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CONFERENCES AND SYMPOSIA

Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (27 October 1993)

Abstract. The scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on 27 October 1993 at the Kapitsa Institute of Physical Problems of the Russian Academy of Sciences. The following reports were delivered at the session:
1. V B Timofeev. Conclusions of the First Russian Conference on the Physics of Semiconductors
2. A B Shvartsburg. Pulse electrodynamics of anharmonic signals.
3. M V Fok, A R Zaritskii, G A Zaritskaya, E V Perevdentseva. Biophysical kinetics of the transport of oxygen by blood.
Brief summaries of two of the reports are given here.

PACS numbers: 0.3.50.D

Pulse electrodynamics of anharmonic signals

A B Shvartsburg

This communication is devoted to the interaction of short wave pulses, containing only several oscillations of the electromagnetic field, with dispersing media. Such interactions are examined here on the basis of new accurate analytical solutions of Maxwell's equations obtained outside the framework of the traditional Fourier expansions. The solutions obtained are used to construct the optics of discrete anharmonic pulses, the reflections and refraction of which are determined by their duration and form.

Short pulses are now attracting attention both in fields of natural origin (for example in the magnetosphere [1]), and in picosecond radiophysics [2] and in femtosecond optics [3]. Such localised fields differ from those investigated traditionally in radiophysics and in the optics of narrow-band amplitude-modulated signals (AM) and frequency-modulated (FM) signals [4], incorporating many field oscillations, by the following features:

(A) the signal envelope is not a harmonic function;

(B) the spectral signal width $\Delta\omega$ is comparable with the carrier frequency ω_0;

(C) the signal may not have a carrier frequency at all (in such cases one speaks of 'videopulses')†.

† In the English scientific literature, the terms 'wavelet' and 'waveform' are employed.

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Translated by A K Grzybowski

The interaction of such fields with media subject to plasma and waveguide dispersion laws is considered below. The description of the dispersion spreading of pulses within the framework of the traditional model of the slowly varying amplitude envelope of a packet of travelling quasimonochromatic waves becomes inapplicable in the case of short wide-band pulses. The rapid development of the deformations of such fields in dispersing systems can be usefully considered without resorting to the concept of travelling quasimonochromatic waves, the expansion of the envelope in terms of the Fourier integral, and the summation of dispersion effects of different orders. Three problems of the electrodynamics of wide-band anharmonic signals are discussed here:

(i) the construction of direct exact analytical solutions of Maxwell's equations describing anharmonic waves in plasma and in a waveguide.

(ii) Representation of anharmonic pulses in a medium without dispersion with the aid of Hermite functions.

(iii) The optics of wide-band discrete anharmonic videopulses (the dependence of the reflection and refraction of such signals on their duration and form).

Analysis of these problems yielded the following new results.

(i) New solutions in pulse electrodynamics were found here within the framework of the traditional Maxwell's equations. In order to explain the physical significance of these solutions, it is useful to note three postulates used in the construction of the electrodynamics of homogeneous isotropic media within the framework of the model of long trains of monochromatic waves:

(a) the periods of the oscillations of the electric and magnetic components are equal;

(b) the ratio of the amplitudes of the magnetic and electric components remains constant at any point in the medium and characterises the refractive index of the latter ($n = \text{const.}$);

(c) the structure of the field is determined by the 'travelling' coordinate $z - v_p t$, where v_p is the phase velocity.

However, it is significant that these properties of the fields do not follow from Maxwell's equations. They correspond to continuous emission conditions, which constituted for many years the experimental basis of optics, radiophysics, and acoustics. The appearance of new sources of pulse emissions has stimulated the search for new solutions in pulse electrodynamics. Such solutions of Maxwell's equations, free from the limitations (a) – (c), are presented below.

Consider the simple problem of the propagation of a transversely polarised electromagnetic wave in the z direction in a homogeneous isotropic plasma. Expressing

the electrical (E_x) and magnetic (H_y) components of this wave in terms of the vector component (the potential A_x) and introducing the dimensionless variables τ, η and the dimensionless function $f(\tau, \eta)$, where

$$\eta = \frac{z\Omega}{c}, \quad \tau = \Omega t, \quad A_x = A_0 f(\tau, \eta)$$

(Ω is the Langmuir frequency of electrons), we find from Maxwell's equations that the function f is defined by the Klein–Gordon equation

$$\frac{\partial^2 f}{\partial \eta^2} - \frac{\partial^2 f}{\partial \tau^2} = f. \tag{1}$$

Standard harmonic solutions of this equation in the form of travelling waves are possible. However, together with this, exact direct anharmonic solutions, expressing explicitly the field envelope as a function of the coordinate η and the time τ were also found [5]:

$$\left.\begin{matrix} E_x \\ H_y \end{matrix}\right\} = -\frac{\Omega A_0}{2c} \sum_{q=1}^{\infty} b_q \left(\frac{\tau - \eta}{\tau + \eta}\right)^{\frac{1}{2}(q-1)}$$

$$\times \left[J_{q-1}(u) \mp \frac{\tau - \eta}{\tau + \eta} J_{q+1}(u)\right], \tag{2}$$

$$u = (\tau^2 - \eta^2)^{1/2} \operatorname{sgn} \tau.$$

where $J_q(u)$ is a Bessel function and $q = 1, 2, 3, 4, \ldots$ In contrast to the properties (a)–(c), the exact solutions (2) of Maxwell's equations are not associated with travelling waves. We may note certain properties of such solutions.

1. The oscillation periods of each harmonic of the electric and magnetic field components are not equal and the ratio of their amplitudes is not constant (Fig. 1). For simplicity, the curves in Fig. 1 as well as in Fig. 2 are constructed only in the region $\tau \geqslant \eta$; some of the curves, being symmetrical, correspond to the regions $\tau \leqslant -\eta$.

2. The structure of the field defined by Eqn (2) is not determined by the 'travelling' coordinate but does depend on the quantities $t \pm zc^{-1}$ and $\Omega(t^2 - z^2c^{-2})^{1/2}$.

3. On propagation into the bulk of the medium ($\eta > 0$), the rapid dispersion of the harmonics leads to the generation of quasiharmonic oscillations at the periphery of the envelope.

4. The electric induction $\boldsymbol{D}$, defined by the general formula [6]

$$\boldsymbol{D} = \boldsymbol{E} + 4\pi \int_{-\infty}^{t} \boldsymbol{j}\, dt,$$

is expressed in a form analogous to Eqn (2):

$$D_x = -\frac{\Omega A_0}{c} \sum_{q=1}^{\infty} b_q d_q.$$

Fig. 1 shows that, in the nonstationary process considered, there is no proportionality between the harmonics of the electric field and the electric induction.

5. The group velocity, determined as a fraction obtained by dividing the energy flux in the field the energy density, does not exceed the velocity of light but can pulsate, diminishing and changing in sign. The pulsations of the group velocity at the boundary of the medium correspond to the flow of energy into the latter and its flow out from it on excitation of the corresponding harmonic [1].

6. After the substitution $c \to v_T$, where v_T is the thermal velocity, Eqn. (1) describes the propagation of longitudinal anharmonic plasma waves represented by Bessel harmonics of the type $[(\tau - \eta)(\tau + \eta)^{-1}]^{q/2} J_q(u)$.

7. The pulses defined by Eqn (2) describe fields in a planar waveguide excited by an anharmonic signal, where the parameters τ and η, corresponding to the n-th mode, are given by the expressions $\eta = K_{\perp n} z$, $\Omega = K_{\perp n} ct$; the component wave vector of the mode $K_{\perp n}$ is determined by the spectrum of the waveguide.

The effectiveness of the excitation of such anharmonic fields at the boundary of the dispersing medium is characterised by the coefficients of Eqn (2) determined from the boundary conditions. The fields (2) are then not excited ($b_q = 0$) following the incidence on the boundary of the medium of a monochromatic wave located in the region of transparency ($\omega > \Omega$).

If the characteristic time of the signal is long ($\Omega T_0 > 1$), then the effectiveness of the excitation of the harmonics (2) depends on the duration and form of the incident videopulses.

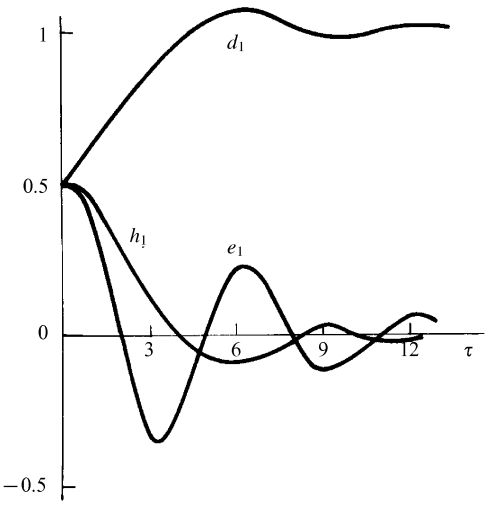

Figure 1. Dimensionless anharmonic envelopes of electric (e_1) and magnetic (h_1) components and the component of the induction d_1 at the boundary of the medium as a function of the normalised time τ.

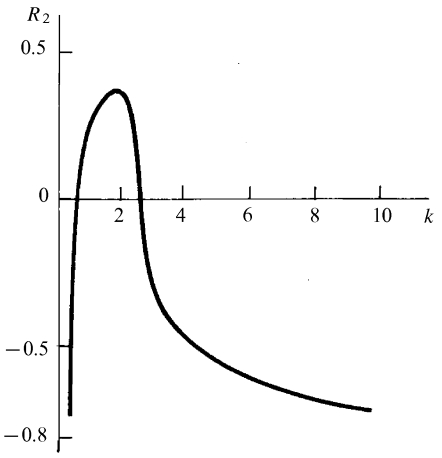

Figure 2. Dependence of the reflection coefficient R_2 of the pulse Hermite function Ψ_2 for normal incidence on the normalised duration of the pulse $\Omega T_0 = K$.

(ii) For the analysis of an anharmonic signal in a medium without dispersion, it is useful to expand the signal envelope in terms of Hermite functions in the range $-\infty < t < \infty$, since these functions represent a unique system of functions orthonormalised over the entire range $-\infty < t < \infty$. Hermite functions have a number of the advantages of the Walsh signals [8] without suffering from their disadvantages associated with the appearance of infinite derivatives on treatment of such signals. The envelopes of many signals in picosecond radiophysics and femtosecond optics are close to the envelope described by the simple odd and even Hermite functions:

$$\Psi_1 = C_1 x \exp(-x^2), \ \Psi_2 = C_2(2x^2 - 1) \exp(-x^2).$$

A similar representation of wide-band anharmonic signals can also be used in problems concerned with the scattering of videopulses by macroscopic bodies.

(iii) By expressing the short signals incident on the boundary of the dispersing medium with the aid of Hermite functions and refraction with the aid of the harmonics (2), it is possible to construct a discrete set of pulses which depend on their duration T_0 through the parameter ΩT_0 (Fig. 2) and, for a fixed duration, on their form. The reflection coefficients of such pulses, determined from the boundary conditions, depend on the angle of incidence and the polarisation of the pulse.

The possible applications of the discrete optics of anharmonic signals are as follows [9]:

1. Controlled formation of femtosecond pulses emitted from an optical compressor.

2. Selection of signals in picosecond radiophysics and femtosecond optics on the basis of their duation.

3. Discrimination of the reflective pulses in terms of the form of the envelope.

4. Filtration of anharmonic signals on the basis of their polarisation.

5. Nondisruptive monitoring and nonstationary changes in the surface parameters of dispersing media.

It is noteworthy that the pulse electrodynamics of anharmonic signals, developed here outside the framework of the concept of travelling waves, does not contain any traditional electrodynamic parameters: the wave frequency and wavelength, the refractive index, and the phase velocity. Nonstationary processes involving rapid deformation of pulses interacting with the dispersing medium are described here in terms of a linear problem model. On the other hand, direct exact analytical solutions of the Klein–Gordon equation [1] are also of interest for many problems of infrastructure, plasma physics, and waveguide systems of different physical nature.

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Biophysical kinetics of the transport of oxygen by blood

M V Fok, A R Zaritskii, G A Zaritskaya,
E V Perevedentseva

It has now come to be assumed that oxygen is retained in erythrocytes as a result of its addition to haemoglobin, while the erythrocyte membrane is readily permeable and does not constitute an obstacle to oxygen. However, analysis of physiological data suggests that the membrane participates in the regulation of the oxygen flux through it. To test this hypothesis, an apparatus was constructed in which the oxygenation and deoxygenation of blood could be investigated quantitatively under conditions where the diffusion of oxygen is susceptible to calculation. In this apparatus, the degree of oxygenation was determined with the aid of an optical oxymeter at each instant. Preliminary results have already been published [1–5].

According to our calculations, the dependence of the degree of oxygenation of blood α on time t in our apparatus is described by the formula

$$\int_{\alpha_O}^{\alpha} \frac{d\alpha}{P_O - P_{er}(\alpha)} = St, \qquad (1)$$

where P_O is the partial pressure of oxygen in the atmosphere; P_{er} its tension in the erythrocyte cytoplasm; $\alpha_O = \alpha(O)$; and S is a constant which depends on the parameters of the apparatus, the amount of blood, and the permeability ρ of the erythrocyte membrane to oxygen. The $P_{er}(\alpha)$ relation is known from the literature. Therefore the left-hand side of Eqn (1) may be calculated theoretically and the $\alpha(t)$ relation may be obtained, When it is plotted on a logarithmic scale along the t axis the experimental relation $\alpha(t)$ may be made to correspond to it by a simple shift along the abscissa axis (Fig. 1a). It is seen that the agreement is satisfactory. Having found S from Eqn (1), we can also calculate the deoxygenation curve, for example at $P_O = 0$. It should coincide with the experimental curve without any shift (Fig. 1b). However, a satisfactory coincidence is observed only for low rates of oxygenation $\dot{\alpha}$. For high values of $\dot{\alpha}$, the experimental $\alpha(t)$ curve deviates from the calculated curve at the end of the oxygenation process. This is particularly notable in terms of the $\dot{\alpha}(t)$ coordinates. Fig. 2 presents this relation for three areas of contact σ between blood and air. At the beginning of the oxygenation a high value of σ corresponds to a high value of $\dot{\alpha}$, as expected, but subsequently the curves intersect and $\dot{\alpha}$ proves smallest for the highest value of σ. Hence it follows that, for a high initial values of $\dot{\alpha}$, an additional obstacle interfering with the permeation of oxygen into the erythrocyte arises. Since the remaining conditions remain unchanged, such an obstacle may only be a decrease in the permeability of the erythrocyte membrane to oxygen.

Having measured the oxygen concentration in the blood plasma and the rate of its consumption in the erythrocyte, we estimated ρ. We found that in the oxygenation process, ρ dimininished on average by a factor of 70 and that the highest value of ρ in our apparatus was almost two orders of magnitude smaller than our estimate for venous blood in lungs, i.e. the overall range of variation of the permeability exceeded three orders of magnitude. The permeabilities of

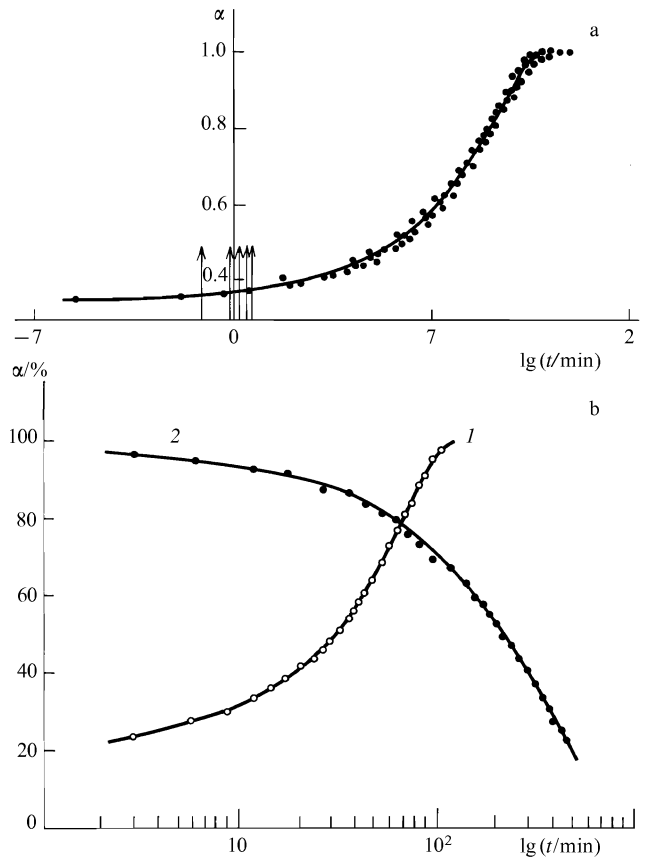

Figure 1. Kinetics of the oxygenation and deoxygenation of donor blood in the apparatus; α = degree of oxygenation (%); t = time (min) (the scale along the abscissa axis is logarithmic). Circles — experimental data; continuous curves — theoretical data. (a) Adjustment to bring into correspondence the experimental and theoretical curves by a shift along the lg t axis. The vertical arrows designate the points at t = 1 min for different experimental curves. The distance between them characterises the difference between the values of S in Eqn (1). (b) Test of the theory on the basis of the deoxygenation curve. (*1*) Theoretical oxygenation curve in best agreement with the experimental curve. The values of S used to calculate the deoxygenation curve (curve *2*), on which the experimental points should fit without any displacement, was found from it.

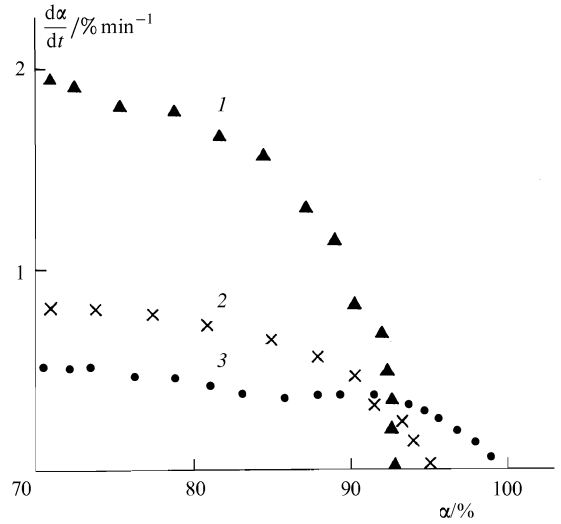

Figure 2. Dependence of the rate of deoxygenation $d\alpha/dt$ on the degree of oxygenation α for three areas of contact between blood and air σ. The increasing numbers opposite each curve correspond to a decrease in the area of contact.

various biological membranes to water vary in the same range [6].

We shall consider the possible molecular mechanism of this effect. An appreciable proportion of the surface of the cell membrane is occupied by a bilayer lipid membrane in which the lipid molecules are directed with their dipolar ends ('heads') to the outside and with their hydrocarbon chains ('tails') towards the interior of the membrane. We suggest that small molecules (O_2, CO_2, H_2O, and possibly also glucose) pass through the bilayer via pores that extend right through the lipid bilayer; the number of such pores actually determines the nonspecific permeability of the membrane, and is determined by the presence or absence of long-range order in the packing of lipid molecules in one or both monolayers. If there is no long-range order in the monolayer (its represents a 'two-dimensional liquid'), then the pores arise and vanish in it regardless of the pores in the second layer and coincide with them only fortuitously. However, if a long-range order has been established in one of the monolayers (it represents a 'two-dimensional crystal'), then this monolayer will act as an ordering template for the establishment of long-range order also in the other monolayer, as a result of which the arrangement of the molecules in both layers becomes concerted. A crystal whose thickness is equivalent to two monomolecular layers is formed. All the pores present previously in the first mono-layer are repeated in the second, i.e. they extend right through the membrane. If in the absence of long-range order the pores occupy 0.1% of the surface of the monolayer, then only one pore out of 1000 passes right through the membrane. Under these conditions, even for an unchanged total number of pores, the transition to the state of a two-dimensional crystal increases the permeability of the membrane by a factor of 1000. However, the permeability can become even greater, since the pores are formed in the crystal mainly along edge dislocations at the boundaries of microcrystal blocks (domains) and not as a result of fluctuations.

We believe that the long-range order in the monolayer arises as a result of the electrostatic interaction of the dipolar heads of the lipids. If they are parallel to the normal to the surface of the layer, then like charges on neighbouring dipoles are closer to one another than unlike charges and the dipoles repel one another. They are held in place by the attraction to the water dipoles and by the interaction of the 'tails'. On the other hand, if they are tilted then the attraction of unlike charges on the neighbouring dipoles may exceed the repulsion of the like charges, since the unlike charges approach one another as a result of tilting while the like charges remain at the same distance from one another and from the water molecules (Fig. 3). The dimensions of the heads are such that they may become inclined only by 10°–15° independently of one another, while altogether they can be inclined by more than 45°. For a pronounced tilt, the distance between neighbouring heads becomes rigorously fixed, since it corresponds to a minimum in the potential energy of their electrostatic interaction. Long-range order arises in this way. It disappears as a consequence of the lateral thermal motion of the molecules after all the dipoles have again assumed the erect position.

We shall consider the way in which the membrane passes from the state with erect heads to one with tilted heads. In the transition from being tilted to becoming erect,

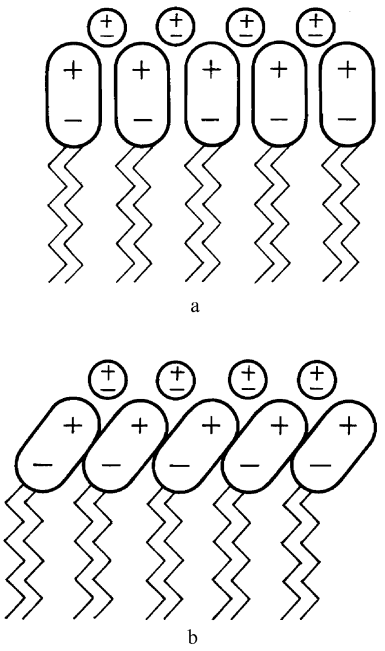

Figure 3. Mutual disposition of the dipolar heads of the lipid molecules and water molecules. (a) Heads oriented along the normal to the surface of the layer (erect heads); (b) tilted heads.

there is a change not only in the electrostatic energy of their interaction but also in the elastic energy associated with the deformation of the covalent bonds between the heads and the 'tails' of the lipids and also in the energy of the mutual repulsion which is responsible for the incompressibility of the condensed phase. Calculation shows that their sum may have two minima corresponding to large and small tilts of the head. The depth and the relative positions of the minima depend also on the electric field strength in the bilayer. When the field strength is low, the minimum corresponding to the tilted heads is deeper than the minimum for the erect heads on either side of of the bilayer. The heads in both monolayers are then tilted for most of the time, there is a long-range order in the disposition of the lipids, and the permeability is high.

The internal medium of the erythrocyte is always negatively charged. In venous blood, the transmembrane potential difference is 8 mV, about half corresponding to the lipid bilayer, since deoxyhaemoglobin is sorbed on the inner side of the membrane and forms a layer of approximately the same thickness as the bilayer itself. Long-range order therefore exists in both monolayers. On the other hand, on rapid oxygenation, the membrane is asymmetric, since the potential difference on the lipid bilayer can reach 40–50 mV according to our estimates and haemoglobin is desorbed from it. The field in the bilayer is stronger and pushes further down the potential minimum of the risen heads on its inner surface. As a result, the heads stay in the erect position longer. However, in such an asymmetric state of the bilayer, the potential differences in the layers of dipolar heads located on either side of the membrane do not cancel out (owing to the difference in their thickness which has arisen). An additional local potential difference arises on the surface of an asymmetric domain and the free charges from the plasma tend to migrate there. They compensate for the potential difference

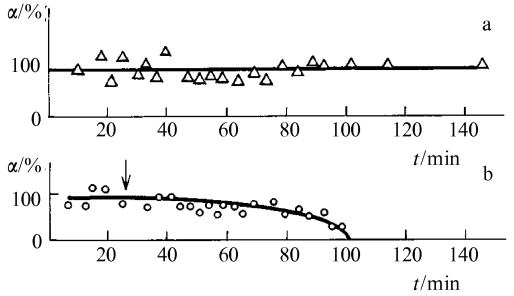

Figure 4. The influence of the electric field on the rate of deoxygenation of blood. The straight line in (a) and the experimental points around it correspond to the situation without a field; the curve in (b) and the points around it correspond to the application of a field.

and fix the heads in the erect position by means of their field. After this, thermal motion disrupts the long-range order in this monolayer and its pores therefore cease to coincide with those in the outer monolayer so that the membrane becomes virtually impermeable to small molecules.

In order to test that the electric field acts on the permeability of the membrane, we constructed an apparatus in which a 50 Hz alternating potential was applied to a thin layer of blood. A steam of carbon dioxide, which, according to the literature [7], promotes the rupture of the bond between oxygen and haemoglobin, was passed over this layer. The potential was such that 15–50 mV corresponded to one erythrocyte. Since the conductivity of blood plasma and of the matter inside the erythrocyte is much greater than the conductivity of the lipid bilayer, this entire potential difference was applied across the erythrocyte membrane. On one side of the erythrocyte, it was added to the trans-membrane potential difference and on the other it was subtracted from it. Since the amplitude of the applied potential was fairly high, the overall potential difference was fairly low in each half-period first on one and then on the other edge of each erythrocyte. On the other hand, there is a possibility of the appearance of long-range order and hence of pores extending right through. It was therefore expected that the outer field would promote the deoxygenation of blood. It was found that, in the absence of a field, blood was not deoxygenated over a period of 1.5 h, whilst under the influence of the field it lost the entire amount of oxygen during this time (Fig. 4). Calculation shows that 1.5 h is the time necessary for the entire amount of stored oxygen to diffuse through the thickness of the layer investigated, i.e. under the influence of the applied field the erythrocyte membranes really ceased to retain oxygen.

Apart from the desorption and adsorption of haemoglobin, the increase in the potential difference on the erythrocyte membrane in the lungs is one of the causes altering the field in the membrane *in vivo*. This occurs, first, because oxyhaemoglobin is a stronger acid than deoxy-haemoglobin. For this reason, oxygenation leads to an increase in the concentration of protons within the erythrocyte, the protons diffusing to the outside, carrying away the positive charge, and increasing the excess negative charge on the cytoplasm. The second cause is the removal of carbon dioxide. It can be removed from blood solely in the form of neutral CO_2 and is present in blood mainly in the form of HCO_3^- ions. On the other hand, the reaction

$H^+ + HCO_3^- \leftrightarrow CO_2 + H_2O$ occurs mainly within the erythrocyte, since the enzyme accelerating it by a factor of hundreds is present only there. Therefore in the lungs HCO_3^- ions enter the erythrocyte and neutral CO_2 molecules emerge, which increases still further its negative charge and hence also the transmembrane potential difference. Subsequently, it is maintained by ion pumps, which transfer in each cycle three Na^+ ions to the ouside and two K^+ ions into the interior of the erythrocyte, maintaining thereby the negative charge on erythrocytes.

In tissue capillaries, these processes proceed in the opposite direction but their onset requires an increase in the permeability of the erythrocyte membrane to prevent the ion pumps from maintaining the potential difference at the previous level. At the beginning, the field in the membrane diminishes somewhat owing to the clamping to the outer erythrocyte surface of the negative charges on glycophorin (one of the membrane proteins) filaments. So long as the blood vessel diameter is greater than the erythrocyte diameter, these filaments float freely in the plasma and their charges are shielded by plasma ions. But when the erythrocyte comes into contact with the wall of the capillary, plasma is squeezed out and the charges on the glycophorin filaments partly neutralise the positive charge in the Debye layer on the outer surface of the erythrocyte. The field in the membrane diminishes and chains of pores extending right through the membrane begin to appear. Oxygen escapes and carbon dioxide enters through these pores, which diminishes still further the potential difference, etc. As a result, the permeability of the membrane increases to an even greater extent.

In conclusion we shall consider the characteristics of the blood circulation system which are difficult to account for from the usual standpoint but which can be explained by the properties of erythrocytes described above.

1. *The existence of the erythrocytes themselves.* A solution of haemoglobin not separated in any way from the walls of blood vessels would give up oxygen in an unlimited amount throughout, including the regions where its excess would be harmful—for example in the brain (artificial blood substitutes may be dangerous for this reason).

2. *The small diameter of the capillaries* (smaller by a factor of 1.5–2 than the diameter of erythrocytes). The onset of the recovery of the permeability of their membranes requires a close interaction with the vessel walls.

3. *The presence of a blood vessel in which part of the venous blood bypasses the lungs and mixes with the oxygen-saturated blood emerging from them.* The erythrocytes from the venous blood absorb the oxygen dissolved in the blood plasma and thereby protect the walls of the arteries against oxidation.

4. *The sharp bends in the capillaries within the brain and the eye retina as well as the internal projections in the eye capillaries.* Oxygen is necessary to supply nerve cells and the cells producing rhodopsin but its excess can oxidise and damage nerve cells. For this reason, the capillary diameter is here greater than the diameter of erythrocytes and the latter 'opens slightly' their membranes only on contact with a projection or with the vessel wall at the site of its bend, releasing a small amount of oxygen precisely where it is necessary, after which the membrane is again 'closed'.

5. *Capillaries in the annular muscles surrounding the large arteries.* These muscles cannot receive directly from the artery, since it is 'imprisoned' in erythrocytes.

6. *The destruction in the spleen of the erythrocytes lacking negative charges on glycophorin.* Such erthrocytes are useless, since they cannot release oxygen in capillaries.

All this confirms both the 'opening–closing' of the erythrocyte membrane and the molecular mechanism of this phenomenon which we have put forward in broad outline. However, there is much work to be done in order to establish its details and quantitative characteristics. This is particularly important, since the existence of a similar mechanism also in other cells, enabling them to adapt to a deficiency of oxygen, follows from normal physiological data.

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