By estimating the maximal error $\delta_a$ and $\delta_s$, we found that substitution of $\Delta V_{\lambda_2}/V_{\text{min} \lambda_2} = 0.1$ and $\alpha = 0.4$ into Eq. (8) gives $\delta_a = 0.27\%$ and $\delta_s = 0.095\%$.

**CONCLUSIONS**

1. Within the range $0.75 < S < 1$, the values of coefficient $\alpha$ are from 0.4 to 1.5 for wavelengths $\lambda_1 = 650, 660 \text{ nm}$ and $\lambda_2 = 805, 940 \text{ nm}$.

2. Errors in calculation of $\delta_s$ within the range of $S$ from 0.75 to 1.0, as calculated from $\alpha$ using simplified Eqs. (5) and (8), are more than 1% and 0.095% for wavelengths $\lambda_1 = 650, 660 \text{ nm}$ and $\lambda_2 = 805, 940 \text{ nm}$, respectively.

**LITERATURE CITED**


**PRINCIPLES OF OPTICAL OXIMETRY IN EXTRACORPOREAL CIRCULATION SYSTEMS**

S. N. Perov, N. P. Korotkov, V. V. Kuzemko, S. D. Zakharov, and V. A. Simanov

The problem of monitoring the degree of blood saturation with oxygen during surgical operations assisted by systems of artificial circulation initiated the development of a class of devices based on optical measurements. Optical recording is possible since oxygenation of hemoglobin changes its absorption spectrum (Fig. 1). In addition, blood can be regarded as a dense, randomly inhomogeneous scattering and absorbing medium ($H = 40\%$) with effective radius of scattering domains of 2.6 $\mu\text{m}$. The basic characteristics of oxygenated and nonoxygenated erythrocytes, such as transport cross-section $\sigma_{\text{tr}}$, absorption cross-section $\sigma_a$, scattering cross-section $\sigma_s$, mean cosine of scattering angle $\mu$, and refraction coefficient $n = n_0 + i\cdot n_0^*$ are known (Table 1).

By the principle of recording, all measuring devices can be divided into two groups. The first group of devices measures the optical density $D$ of prehemolized blood over several ranges of wavelengths and calculate concentration of oxyhemoglobin from the measured data. The Radiometer OSM-2 oximeter (Denmark) is a representative of this group. Devices of the second group measure the degree of oxygenation of $\text{StO}_2$ in the whole blood. These devices measure light scattering in erythrocytes, which is recorded as light reflection from a semi-infinite layer of blood over two spectral ranges. The scheme for such measurements is presented in Fig. 2. Table 1 shows that oxygenation considerably changes the absorption cross-section $\sigma_a$, leaving the scattering cross-section $\sigma_s$ practically unchanged, thus allowing changes in reflected light intensity to be correlated with the level of saturation of blood with oxygen. The Physio-Control (USA) and Bentley OxySAT Meter (USA) oximeters are representatives of this group, the former being equipped with a fiber-optic probe for intravascular measurements, and the latter measuring light reflected from a cell with a plane-parallel front wall. An empirical equation linking the blood saturation with oxygen and reflectance in the infrared $R_i$ and red $R_r$ spectral ranges is valid for these devices:

$$a = A - B \cdot (R_i/R_r),$$

where $A$ and $B$ are empirical constants determined by the design of the device.
Fig. 1. Absorption spectra of hemoglobin (1) and oxyhemoglobin (2). Abscissa axis, monitoring wavelength $\lambda$; ordinate axis, molar extinction coefficient $\kappa$.

Fig. 2. Measurement of light reflection by two fiber-optic light guides: 1) erythrocytes; 2, 3) fibers for sending and receiving of light, respectively.

TABLE 1. Basic Optical Characteristics of Erythrocytes [5]

<table>
<thead>
<tr>
<th>StO$_2$, %</th>
<th>$\lambda$, $\mu$m</th>
<th>$\pi$</th>
<th>$n^2 \cdot 10^4$</th>
<th>$\sigma_s$, $\mu$m$^2$</th>
<th>$\sigma_t$, $\mu$m$^2$</th>
<th>$\mu$</th>
<th>$\rho \sigma_r$, $\mu$m$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.665</td>
<td>1.036</td>
<td>0.240</td>
<td>57.20</td>
<td>0.080</td>
<td>0.9951</td>
<td>0.747</td>
</tr>
<tr>
<td>0.955</td>
<td>0.665</td>
<td>1.036</td>
<td>0.111</td>
<td>33.47</td>
<td>0.191</td>
<td>0.9925</td>
<td>0.666</td>
</tr>
<tr>
<td>0</td>
<td>0.655</td>
<td>1.036</td>
<td>2.203</td>
<td>56.58</td>
<td>0.542</td>
<td>0.9951</td>
<td>0.738</td>
</tr>
<tr>
<td>0.955</td>
<td>0.655</td>
<td>1.036</td>
<td>0.052</td>
<td>33.54</td>
<td>0.090</td>
<td>0.9925</td>
<td>0.668</td>
</tr>
</tbody>
</table>

It should be noted that the spectral range 0.6-0.7 $\mu$m is most sensitive to change in StO$_2$, while another range, 0.8-0.9 $\mu$m, is practically insensitive and can serve for excluding effects of other parameters (pH, blood flow rate, etc.) on the blood reflectance, since the latter factors similarly influence both spectral ranges.

We have developed a cell-less oximeter whose performance satisfies contemporary international standards.

Since blood is a dense, randomly inhomogeneous medium ($H = 40\%$), then a diffusive approximation of radiation transfer theory can be applied to it. In the framework of this approximation, the problem of a point source of radiation scattering in an infinite medium can be solved for diffuse intensity [3]:

$$U_d = [(\rho \sigma_n P_0 3/4\pi) \exp (-\kappa r)]/4\pi r,$$

where $U_d$ is the mean diffuse intensity, $\sigma_{tr} = \sigma_s (1 - \mu) + \sigma_n$ the transport cross-section, $\kappa_d^2 = 3 \rho \sigma_n \rho \sigma_{tr}$, $\rho$ the concentration of diffusers, $P_0$ the radiant power of the light source, and $r$ the linear coordinate of the point. Using this equation, we can estimate