Research Article

Transport of Carbon Dioxide through a Biomimetic Membrane

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Biomimetic membranes (BMM) based on polymer filters impregnated with lipids or their analogues are widely applied in numerous areas of physics, biology, and medicine. In this paper we report the design and testing of an electrochemical system, which allows the investigation of CO₂ transport through natural membranes such as alveoli barrier membrane system and also can be applied for solid-state measurements. The experimental setup comprises a specially designed two-compartment cell with BMM connected with an electrochemical workstation placed in a Faraday cage, two PH meters, and a nondispersive infrared gas analyzer. We prove, experimentally, that the CO₂ transport through the natural membranes under different conditions depends on pH and displays a similar behavior as natural membranes. The influence of different drugs on the CO₂ transport process through such membranes is discussed.

1. Introduction

Nitrocellulose filters impregnated with fatty acids and their esters are suitable for modeling of many physicochemical properties of natural biomembranes, including selective barrier properties [1–10]. Such properties are connected both with the presence of a nitrocellulose matrix with fixed cation-exchange groups in the pores impregnated with lecithin and their interaction with water molecules. The similarity of several physical properties of impregnated nitrocellulose filters and biomembranes is determined by the simultaneous coexistence of polymer matrixes with immobilized cation-exchange groups and pores, whose surface is covered with a thin layer of water while they are filled with liquid crystal of lipid-like substances.

In this paper we demonstrate experimentally that carbon dioxide transport through BMM membranes depends on pH using an electrochemical setup combined with two pH-meters and an IR-gas analyzer. The interest in this problem is related to the CO₂ and O₂ exchange in biological membranes of the blood system.

In animal with lungs, the bicarbonate buffer system is an effective physiological buffer with pH = 7.4, because

H₂CO₃ of blood plasma is in equilibrium with a large reserve capacity of CO₂ in the air space of the lungs. This buffer system involves three reversible equilibria between gaseous CO₂ in the lungs and bicarbonate (HCO₃[−]) in the blood plasma (Figure 1) [11–16]. On Figure 2 a SEM picture of a nonimpregnated membrane is given.

2. Materials and Methods

Millipore nitrocellulose membrane filters (average pore diameter about 8 μm; Ireland, Millipore Cat no. SCWP04700) impregnated with 320 mg/mL Lecithine (Sigma Aldrich) in n-tetradecane (Sigma Aldrich; surface area 172 mm² and thickness 100–120 μm, Figure 2), were placed between two compartments (chambers, half-cells) made of Plexiglas (LI and RI). At the opposite side each chamber possesses Ag/AgCl, Au, and Pt electrodes (Figure 3). Both chambers were filled with KCl 10^{−1} M. The whole membrane module was placed in a Faraday cage to prevent electromagnetic interferences. All measurements were performed at 36°C as the solutions were intensively stirred (agitated). The A.C. transmembrane impedance was measured before and after

FIGURE 1: Relations between the respiration and blood plasma buffer system. Notations: HbO_2^- , HbH^+ .

FIGURE 2: SEM image of a cross-section of the non-impregnated membrane, the yellow arrow indicates the thickness of the membrane.

every experimental step in a frequency range from 100 mHz to 100 kHz (signal amplitude applied to the membrane 50 mV) by an electrochemical workstation CHI604 (CH Instruments Ltd., USA). The impedance was plotted in a complex plane (Nyquist Plot). SEM investigations of membranes are performed with a S-570 Hitachi microscope.

3. Experimental Setup

The left (LI) and right (RI) chambers were connected to other two thermostated glass chambers (LII & RII) by silicon tubes. The solutions in the pairs (LI and LII, and RI and RII) compartments were driven to permanent circulation.

At the left chamber (LI) the CO_2 dissolving was accomplished by gas bubbling (blowing) through the

FIGURE 3: The biomimetic membrane divide LI & RI chambers.

corresponding water solution. The process was controlled through pH measurements by a standard pH-meter (pH/mV/Cond/Temp-meter 6350 Lasar Laboratories), connected to PC data acquisition station. CO_2 passes through the membrane into RI compartment and, after the solution reaches the chamber RII, the other pH-meter (pH/mV/ION/Temp-meter 6250, Lasar Laboratories) registrates the changes of pH in right compartment. The CO_2 gas-phase concentration in RII chamber arising due to its desorption from the solution was measured by non-dispersive infra-red gas analyzer (model DX6210, RMT Ltd. accuracy 0,5%, Figure 4).

FIGURE 4: Block scheme of the experiment.

FIGURE 5: Change in CO_2 concentration versus time. (1) Dry non impregnated membrane, empty chambers. (2) Nonimpregnated membrane, compartments filled with 0, 1 M of KCl solution. (3) Membrane impregnated with 320 mg/mL of lecithine in tetradecane solution, chambers filled with 0, 1 M KCl solution.

4. Experimental Results

On Figure 5 the change of CO_2 concentration versus time is demonstrated. BMM is a microheterogeneous structure consisting of polysaccharide matrix contained in fixed ion-exchange groups. These groups interact with water molecules and impregnated lipid-like liquids. The influence of gas inclusions on the experimental data seems of no importance,

because the total cross-section area at the membrane surface is less than 10% of the whole filter area. The data obtained prove that the CO_2 transport depend on liquid impregnation and the mass transport can be controlled in this way.

The first experimental stage is measurements using a dry nonimpregnated membrane with empty compartments of the electrochemical cell. We depicted very short times necessary for CO_2 to pass from LI into RI and then to RII chambers (Figure 5) compared to that measured under other conditions.

The same experimental procedure was applied to non-impregnated filter membranes and LI, LII, RI, and RII chambers filled with 10^{-1} M KCl solution, and then to a lecithin-impregnated filter in the same solution (Figure 5). The results illustrates that the CO_2 transport through BMM is a slow process compared to the transport through non impregnated filters. On Figure 6 the CO_2 transport through an impregnated membrane is depicted in connection with our experimental data for pH. The membrane filter used was impregnated with a lecithine solution in n-tetradecane with a concentration 320 mg/mL.

The change in the gas phase carbon dioxide (CO_2) concentration in RII compartment is combined with changes in pH in RI/RII chambers due to formation of carbonic acid. It is worthwhile to mention here that before and after each CO_2 transport measurement, we have checked the membrane integrity by measuring their impedance (Figure 7).

From data depicted in Figure 6 a dependence of the carbon dioxide content in the gas phase versus pH can be calculated (Figure 8). More details about the dependence obtained will be given in a next contribution.

FIGURE 6: Change in CO₂ concentration and pH value versus time, in RI chamber caused by transport through the BMM.

FIGURE 7: Nyquist plot of the millipore membrane (pore diameter 8 μm) impregnated with 320 mg/mL lecithine in tetradecane versus time: (1) $t = 0$ s (beginning of the experiment), (2) $t = 1800$ s (30 min), (3) $t = 3600$ s (60 min), and (4) $t = 5400$ s (90 min; after the end of the experiment). The BMM impedance remains over 3 M Ω . This means that the BMM is intact.

The as-constructed experimental setup was checked with additional impedance measurements of dense cristobalite ceramic discs with a thickness of 2 mm. From the impedance spectra of the ceramic discs, prepared in our laboratory using a sol-gel procedure, pressing and heating at 1300°C [17], we calculated the dielectric constant of β -cristobalite discs $\epsilon \approx 4.5$ at 100 kHz which is in good agreement with the data published for quartz [18, 19]. For this measurement a special capacitive cell with Au-electrodes was constructed. The calculations of ϵ were performed by removing the impedance spectra of the empty capacitive cell from that the ceramic discs.

5. Conclusions

The CO₂ transport through natural membranes such as alveoli barrier membrane systems can be quantitatively

FIGURE 8: Experimentally proved pH dependence of the CO₂ gas-phase concentration.

described by electrochemical measurements combined with pH measurements and a non-dispersive infra-red gas analyzer. We proved experimentally that the CO₂ transport through BMM under different conditions depends on pH. The demonstrated electrochemical setup allows an additional check of the membrane integrity using impedance spectra measurements during the gas transport and also can be applied for solid-state measurements for dielectric constant measurements.

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