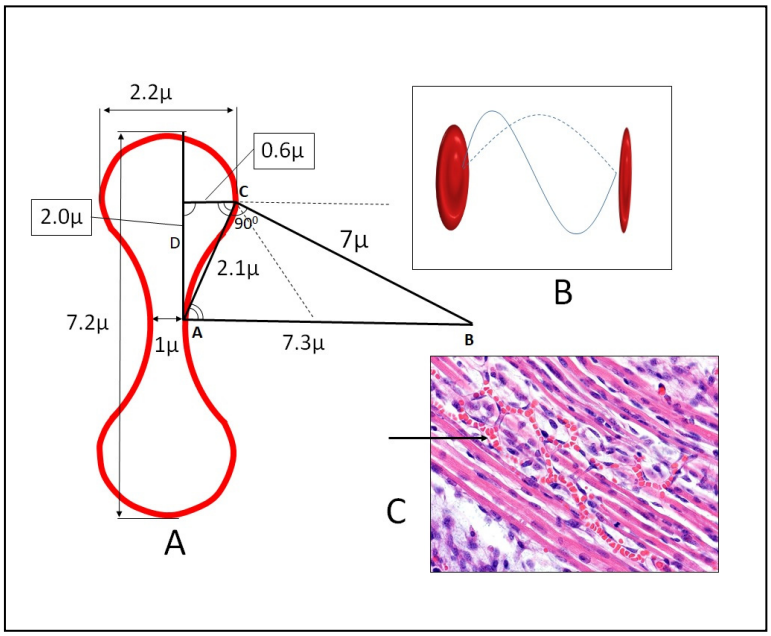

Figure 5. The ultrasound fundamental wavelength in the blood can be calculated by the concavational radius of the RBC, and the distance between the cells. A. Calculation of the fundamental wavelength. The lines AB and CB are perpendicular to the reflection surfaces. As the angle of incidence and reflection are equal to zero, at the reflected areas the wave nodule is formed. B. Standing wave between the RBCs. C. Erythrocytes in the capillary flow, under the microscope

At acoustic oscillations between nodes, an integer number of half waves can be generated.

Thus, the longest (fundamental) wavelength between RBCs will be 1.0×10^{-3} -1.4×10^{-3}cm, and the wavenumber is about 714-1000 cm^{-1}. As erythrocytes approach each other, the wavelength will decrease and the wave number and frequency will increase correspondingly.

RBC vibration is a driving mechanism of resonance in standing waves. The system will facilitate harmonics too, and besides the fundamental wave tones between RBCs, there must be higher frequencies of the ultrasound overtone oscillations.

The velocity of the ECG in the human body is up to 1500 m/sec (Buchner et al., 2023). ECG propagates as an electroacoustic wave. The limitation of the velocity may be due to the ultrasound wave velocity. The fundamental wavelength in a standing wave is constant, so the ultrasound frequency from the RBC must be up to 15×10^7 Hz. (Table 2). Overtones can have higher frequencies, 2,3,4 times that amount.

In wave propagation, the density, viscoelasticity, and dielectric properties of the conductive medium must be considered. When a wave travels from a low-density medium to a high-density medium, its frequency per unit of time remains the same, but its wavelength decreases. However, the resonance frequency in a dense substance is higher, and the velocity can be higher. In cases where the wave emitter changes in a new medium, the frequency can differ.

Table 2. Electroacoustic wavenumber done from the erythrocytes is in range of the infrared waves.

Wave	**Velocity cm/sec.**	**Wave number cm^{-1}**	**Wave length cm.**	**Frequency Hz.**
Ultrasound fundamental standing waves between the RBC	15.10^4	**714-1000**	$1.0.10^{-3}$-$1.4.10^{-3}$	$10.7.10^7$-15.10^7
Electromagnetic infrared (IR)	3.10^{10}	10 - 13333	$7.8.10^{-5}$ -0.1	3.10^{11}-4.10^{14}
Most used IR	3.10^{10}	**667- 5000**	2.10^{-4} – $1.5.10^{-3}$	$1.2 .10^{14}$ - $3.8.10^{14}$
Electromagnetic waves (visible)	3.10^{10}	14300- 25000	4.10^{-5} - 7.10^{-5}	$4.3.10^{14}$ – $7.5.10^{14}$

Significantly, changes in the external electric field can affect RBC not only by the rotational heart dipole (ECG) but also by light. Waves are not only reflected from surfaces but refracted into the medium. Wavenumbers in photoacoustic waves are in the spatial frequency range of the infrared electromagnetic waves emitted from erythrocytes, but the temporal frequencies are different. This is key for affecting molecular bonding.

The length of chemical bonds is not fixed, and molecules vibrate. The typical vibrational temporal frequencies of molecules range from less than 10^{13} Hz to approximately 10^{14} Hz, corresponding to wavenumbers of approximately 300 to 3000 cm^{-1} and wavelengths of approximately 3.10^{-3} - $3.3.10^{-4}$ cm.

The spatial and temporal continuum is significant for the investigation of wavelength. However, there is no order of time in the quantum world - temporal order appears only when processes such as measurement irreversibly turn quantum phenomena into observable classical phenomena (Brooks, 2018). In physics, the wavenumber is the spatial frequency of a wave, measured in cycles per unit distance or radians per unit distance (angular wavenumber). It is analogous to temporal frequency, defined as the number of wave cycles per unit of time or radians per unit of time (angular frequency). In multidimensional systems, the wavenumber is the magnitude of the wave vector. For quantum mechanical waves, the wavenumber multiplied by the reduced Planck's constant is the canonical momentum and is related to the energy.

Visible light is substantially absorbed by hemoglobin, melanin, and other component organic chromophores of human skin. The near-infrared wavelength region penetrates through the skin further than any other waves on the light spectrum, acting as "a window to living organisms". The light that hits the chromophore can be absorbed by exciting an electron from its ground state into an excited state. Hemoglobin is found in the microvascular network of the dermis, typically 50–500μm below the skin surface.

The higher velocity (and temporal frequency) of the electromagnetic-IR wave, at the same wavenumbers as for acoustic, is due to wave propagation inside the molecules. An ultrasound wave, at the oscillation of charged particles in a colloid substance, also forms an electromagnetic field. Simultaneous affection of RBC by electro-acoustic and IR waves, accompanied by allosteric transformation of hemoglobin, is expressed as cell membrane oscillation. It forms a group of electromagnetic waves, modulated by frequency - informational waves - and can affect molecular bonding. Electromagnetic oscillation/information through the capillary is transmitted to the extra/intracellular spaces and endoplasmic reticulum of cells by the displacement current, up to the inner membrane of the mitochondria (Fig. 6).

For this reason, red blood cells pass through capillaries in a single file line, whereas the distance between RBC and endothelial cells is minimal. The surface charge of endothelial cells, like RBCs, is negative, and cells generally have a thickness of 0.1–10 μm. In the capillary flow, between RBC and endothelial cell membranes, resonance oscillations can be formed.

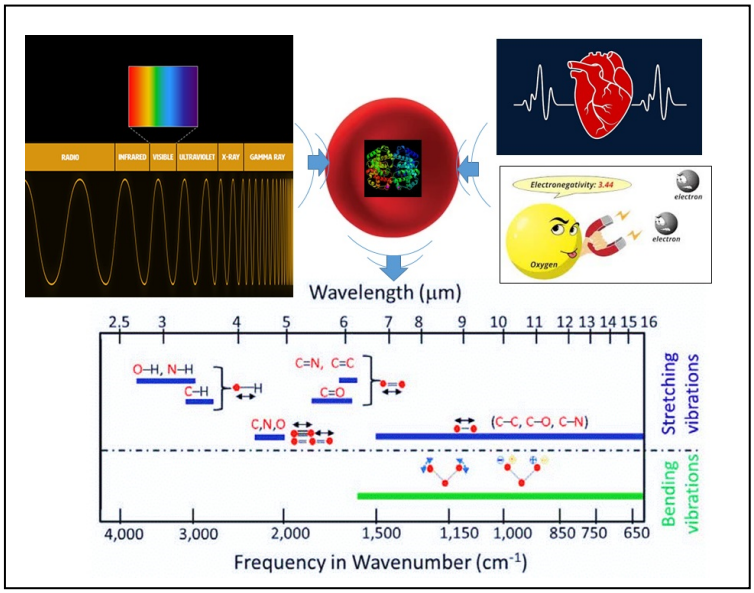

Figure 6. Information regulating the chemical bonding in the biological systems is formed by the superposition of the electroacoustic electromagnetic wave and NIR light in the RBC. The direction of the informational flow is ruled by the electronegativity of the oxygen

As IR waves and electroacoustic waves have the same (or nearly the same) wavelength, they simultaneously affect the same space. The phase difference is constant, as the waves are formed from the same source (RBC). The waves are coherent and can interfere, forming frequency modulation.

The length of the carrier (in the frequency-modulated) wave is larger than the size of molecules inside the substance, as waves can propagate in an elastic medium only if their lengths are greater than the intermolecular distances in liquids and solids. While the IR frequencies are in temporal resonance with molecular vibration. A criterion for IR absorption is a net change in dipole moment in a molecule as it vibrates or rotates.

The absorption and re-emission of the wave energy by the medium is the mechanism of energy/information transmission. Acoustic and electromagnetic waves at resonance frequencies increase the entropy of the substance at different ground levels and simplify intermolecular remodeling.

Information is the knowledge obtained from investigation and/or instruction. Electromagnetic information is encoded into the wave by modulating its parameters - a process of adding information to an electronic or optical carrier signal. A carrier signal has a steady waveform, while signal modulation is expressed by varying its amplitude, frequency, phase, polarization, and spin.

In the human body, RBC ultrasound oscillation can be the carrier frequency, while modulated by infrared oscillation from the universe, the electroacoustic wave can transfer and/or uptake information from chemical bonds (infrared spectroscopy), providing the "spontaneity" of biochemical processes. Chemical bonding does not depend only on temperature, change in enthalpy, and entropy (Gibbs free energy). It must be regulated by light (Gentili & Micheau, 2020; Cho et al., 2021; Li et al., 2023) - the information from the universe, as a regulator of chemical resonance oscillations. This defines the high number of RBCs, the solitary flow of cells in the capillary, and the large area of capillaries in the human body.

By artificially electroacoustic signals, frequency modulated by infrared light, locally generated in the pathological area by the magnetic resonance system, in phase with the ECG, biological processes at the molecular level can be investigated and managed.

4. Conclusion

The AC field, originating from the heart's rotational dipole, can generate a magnetic field in RBCs, facilitating the allosteric transformations of hemoglobin. Hemoglobin's thermoelastic expansion and magnetostriction cause biconcave membrane oscillations at ultrasound frequencies. The resulting electroacoustic wave rotates charges at the cell's z-potential area, aids RBC migration into the flow plane, and boosts substances' transcapillary diffusion.

Between the oscillating RBCs, an electroacoustic standing wave arises, coinciding with the wavenumber of the infrared light penetrating externally. By the synergic influence on hemoglobin, in capillaries, the RBC membrane creates the temporally frequency-modulated wave, carrying resonance molecular frequencies, and regulating biochemical processes in and outside body cells.

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Informed Consent

Obtained.

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The data that support the findings of this study are available on request.

Competing Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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