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ON THE ABSORPTIVITY OF A LIMITED VOLUME OF BLOOD SUBJECTED TO EXTRACORPOREAL ULTRAVIOLET IRRADIATION

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A method and results of calculations of the absorptivity of a limited volume of blood under the conditions of ultraviolet irradiation in extracorporeal-type apparatuses up to practical use in clinics are presented. The method is based on an approximate analytical solution of the equation of radiation transfer in the 3D geometry for a disperse medium that models blood in a chamber for irradiation. For the given shape of the chamber with relative dimensions 5 × 3 × 1, data on the density of multiply scattered ultraviolet radiation formed at each point of the medium have been obtained. The spectra of the absorptivity, the values of the radiation energy absorbed by the irradiated volume of blood and issuing from the medium through the chamber walls, as well as the volumes of the zones of effective irradiation of erythrocytes for the whole and diluted blood have been calculated.

Introduction. Medical and clinical practice makes wide use of the ultraviolet (UV) irradiation of blood by a laser or other types of sources [1–3]. As evidenced by many biophysical and clinical-experimental investigations, the most probable mechanism responsible for the medicinal effect of UV radiation is in stimulation of the functional activity of the blood cellular elements (mainly erythrocytes) which is increased as a result of the freeing of their membrane layer of the accumulated products of inflammatory reactions in the organism [4]. In the medical literature UV irradiation of blood is related to the field of quantum photohemotherapy [5–7]. For carrying out irradiation, apparatuses of intercorporeal and extracorporeal types are used. In apparatus of the latter type the blood is drawn into a chamber with transparent walls, it is irradiated *in vitro* from a source of UV radiation, and is then brought back into the patient's organism [6]. Usually, the volume of blood in the chamber is limited (no more than 1 ml). Blood is an optically dense disperse medium with a low transmission coefficient. Attenuation of UV radiation in such a medium occurs predominantly due to the events of multiple scattering. Therefore an irradiated volume of blood is related to a class of strongly scattering three-dimensional objects. Whole blood is a multicomponent disperse medium consisting of optically active cellular elements: mainly erythrocytes (with a volume concentration $C_v \approx 0.4$) and leukocytes and thrombocytes ($C_v \approx 0.01$). The remaining part of the blood volume is occupied by a practically transparent plasma. The erythrocytes contain molecules of hemoglobin that are easily oxidized into molecules of oxyhemoglobin, thus determining the needed saturation of blood with oxygen (oxygenation O_{bl}). The high intrinsic absorption of the hemoglobin and oxyhemoglobin molecules in the UV region of the spectrum exerts a small influence on the characteristics of radiation scattered by an erythrocyte as an individual particle. At the same time, this relatively weak absorption of radiation in each elementary event of scattering is increased considerably due to the high multiplicity of scattering in the volume of the medium. Therefore correct estimation of the efficiency of UV irradiation of the blood erythrocytes *in vitro* requires the solution of a complex boundary-value problem of the theory of transfer for multiply scattered radiation in a limited volume of the medium. This problem refers to the class of problems in the theory of radiation transfer in 3D geometry that arise in solving the problems of transfer in biophysics, atmospheric optics, nuclear power engineering, astrophysics, gas dynamics, etc. Usually they are solved either by the Monte Carlo method or by methods of numerical solution that require much computer time. By essence the radiation transfer represents an infinite sequence of collisions of photons with a medium up to the moment of their escape beyond the medium limits through the boundary. The necessity of taking into account the effects on the medium boundary under the conditions of mul-

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tiple scattering of photons makes the solution of the problem difficult. The well-known approximations of the radiation transfer theory for an infinite or semiinfinite geometry often do not allow one to obtain physically correct inferences on the magnitude of absorbed radiation in limited real media and therefore make investigations of the efficiency of extracorporeal UV irradiation of blood difficult. Devoid of the reliable information on the absorptivity of a limited volume of blood, in carrying out investigations in the practice of medicinal investigations one has to restrict oneself up to now to controlling the doses of external UV irradiation.

The aim of the present investigation is to develop an efficient method for studying the theory of radiation transfer for a three-dimensional medium at a high scattering anisotropy, to calculate the magnitudes of absorbed and scattered UV radiation by a limited amount of blood, and to study the possibilities of optimizing the clinical method of extracorporeal UV irradiation.

Statement of the Problem of Radiation Transfer Theory for a Limited Amount of Blood. Radiation transfer in a disperse medium under the conditions of multiple scattering is described by the integrodifferential equation

$$(\Omega\nabla)\, I(\mathbf{r}, \Omega) + \varepsilon I(\mathbf{r}, \Omega) = \frac{\varepsilon\Lambda}{4\pi} \int_{\Omega'} x(\Omega, \Omega')\, I(\mathbf{r}, \Omega')\, d\Omega' + B_1(\mathbf{r}, \Omega)\,. \tag{1}$$

Here $I(\mathbf{r}, \mathbf{\Omega})$ is the intensity of scattered radiation as a function of the position of the point $\mathbf{r} = \mathbf{r}(x, y, z)$ and of the beam direction $\mathbf{\Omega} = \mathbf{\Omega}(\vartheta, \varphi)$ in the medium; $x(\mathbf{\Omega}, \mathbf{\Omega}') = 4\pi f(\mathbf{\Omega}, \mathbf{\Omega}')$ is the light scattering indicatrix (phase function), $(\mathbf{\Omega}, \mathbf{\Omega}') = \cos\theta = \mu$; ε and Λ are the radiation attenuation index and the probability of the survival of a quantum (albedo of single scattering), respectively. The source function $B_1(\mathbf{r}, \mathbf{\Omega})$ is expressed in terms of the irradiance created at the medium boundary:

$$B_1(\mathbf{r}, \Omega) = \frac{\varepsilon\Lambda}{4\pi}\, x(\Omega, \Omega_0)\, \pi F_0 \exp(-\varepsilon z)\,. \tag{2}$$

To obtain dimensionless data normalized to the irradiation dose, we assume that $F_0 = 1/\pi$.

The irradiated volume $V = a \times b \times c$ of blood in the form of a rectangular parallelepiped is oriented along the axes of the Cartesian coordinate system $0xyz$. The boundary of the medium is assumed to be free with the albedo equal to zero. An outer source irradiates the medium along the normal to the face $z = 0$. The equation of transfer (1) is supplemented with the boundary condition

$$I(\mathbf{r}, \Omega) = 0\,, \quad \mathbf{r} = \mathbf{r}_b\,, \tag{3}$$

which shows that there is no scattered radiation incident on the boundary from outside. The problem (1), (3) belongs to a class of multidimensional boundary-value problems of the radiation transfer theory. Its arguments are three spatial and two angular coordinates, and ε, Λ, $x(\mu)$, $B_1(\mathbf{r}, \mathbf{\Omega})$ are the given functions and parameters. Its solution in a general form presents certain difficulties. In [8] we obtained an analytical solution for an idealized linear scattering indicatrix $x(\mu) = 1 + 3g\mu$.

Solution of the Boundary-Value Problem for a Linear Scattering Indicatrix. The solution of the equation of transfer for a linear scattering indicatrix has the form

$$I(\mathbf{r}, \Omega) = J_0(\mathbf{r}) + J_1(\mathbf{r})\, \Omega_1(\Omega) + J_2(\mathbf{r})\, \Omega_2(\Omega) + J_3(\mathbf{r})\, \Omega_3(\Omega)\,, \tag{4}$$

where the functions $\Omega_1(\mathbf{\Omega})$, $\Omega_2(\mathbf{\Omega})$, and $\Omega_3(\mathbf{\Omega})$ correspond to the direction cosines of the beam direction vector. The spatially dependent flow components $J_1(\mathbf{r})$, $J_2(\mathbf{r})$, and $J_3(\mathbf{r})$ can be found on the basis of the expression for the vector $\mathbf{J}(\mathbf{r}) = \mathbf{J}(J_1, J_2, J_3)$:

$$\mathbf{J}(\mathbf{r}) = -\frac{1}{\varepsilon(1 - \Lambda f_1)} \Big[\nabla J_0(\mathbf{r}) - \varepsilon\Lambda f_1\, \mathbf{J}'(\mathbf{r})\Big]\,, \tag{5}$$

where the prime indicates that the primed quantity belongs to the function of sources, $f_1 = g$. The function $J_0(\mathbf{r})$ corresponds to the spherical mean intensity at the point $\mathbf{r}$. It can be found as the solution of the boundary-value problem for the partial differential equation of the second order:

$$\Delta J_0(\mathbf{r}) - D^{-1} 3\varepsilon (1 - \Lambda) J_0(\mathbf{r}) = \varepsilon \Lambda f_1 \nabla \mathbf{J}'(\mathbf{r}) - D^{-1} 3\varepsilon \Lambda J_0'(\mathbf{r}) , \tag{6}$$

where $D = [\varepsilon(1 - \Lambda f_1)]^{-1}$ at the boundary condition

$$\mathbf{n} \nabla J_0(\mathbf{r}) - \frac{3}{2D} J_0(\mathbf{r}) = 0 , \quad \mathbf{r} = \mathbf{r}_b , \quad \mathbf{n} = \mathbf{n}_b . \tag{7}$$

The solution for $J_0(\mathbf{r})$ is expressed in the form of a double series in eigenfunctions [8]. Its successive substitution into Eqs. (5) and (4) leads to corresponding expressions for the vector $\mathbf{J}(J_1, J_2, J_3)$ and intensity $I(\mathbf{r}, \mathbf{\Omega})$ of scattered radiation. In using them, it is possible to find all the needed characteristics of irradiation at each point $\mathbf{r}$ inside the medium and at its boundary. Thus, the flows of multiply scattered radiation outgoing from the irradiated volume through each of the faces is calculated via integration of $I(\mathbf{r}, \mathbf{\Omega})$:

$$F_{x0} = F_{xa} = \int_0^b \int_0^c \int_{\mathbf{n\Omega}<0} I(x = 0, y, z, \mathbf{\Omega}) (\mathbf{n\Omega}) \, dydzd\Omega ,$$

$$F_{y0} = F_{yb} = \int_0^a \int_0^c \int_{\mathbf{n\Omega}<0} I(x, y = 0, z, \mathbf{\Omega}) (\mathbf{n\Omega}) \, dxdzd\Omega ,$$

$$F_{z0} = \int_0^a \int_0^b \int_{\mathbf{n\Omega}<0} I(x, y, z = 0, \mathbf{\Omega}) (\mathbf{n\Omega}) \, dxdyd\Omega ,$$

$$F_{zc} = \int_0^a \int_0^b \int_{\mathbf{n\Omega}>0} I(x, y, z = c, \mathbf{\Omega}) (\mathbf{n\Omega}) \, dxdyd\Omega + \pi F_0 ab \exp(-\varepsilon c) . \tag{8}$$

Here too the flux $\pi F_0 ab \exp(-\varepsilon c)$ produced by nonscattered radiation at the outlet from the medium is taken into account. The flux issuing from the volume through the side faces is equal to $F_{xy} = 2F_{x0} + 2F_{y0}$. The energy of the radiation scattered by the volume in all directions is characterized by the scattering coefficient $W_s = F_{xy} + F_{z0} + F_{zc}$ calculated by summing the fluxes (8). Then the absorptivity W_{abs} (absorption coefficient) of a restricted volume of the medium is determined as the difference

$$W_{abs} = \pi F_0 ab - W_s . \tag{9}$$

However, we note that direct application of the above solution to the problem of blood absorptivity is impossible and requires additional consideration due to the necessity of taking into account the extremely high asymmetry of the blood scattering indicatrix.

Renormalization of the Scattering Indicatrix, the Effective Parameters of the Medium. According to [9], the coefficient of asymmetry of the blood scattering indicatrix lies in the range 0.99–0.995. This means that in an elementary event of scattering the main portion of radiation propagates predominantly forward in the directions close to the direction of external irradiation. We will approximate the blood scattering indicatrix by the Henyey–Greenstein indicatrix with the asymmetry parameter $g = 0.99$:

$$x(\mu) = (1 - g^2)/(1 + g^2 - 2g\mu)^{3/2} . \tag{10}$$

We will define the integral scattering indicatrix as

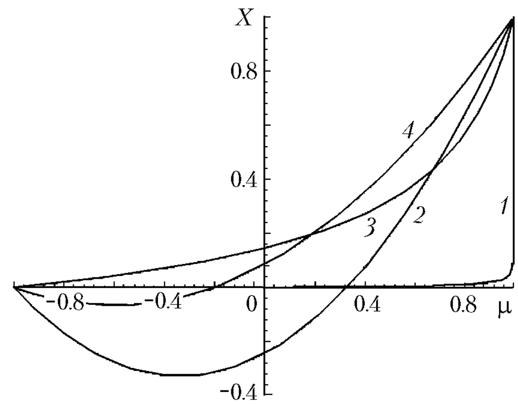


Fig. 1. The Henyey–Greenstein integral scattering indicatrices (1, 3) and linear ones (2, 4): initial (1, 2) and renormalized (3, 4).

$$X(\mu) = \frac{1}{2}\int_{-1}^{\mu} x(\mu)\, d\mu \tag{11}$$

and based on it we will analyze the characteristic features of the scattering of radiation by an elementary volume of blood.

Figure 1 presents the corresponding integral indicatrix 1. Its characteristic feature is the presence of a sharply expressed peak at values of μ close to unity; this corresponds to the direction $\theta = 0^{\circ}$. As is seen from Fig. 1, most of the scattered radiation is concentrated in a certain comparatively small interval $\Delta\mu = 0.9$–1. The figure also contains an integral linear indicatrix 2. It differs substantially from curve 1 that approximates the blood indicatrix. Their comparison clearly demonstrates the impossibility of using directly the analytical solution of [8]. We will show that the below-described operation of the renormalization of the blood scattering indicatrix allows one to remove this restriction. For a strongly elongated indicatrix we will relate the scattered radiation in the indicated interval of $\Delta\mu$ to the directly transmitted (unscattered) one without introducing large errors into the integral parameters. This means that in the interval $\Delta\mu = (\mu_n - 1)$ with the parameter $\mu_n = 0.9$ the scattering indicatrix $x(\mu - \Delta\mu)$ takes a value equal to zero. Needless to say, such a change in the indicatrix is only a convenient mathematical technique making the approximate analytical solution of the problem easier. At the same time it is known that at a high volume concentration of blood erythrocytes under real conditions a substantial decrease in scattered radiation may occur in the region of the diffraction peak. As it follows from the theory of fluids and optics of densely packed media [10, 11], this is possible due to the geometric correlation in the spatial position of erythrocytes and to the influence of the physical factor associated with the interference of scattered waves. The thus altered scattering indicatrix in the indicated interval of $\Delta\mu$ already ceases to be a normalized characteristic of blood; it requires renormalization according to the condition

$$\frac{1}{2}\int_{-1}^{1} x_n(\mu)\, d\mu = 1\,. \tag{12}$$

The integral radiation scattering indicatrix $X_n(\mu)$ obtained as a result of renormalization for an elementary volume of blood is represented by curve 3. Its asymmetry coefficient is equal to $g_{red} = 0.55$, which is much lower than the given initial value. For comparison Fig. 1 presents a linear integral indicatrix 4 with the same asymmetry parameter. As is seen, it already satisfactorily reproduces the form of the approximated normalized scattering indicatrix of blood. Due to the high multiplicity of scattering, their observed differences manifest themselves weakly in the angle-integral characteristics of scattered radiation (relative changes in the fluxes do not exceed 2%). Here we note that small variations of the introduced parameter μ_n relative to the selected value 0.9 do not lead to noticeable errors in g_{red}. Account for the introduced renormalization of the scattering indicatrix in carrying out calculations by the method of [8] requires

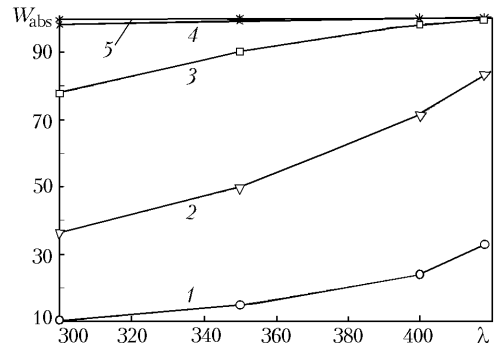


Fig. 2. Spectra of the absorptivity $W_{abs}(\lambda)$ of a limited volume of blood at different degrees of dilution: 1) $(1 - \lambda)\cdot 100$; 2) n = 100; 3) 30; 4) 10; 5) 3. λ, nm.

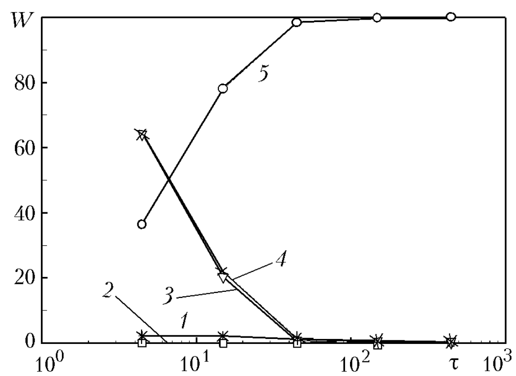
transition to reduced parameters of the elementary volume of the medium. The given values of the attenuation index ε_{red} and of the probability of the survival of the quantum Λ_{red} are calculated from the formulas

$$\varepsilon_{red} = \varepsilon \left\{ 1 - \Lambda \left[1 - X(\mu_n)\right] \right\}, \quad \Lambda_{red} = \Lambda X(\mu_n) / [1 - \Lambda (1 - X(\mu_n)] \,. \tag{13}$$

Thus, the transformation of the equation of transfer (1) to the system of differential equations (5), (6), the renormalization of the initial scattering indicatrix according to (11) and (12), and transition to the reduced parameters of the elementary volume of the medium (13) are the major features of the approximate analytical method employed here for solving the problem of absorption by a limited volume of blood in the case of extracorporeal UV irradiation.

Comparison of Calculations with the Data of Other Methods. The proposed method of calculation of the blood absorptivity was error-tested by comparing it with the well-known most accurate data from the optics of clouds obtained by the Monte Carlo method for a plane cloud layer [12] and by the finite-difference method [13] for a cloud having the shape of a cube. The comparison is based on the fact that the dimensionless optical parameters of the cloud medium and blood in a diluted state have close values. The plane cloud layer with the dimensionless optical thickness $\tau = \varepsilon c = 64$, $\Lambda = 0.9$ and the scattering indicatrix of the type of C.1 [12] with the asymmetry factor $g = 0.855$ was modeled by a limited volume with the relative dimensions $20 \times 20 \times 1$ ($a/c = 20$, $b/c = 20$). The Monte Carlo method for the plane cloud layer yields the values for the reflected flux $F_{z0} = 11.77\%$ and the absorption coefficient $W_{abs} = 88.23\%$. The calculation by the proposed method with $\mu_n = 0.9$ yields: $F_{z0} = 11.44\%$, $W_{abs} = 88.30\%$, $W_s = 11.70\%$, $F_{xy} = 0.26\%$ with the time of calculation on a computer in the MATLAB medium being equal to about 1 sec. These data point to the good agreement of the results. For a cloud in the form of a $1 \times 1 \times 1$ cube a comparison of the distribution of the radiation flux density E_{z0} on the upper boundary of the cloud was carried out at $x/c = 0.5$, $\tau = 10$, $\Lambda = 0.9$, and $g = 0.75$. The flux density obtained by the finite-difference method was equal to $E_{z0}(x/c = 0.5;\ y/c = 0.5;\ z/c = 0) = 0.45$. The calculation by the proposed method yields the value $\pi J_0(\cdot) - (2/3)\pi J_3(\cdot) = 0.455$, whereas the horizontal distributions $E_{z0}(y/c;\ x/c = 0.5)$ agree well in form, i.e., the calculated data virtually coincide. The errors in the results of calculations depend on both the assumptions made and the errors in the initial data on the parameters of the elementary volume of blood.

Results of Calculation. In calculations we considered a limited volume of blood in the form of a rectangular parallelepiped with relative dimensions $5 \times 3 \times 1$; this corresponds to the shape of the UV irradiation chamber [6]. The geometric dimensions of the chamber are equal to $1 \times 0.6 \times 0.2$ cm. The initial parameters of the elementary volume of the whole blood at the hematocrit value H = 0.4 and oxygenation $O_{bl} = 0.75$ have been selected according to the data of [9, 14]. The following wavelengths were considered: λ = 300, 350, 400, and 418 nm. The respective values of the radiation attention index and of the probability of quantum survival are equal to ε = 2222.7, 2345.9, 2624.2, and 2730.7 1/cm, Λ = 0.899, 0.852, 0.762, and 0.672. The coefficient of the scattering indicatrix asymmetry is g = 0.99 [9]. Note that the initial data on the value of ε for the UV range of waves obtained from different sources differ substantially, and the differences may reach three times or more. Models of blood in a diluted state with lower values of ε resulting after the initial data for a whole blood were decreased an n number of times. In the calculations we



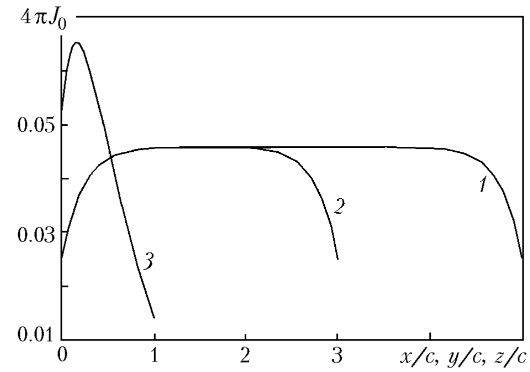


Fig. 3. Dependence of the integral characteristics W of scattered radiation on the optical thickness τ at λ = 300 nm: 1) F_{xy}; 2) F_{z0}; 3) F_{zc}; 4) W_s; 5) W_{abs}.

Fig. 4. Distribution of the UV irradiance of erythrocytes over the symmetry axes of a limited volume of blood inside the chamber: 1) in the $0x$ direction; 2) $0y$; 3) $0z$.

selected the values of n equal to 3, 10, 30, and 100. Values of ε whose step differed by three times were selected in order to estimate the results with account of the mentioned discrepancies in the initial data.

The spectra of the absorptivity $W_{abs}(\lambda)$ of the given volume of blood (whole and diluted blood) under the conditions of multiple scattering in the range λ = 300–418 nm are given in Fig. 2. Curve 1 corresponds to $(1 - \Lambda)\cdot 100$ for blood on the condition of single scattering. As is seen from Fig. 2, in going over to higher blood concentrations (curves 2, 3, 4, 5) the spectral dependence is first somewhat enhanced and then is sharply attenuated. For an undiluted blood it disappears entirely; at all wavelengths the absorptivity (within the error) is close to 100%. The above-noted discrepancy in the initial data does not alter this inference. Vice versa, for diluted blood, account for the data discrepancy is very important.

Changes in the absorptivity of the irradiated volume of blood scattering coefficient, and in the fluxes of scattered radiation issuing through different faces on increase in the optical thickness are shown in Fig. 3. With increase in the optical thickness the absorptivity W_{abs}, beginning from the value 36% at τ = 4.4, increases rapidly and reaches 100%. The scattering coefficient W_s, determined predominantly by the transmitted flux F_{zc}, decreases with increase in the optical thickness, beginning from the value 64.6% that exceeds the value of W_{abs}. However, this relationship is preserved only for wavelengths near λ = 300 nm. In the range $350 < \lambda < 418$ nm, $W_s < W_{abs}$ at all optical thicknesses. The flux F_{xy} outgoing through the side faces of the volume is insignificant.

Figure 4 presents the distributions of the spatial irradiance $4\pi J_0$, which is proportional to the volumetric density of radiation, along the symmetry axes of the irradiated volume in the transverse $0x$, $0y$ and longitudinal $0z$ directions formed by the scattered UV radiation at λ = 350 nm and τ = 15.6. In the transverse directions the dependences obtained (curves 1 and 2) have a characteristic symmetric form with a central maximum. In the $0x$ direction the distribution maximum is not so distinct as in the $0y$ direction. For the longitudinal direction $0z$ (curve 3) the distribution is asymmetric with the maximum displaced toward the irradiated face. As τ increases, the distributions in the transverse directions are gradually smoothed, whereas in the longitudinal direction one observes an increasing displacement of the maximum toward the irradiated face. It should also be noted that inside the medium the scattered radiation density in the maximum is more than 25% higher than its value at the inlet to the medium. In the case of whole blood with a maximum concentration of erythrocytes virtually the entire energy of the UV radiation is concentrated in a very small zone (with a thickness of 2–3% of the value of c) adjoining the irradiated face. The remaining part of the blood volume remains practically unirradiated, pointing to the extremely nonuniform irradiation of erythrocytes. Their more uniform irradiation is attained by diluting the whole blood.

The volumes of the zones of effective irradiation of erythrocytes (in % of the chamber volume) that correspond to the levels >1, 1/2, 1/4, 1/8 relative to the irradiation level at the inlet to the medium are illustrated by Fig. 5. The dependences of the volumes on the optical thickness τ are expressed by curves 1–3 for the scattered radiation and by 4–6 for the unscattered one. The errors of the volumes are of the order of 5%. The quantitative data given allow

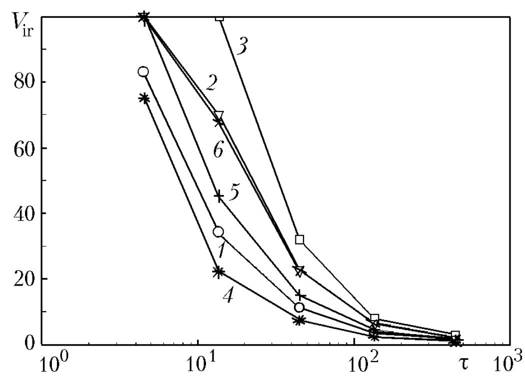


Fig. 5. Dependence of the relative volumes V_{ir} of the zones of effective irradiation of erythrocytes due to the scattered (curves 1–3) and unscattered (4–6) components on the optical thickness τ at λ = 350 nm and different levels of irradiance: 1) level >1; 2 and 4) 1/2; 3 and 5) 1/4; 6) 1/8.

one to estimate the changes occurring in the volumes of the zones of effective irradiation of erythrocytes due to both blood dilution and selection of the irradiation level. It is seen that in a diluted state it is possible to attain even a 100% volume of the zone of effective irradiation of erythrocytes at its rather high level (of the order of 1/4), i.e., to ensure a relatively uniform irradiation in the entire volume of the chamber. The data given may be of interest for optimization of the technique of extracorporeal UV irradiation of blood.

Conclusions. An approximate analytical method of solving the equation of radiation transfer in a 3D geometry for disperse media with a highly elongated scattering indicatrix is suggested. The method consists of transformation of the transfer equation into a system of partial differential equations and its solution, of carrying out renormalization of the scattering indicatrix of radiation, and of transition to reduced parameters of an elementary volume of the medium. The method is applied to the solution of the problem of absorption by a limited volume of blood in the form of a rectangular parallelepiped with relative dimensions $5 \times 3 \times 1$ under the conditions of extracorporeal UV irradiation. The results of calculations allow the following conclusions to be drawn. In the UV region of the spectrum the investigated volume of whole blood is characterized by absorption that is close to 100% and that practically is spectrally independent. The spectral dependence is evident only for blood in a diluted state. Dilution of blood leads to a sharp decrease in the absorptivity W_{abs} and to an increase of the scattering coefficients W_s that may exceed the value of W_{abs}. The distributions in the density of scattered radiation inside the chamber in the transverse and longitudinal directions relative to the direction of irradiation have been found. The dimensions of the zones of effective irradiation of erythrocytes and zones free of irradiation for whole and diluted blood have been found. The data obtained may be of interest for refining the corresponding techniques of clinical investigations.

NOTATION

a, b, c, length, width, and height of a parallelepiped; $B_1(\mathbf{r}, \mathbf{\Omega})$, function of sources; D, length of diffusion of scattered radiation; E_{z0}, radiation flux density; f_1, average cosine of the scattering indicatrix; πF_0, incident light flux; F_{x0}, F_{xa}, F_{y0}, F_{yb}, F_{z0}, and F_{zx}, scattered radiation fluxes outgoing through the faces $x = 0$, $x = a$, $y = 0$, $y = b$, $z = 0$, and $z = c$, respectively; g, g_{red}, coefficients of the asymmetry of scattering indicatrices; H, hematocrit vale; $I(\mathbf{r}, \mathbf{\Omega})$, scattered radiation intensity; $J_0(\mathbf{r})$, spherical-mean intensity; $4\pi J_0$, spatial irradiance; $J_1(\mathbf{r})$, $J_2(\mathbf{r})$, $J_3(\mathbf{r})$, densities of scattered radiation fluxes along the axes $0x$, $0y$, $0z$, respectively; $\mathbf{n}_b$, unit vector of the internal boundary normal to the medium; n, multiplicity of changes in the initial data; O_{bl}, parameter of blood oxygenation; $\mathbf{r}$, radius-vector of a point; V, volume of the chamber; V_{ir}, relative volume of the zone of effective irradiation; $W \equiv \{F_{xy}, F_{z0}, F_{zc}, W_s, W_{abs}\}$; W_s, coefficient of scattering of a limited volume of the medium; W_{abs}, absorptivity; $x(\mu)$, $x_n(\mu)$, radiation scattering indicatrices; $X(\mu)$, $X_n(\mu)$, integral indicatrices of scattering; ε, ε_{red}, indices of radiation attenuation; λ, radiation wavelength; Λ, Λ_{red}, probabilities of quantum survival; μ, cosine of scattering angle; μ_n, parameter of renormalization of the scattering indicatrix; ϑ, φ, polar and azimuthal angles in a spherical coordinate system; θ, angle of scattering; τ, optical thickness;

$\mathbf{\Omega}'$, $\mathbf{\Omega}$, unit vectors of the direction for incident and scattered beams; $\mathbf{\Omega}_0$, unit vector of the direction of external irradiation; Ω_1, Ω_2, Ω_3, direction cosines of the vector of beam direction. Subscripts: abs, absorbed; b, medium boundary; bl, blood; ir, irradiation; n, normalized; red, reduced; s, scattered; v, volumetric.

REFERENCES

1. V. V. Kirkovskii, O. V. Klimovich, and G. I. Levashenko, Extracorporal UV irradiation of blood in a single-use blood-flow device, *Izv. Bel. Inzh. Akad.*, No. 2 (16), 66–69 (2003).
2. B. I. Verkin, A. V. Beresneva, V. F. Udovenko, et al., *Apparatuses for UV Irradiation of Blood*, Preprint, FTINT, Khar'kov (1986).
3. Mechanisms of the effect of UV-irradiated blood on the organism of a human being and animals, in: *Collected papers of the Institute of Physiology*, *Academy of Sciences of the USSR* [in Russian], Nauka, Leningrad (1986).
4. L. A. Dement'eva, *Possible Mechanism of the Biological Action of UV Irradiation of Blood*, Preprint 132B of the Institute of Biophysics, Academy of Sciences of the USSR, Krasnoyarsk (1990).
5. *Application of UV Irradiation of Blood in Medicine*, *Collected papers of Mordovia University*, Saransk (1992).
6. G. I. Levashenko and N. V. Mazaev, UV irradiator of blood with a single-use blood flow system, *Zh. Prikl. Spektrosk.*, **66**, No. 2, 289–292 (1999).
7. G. I. Levashenko, V. S. Ulashchik, V. V. Kirkovskii, and I. V. Kremenevskii, On certain aspects of the application of UV irradiation of blood, *Izv. Bel. Inzh. Akad.*, No. 1 (9), 50–53 (2000).
8. A. B. Gavrilovich and N. Ya. Radyno, Solution of the boundary-value problem for the equation of radiation transfer in a limited volume of a dispersion medium with a linear scattering indicatrix, *Inzh.-Fiz. Zh.*, **79**, No. 2, 27–34 (2006).
9. W.-F. Cheong, S. A. Prang, and A. J. Welch, A review of the optical properties of biological tissues, *IEEE J. Quantum Electronics*, **26**, No. 12, 2166–2184 (1990).
10. R. Balescu, *Equilibrium and Nonequilibrium Statistical Methods* [Russian translation], Mir, Moscow (1978).
11. A. P. Ivanov, V. A. Loiko, and V. P. Dik, *Propagation of Light in Densely Packed Media* [in Russian], Nauka i Tekhnika, Minsk (1988).
12. J. Lenoble (Ed.), *Radiative Transfer in Scattering and Absorbing Atmospheres* [Russian translation], Gidrometeoizdat, Leningrad (1990).
13. S.-Ch. S. Ou and K.-N. Liou, Numerical experiments on the Helmholtz equation derived from the solar radiation transfer equation in three-dimensional space, *Appl. Math. Comput.*, **7**, No. 2, 155–175 (1980).
14. B. B. Barun and A. P. Ivanov, Effect of hemoglobin localization in erythrocytes on optical absorption by human blood, in: *Proc. 10th Conf. on Electromagnetic and Light Scattering*, Bodrum, Turkey (2007), pp. 5–8.