A BLOOD FLOW METER BASED ON pO₂ PRIMARY TRANSDUCERS

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In the general case the current of electrochemical reduction of oxygen on the electrode indicator surface of a chronoamperometric primary oxygen transducer (PT) is a function of the parameter of the oxygen concentration in the test medium and its transport to the reaction zone [1].

To solve the problem of determining the oxygen concentration in biological objects by means of such PT, measures are taken to exclude the effect of the "convective" component—the measurement is made in a stationary medium or in a medium with unchanged convective conditions, the diffusion region of PT is reduced by reducing the surface of the indicator electrode and by introducing an additional diffusion membrane resistor and, in some situations, introducing an immobilized layer of the test medium [2, 3]. However, the opposite problem can also be formulated: to distinguish as the value to be measured a signal that is independent of the oxygen concentration in the medium and which reflects the characteristics of the "convective" component of the PT current—the velocity of movement of the medium (for example, the blood flow rate).

The use of the current of the electrochemical reaction on the electrode surface to measure the flow rates of electrically conducting liquids, known as the "electrodiffusion method," has been worked out in detail on the theoretical plane [4] and it lies at the basis of concrete systems for the measurement of velocity and its components [5, 6]. In all cases the concentration of current-forming substances introduced artificially into the test liquid is maintained constant and, consequently, the current of the electrode depends only on the convective characteristics of the medium.

It will be evident that for measurements in biological objects, in the case when molecular oxygen dissolved in them serves as the reagent, such constancy cannot be achieved. For that reason, to distinguish the "convective" component it is necessary to correct the signal received relative to the real level of the oxygen concentration, determined by some other method, for example, by means of a separate oxygen PT insensitive to the dynamic state of the medium (pO₂-PT with a diffusion region that does not extend outside the membrane). This usage of a system of two oxygen-sensitive PTs, one with a large indicator electrode surface and sensitive both to the oxygen concentration and to the velocity of the oxygen-containing medium, the other with a smaller electrode surface, covered with a gas-permeable membrane, which is sensitive only to oxygen concentration, has recently been suggested for measurement of the linear blood flow rate [7]. When PT signals are compared, a component which is a nonlinear function of the blood rate is distinguished. However, the special features of construction of the PT in this case lead to the appearance of unverifiable changes in the graduation characteristics. The currents of PT are proportional to physically different parameters, linked with the oxygen concentration: the current of the large, so-called open, PT is proportional to the oxygen concentration, whereas that of the small PT, covered with a membrane, is proportional to its chemical potential (partial pressure [8]). When conditions affecting the solubility of oxygen in blood plasma change, proportionality between the "oxygen" components of the parameters of both PT therefore changes also, and this leads to the appearance of additional errors. Prolonged exposure of the open electrode to blood results in mechanical and electrochemical contamination of its surface, disturbing both the stability of its work and its sensitivity to the blood flow rate.

These disadvantages can be abolished if both PT of the system for measuring the blood flow rate incorporate a membrane-covered indicator electrode [9].


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The current on a membrane pO₂-PT for a flat indicator electrode is given by the equation [10]:

\[ I = \frac{nFSpO_2}{P_e + P_m + P_c} \]

where \( n \) is the number of electrodes taking part in the electrochemical reaction, \( F \) the Faraday number, \( pO_2 \) the partial pressure of oxygen in the medium for analysis; \( a, b, \) and \( \delta \) the thickness of the layer of the inner electrolyte, the membrane, and the diffusion region respectively, \( P_e, P_m, \) and \( P_c \) the permeability of the above-mentioned components of the juxtaelectrode region to the gas; and \( S \) the area of the indicator electrode.

The only value in (1) which depends on flow rate is the thickness of the diffusion zone \( \delta \). Once the character of this dependence has been established, the requirements for the parameters of the design elements of PT can be determined in order to endow it with the required sensitivity to the rate of flow of the medium for analysis.

For an "open" PT, whose indicator electrode consists of the inner surface of a tube, this problem is solved in [1], and for a flow density \( j \) of current-forming substance in the composition of a homogeneous liquid medium the following equation is obtained

\[ j = 0.67cD \left( \frac{V}{DR} \right)^{1/3} \]

where \( c \) is the concentration of the current-forming substance in the medium for analysis, \( D \) the diffusion coefficient of this substance in the medium, \( V \) the rate of flow of the medium for analysis near the surface of the electrode, \( R \) the radius of the tube, \( \ell \) the length of the indicator electrode along the axis of the tube.

Using the sequence of operations described in [1], when deriving Eq. (2) and integrating for the case when the indicator electrode is a circle with radius \( r \), located flush with the inner surface of the tube, for the complete current of PT we obtain

\[ I = 4.02nFcD \left( \frac{V}{DR} \right)^{1/3} \int_0^r \left( r^2 - z^2 \right)^{1/3} \, dz \]

where \( z \) is the integration variable.

The membrane (closed) PT can be represented as an "open" PT whose indicator electrode serves as the outer surface of the membrane. In that case, if the change in boundary conditions is taken into account during derivation of Eq. (2), the density of flow of the molecules of the current-forming substance will be

\[ j = 0.67 (c - c_1) D \left( \frac{V}{DR} \right)^{1/3} \]

where \( c_1 \) is the concentration of molecules of the current-forming substance (in the present case, oxygen molecules) on the membrane surface \( c_1 < c \).

Meanwhile the density of flow of molecules can be represented in the form [1]

\[ j = \frac{(c - c_1)D}{\delta} \]

whence, considering (3) and (4), an equation reflecting dependence of \( \delta \) on \( V \) is obtained: