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Experimental Evaluation of the Importance of the Pulmonary Surfactant for Oxygen Transfer Rate in Human Lungs

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The rate of oxygen transport from atmospheric air into water and perfluorocarbon compound (PFC) was investigated. Static and dynamic systems with and without the presence of the lung surfactant monolayer were considered. For the case of water used as an oxygen absorbent, the monolayer activity allowed a simulation of the gas uptake into the lung hypophase. In the second case, a two-phase liquid system with water as a hypophase and PFC as the blood substitute simulated oxygen transport in the alveolus-blood system. Original experimental measurement devices gave the opportunity of determining the gas transport rate with the possibilities of indicating the role of the lung surfactant in the process and evaluating the influence of environmental conditions on the transport phenomena. Results of that work suggest a possible enhancing role of the lung surfactant in the oxygen transfer rate.

lung surfactant blood oxygenation perfluorocarbon compound

1. INTRODUCTION

The pulmonary surfactant (PS) is an essential component of the human lungs. It is composed of specific phospholipids and proteins produced by specialized cells of the alveolar epithelium. The PS forms an active

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monolayer at the gas-liquid interface of the hypophase covering alveoli and non-ciliated bronchioles. The surface activity of the PS plays an important role both in the mechanics of breathing and in the defense processes of the respiratory tract (Gehr et al., 1996; Gradoń & Podgórski, 1995; Podgórski & Gradoń, 1993; Van Iwaarden, 1992). A deficiency of the surfactant, which usually occurs in premature babies, causes a severe lung dysfunction known as the infant respiratory distress syndrome (IRDS) or hyaline membrane disease (HMD). Destruction of the PS stability as a result of inhaling toxic air pollutants (e.g., NO_x, ozone, phosgene, organic vapors, acidic aerosols) typically causes a similar lung disease recognized as the adult respiratory distress syndrome (ARDS). It is often followed by lung edema, which can eventually lead to death. Primary mechanisms of adverse processes in the lungs, which result in ARDS, are most probably related to a disturbance of the thermodynamic state of the PS system.

As demonstrated by several physicochemical studies of the lung surfactant monolayer under simulated toxic conditions (Sosnowski & Gradoń, 1993, 1995, 1997), there is evidence of the degradation of a stable monomolecular film that is believed to be essential for the normal physiological action of PS (Keough, 1992; Notter & Finkelstein, 1984). The presence of such a unique structure in the breathing organ leads to a question of its role in the gas exchange. In this paper, we present the results of experimental studies on oxygen transport from atmospheric air into a liquid hypophase and we consider a possible role of the PS monolayer in this process. The question of the efficiency of oxygen transfer in relation to the quality of the surfactant becomes really important when the PS system is likely to be damaged by external factors. This can be the case of occupational exposure to certain toxic agents, which can slightly or seriously disturb the physicochemical construction of the lung surfactant system. In such situations, an impaired gas exchange resulting from breathing difficulties can be multiplied by the significant reduction of the mass exchange coefficient for oxygen due to the destruction of the thermodynamic stability of the PS system.

2. MATERIALS AND METHODS

The studies were divided into three parts. The first stage of experimental work explained the role of the static phospholipid monolayer in the rate

of oxygen absorption from atmospheric air into water. The second part considered dynamic conditions associated with the motion of the gas-liquid alveolar interface during the breathing cycle. In the last stage, the investigations were extended by the application of perfluorocarbon compound (PFC) acting as artificial blood in the experimental model.

2.1. Oxygen Absorption Under Static Conditions

The aim of this part was to explain whether the presence of the monomolecular phospholipid film on the stationary air-water interface can retard or enhance the rate of oxygen absorption. In comparative studies, each of 10 identical polypropylene cylinders was filled with 50 ml of distilled and deoxygenated water. Oxygen removal from water prior to experiments was done by stripping with nitrogen. In five cylinders (denoted as sample A), monolayers of the surfactant were produced by introducing a few droplets of a chloroform solution of dipalmitoylphosphatidylcholine (DPPC). This phospholipid is typically chosen as a model substance of PS as its content in the natural surfactant is predominant (e.g., Akino, 1992). The other five cylinders

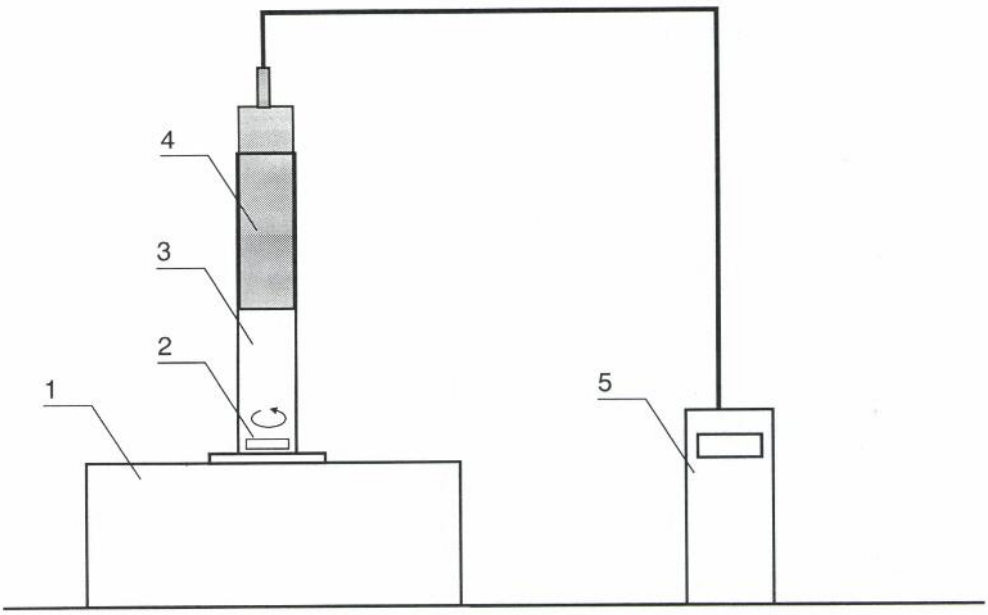

Figure 1. Measurement of oxygen concentration in samples A and B. *Notes.* 1—magnetic stirrer, 2—magnetic stir bar, 3—cylinder, 4—oxygen probe fitted to the wall of the cylinder, 5—dissolved oxygen meter.

(denoted as sample B) were left untouched. All cylinders were kept at room temperature to allow oxygen from the air to be absorbed in water. At given time intervals, oxygen concentration was determined in the water in two cylinders (sample A and B) with an oxygen probe (type: CTN-9212, MESEKO, Poland) using a technique depicted in Figure 1. The experiments allowed an evaluation of the influence of the static equilibrium DPPC monolayer on the rate of oxygen transfer to the water hypophase.

2.2. Oxygen Transfer Under Dynamic Conditions

The hydrodynamic analogy of the PS system during breathing can be achieved with a Langmuir film balance (LFB) as shown by, for example, Gradoń, Podgórski, and Sosnowski (1996) and Sosnowski and Gradoń (1993). Also in the current study we employed this device, additionally supplementing it with equipment for measuring oxygen transfer rate. As the construction and operation of the LFB (Lauda DR Wobser, Germany) were described in detail elsewhere (e.g., Gradoń et al., 1996), only the basic features of the device will be given here. The shallow measuring vessel of the LFB (Figure 2) is filled with an aqueous solution acting as a hypophase. Area changes in the device are forced by a barrier that moves back and forth at a programmable speed. The actual physical quantity measured in the LFB is the surface pressure (π, mN m^{-1}), which reflects the surface activity of the surfactant monolayer being confined between the barrier and the measuring float. The surface pressure hysteresis during successive compression and expansion of the interfacial film is a well-known characteristic phenomenon in the PS measurements (e.g., Notter, Taubold, & Mavis, 1982; Sosnowski & Gradoń, 1993). For our study, information about the surface activity had minor importance as the LFB was used mainly for simulations of area changes. The basic measuring device here was an original electrochemical system for determining oxygen transfer rate through the hypophase. It was based on the electrolysis process occurring in a buffered 0.34M KCl aqueous solution. At 1.65 V overvoltage, the following reactions take place at the silver electrodes:

$$\text{cathode: } O_2 + 2\,H_2O + 4\,e^- \rightarrow 4\,OH^-, \tag{1}$$

$$\text{anode: } Ag \rightarrow Ag^+ + e^-. \tag{2}$$

At a given overvoltage only dissolved oxygen undergoes reduction at the cathode, so the current measured in the system is proportional to the amount of oxygen being transferred from the air through the liquid hypophase to the electrode. When the cathode is constructed as a flat silver sheet of known area, A_c, then by combining the Faraday law

$$\dot{n} = \frac{i}{zF} \tag{3}$$

with the mass transfer equation

$$\dot{n} = k_l(c_i - c)A_c \tag{4}$$

the mass transfer coefficient for oxygen, k_l, can be calculated from the measured electric current, i. In Equations 3 and 4, $\dot{n}$ denotes the molar flux of dissolved oxygen (mol s^{-1}), z—valence (for oxygen $z = 2$), F—Faraday constant ($F = 96848$ C mol^{-1}), c_i—saturation oxygen concentration (at the gas-liquid interface, mol m^{-3}), c—oxygen concentration at the cathode (for an instantaneous electrochemical reaction $c = 0$ can be assumed). The arrangement of the measuring electrochemical system in the LFB is presented in Figure 2.

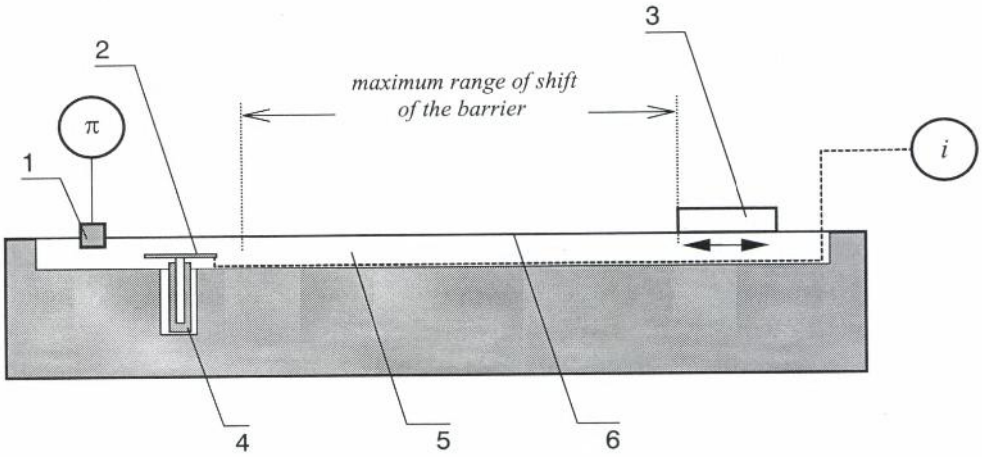

Figure 2. Experimental setup for electrochemical determination of oxygen mass transfer rate in the Langmuir film balance. *Notes.* 1—measuring float, 2—measuring electrode, 3—moving barrier, 4—base of measuring electrode located in the Langmuir-Blodgett well, 5—aqueous hypophase, 6—DPPC monolayer, DPPC—dipalmitoylphosphatidylcholine, π—surface pressure, i—electric current.

The 50-cm^2 silver cathode was mounted on a Plexiglas plate fastened to a base, which was inserted into the well in the bottom of the LFB

measuring vessel. This well is typically used in the so-called Langmuir-Blodgett transfer technique. As this technique was not used in our study, the well could be used for a different purpose. The plate with the cathode was fastened to the base by a screw, which allowed for a change of the depth of the hypophase layer above the cathode. A silver wire was used as the anode. Measurements of electric current (i.e., determination of the mass transfer coefficient) were conducted in four cases:

a. no surfactant in the system, stationary barrier;
b. surfactant monolayer present in the system, stationary barrier;
c. no surfactant in the system, moving barrier;
d. surfactant monolayer present in the system, moving barrier.

Runs a and b repeated static measurements from the previous part, which could be verified here with a different technique. The ratio of area changes at runs c and d simulated the one of alveolar interface during the breathing cycle. All experiments were conducted at two temperatures: 21 $\pm$ 0.3 °C (room temperature) and 37 $\pm$ 0.3 °C (physiological conditions). For each type of experiment the influence of the depth of the hypophase was investigated—the measuring cathode was placed 2, 4, or 6 mm below the gas-liquid interface.

2.3. Measurements With the Use of PFC as a Laboratory Blood Model

Efforts to investigate the physiological system in the most realistic way led us to using a physicochemical model of blood in further experiments. Various pelfluorocarbons (PFCs) emulsified in water can be used as blood substitutes in clinical practice taking advantage of an extremely high oxygen solubility (up to 60 ml O_2 per 100 ml PFC at 25 °C; Wesseler, Iltis, & Clark, 1977). In our studies, we used a perfluorocarbon compound known as FC43 (perfluorotributylamine: $(CF_3CF_2CF_2CF_2)_3N$), which was obtained by courtesy of Prof. Stephen R. Thomas from the University of Cincinnati. Because of the lack of detailed physicochemical data, the liquid was tested in our laboratory before its use in the final experiments:

- Density was determined by weighing the precisely known volume of the FC43,

- Surface tension was measured with a du Noüy ring tensiometer (CSC Scientific Company, Inc., Fairfax, VA),
- Oxygen solubility (Henry's constant) was determined by chemical analysis with a modified Winkler method following oxygen extraction from PFC (immiscible with water) to an aqueous reagent,
- Kinetics of absorption of oxygen from atmospheric air into FC43 under static conditions was determined by comparing oxygen concentration in several 5-ml PFC samples of various time of contact with the air. Initial PFC deoxygenation was done by shaking it with an aqueous solution of Na_2SO_3 in a closed vessel for 10 min.

All the aforementioned measurements were done at 24 ± 0.5 °C.

Application of FC43 in the Langmuir balance was very troublesome due to the time-consuming procedure of LFB operation, which had to be coordinated with the procedure of oxygen determination in PFC samples, which in turn were relatively quickly saturated with the air. Thus, the whole measurement consisted of

1. deoxygenating water (by stripping with nitrogen) before filling the LFB measuring vessel. All the time after oxygen removal and before introducing into the LFB, water had to be kept without contact with the air;
2. deoxygenating PFC (by stripping with nitrogen). After removing oxygen, the PFC sample had to be kept without contact with the air;
3. determining oxygen concentration in a portion of deoxygenated water that would be used as a background for determining the oxygen dissolved in PFC (operation 10). This water had to be kept with no contact with the air the whole time before the chemical analysis;
4. filling the LFB measuring vessel with deoxygenated water;
5. cleaning the surface of the hypophase in the LFB;
6. calibrating LFB;
7. introducing a DPPC monolayer from a chloroform solution;
8. injecting the PFC sample below the surface of water;
9. running the compression-expansion program of the LFB (physiological oscillation of the interfacial area);
10. taking the PFC sample from the LFB at a given time and determining the dissolved oxygen with a modified Winkler method. Oxygen concentration was calculated on the basis of the measurement of dissolved oxygen in a sample of background water mixed with a 250-μl

sample of PFC. Dissolved oxygen was measured with a standard AQUAMERCK test (Merck, Germany). PFC was sampled with a 250-μl microsyringe (Hamilton, Switzerland).

After the end of a measurement, the LFB was emptied from water and cleaned, and the whole procedure (operations 1–9) had to be repeated. Then, the PFC was sampled at a different time from the start of the experiment. In this way, the kinetics of atmospheric oxygen uptake by FC43 through the aqueous hypophase could be determined taking into account interfacial processes related to the surfactant activity.

3. RESULTS AND DISCUSSION

3.1. Oxygen Absorption Under Static Conditions

Results of the measurements conducted in the system depicted in Figure 1 are presented in Figure 3. It is evident that no essential influence of

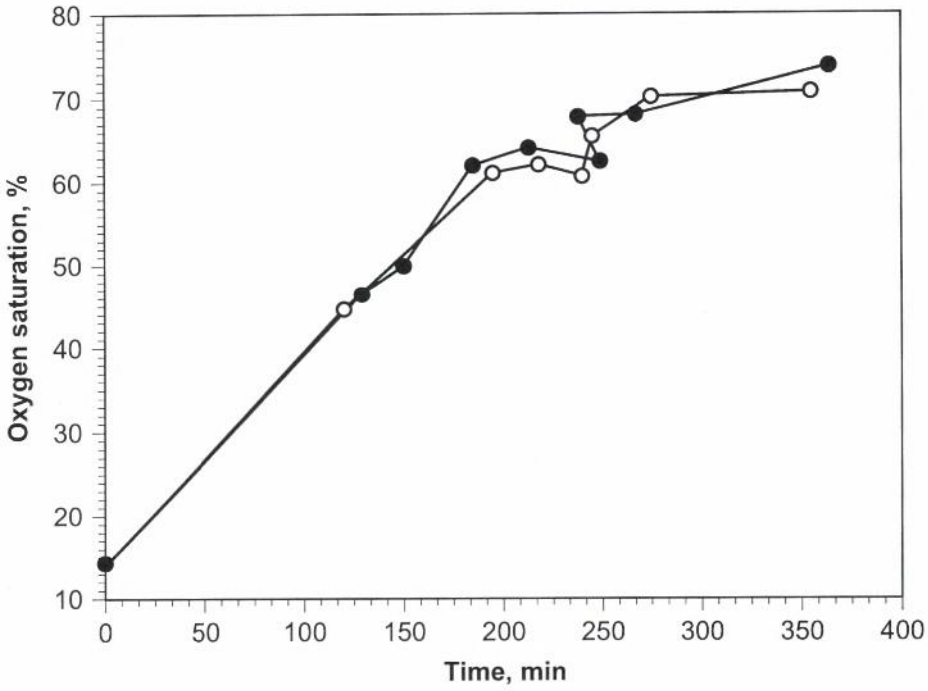

Figure 3. Increase of oxygen concentration in water during static experiments at room temperature. *Notes.* Empty circles—pure water, filled circles—water with DPPC monolayer, DPPC—dipalmitoylphosphatidylcholine.

the equilibrium DPPC monolayer on oxygen transport rate could be observed. As demonstrated by Blank and Roughton (1960), certain saturated long-chain alcohols and acids decrease the rate of carbon dioxide absorption in water when they form a packed interfacial film. On the other hand, monolayers formed by more complex molecules, such as of cholesterol or proteins do not have this retarding effect.

It seems, therefore, that the influence of a monolayer on gas absorption depends on the configuration of amphiphatic molecules, which determines their organization in the interfacial film. For condensed monolayers (known as solid films; Gaines, 1966), interfacial permeability can be lowered. However, this is not the case of the discussed experiments as the surface tension measured by the du Noy technique for the system with a DPPC monolayer was 35 mN/m (surface pressure: 37 mN/m), which clearly indicated that the interfacial film was not fully condensed. It may be concluded that such a DPPC monolayer does not block air-water interface for oxygen transfer.

An analogous experiment was performed in the LFB for a more condensed DPPC monolayer obtained by compressing the interfacial

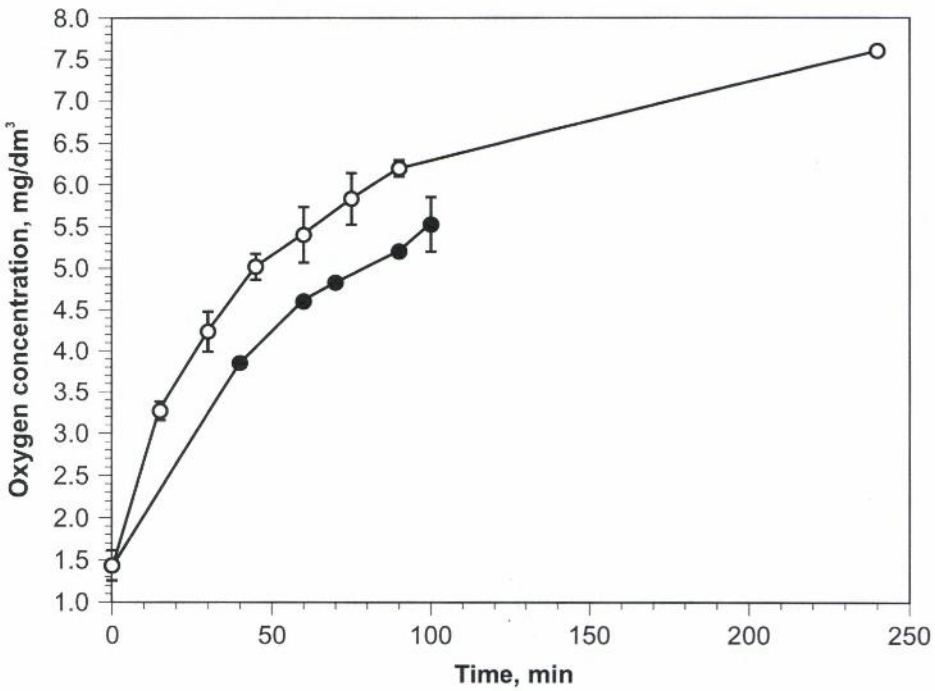

Figure 4. Influence of condensed stationary DPPC monolayer on the rate of oxygen absorption. *Notes.* Empty circles—pure water, filled circles—water with DPPC monolayer. $T = 21\,^{\circ}C$, DPPC—dipalmitoylphosphatidylcholine.

film to surface pressure equal 50 mN/m. Oxygen concentration was measured with the AQUAMERCK test. In this case, a noticeable effect of the retardation of oxygen transfer rate was measured (Figure 4).

A comparison of the permeability coefficient, K (s^{-1}), for both cases illustrated in Figure 4, can be done by employing a mass transfer equation:

$$\frac{d\bar{c}}{dt} = K(c_i - \bar{c}), \tag{5}$$

where $\bar{c}$ (g m^{-3}) denotes instantaneous average oxygen concentration in the liquid phase. Interfacial oxygen concentration, c_i, is assumed as the concentration of saturation, because mass transfer resistance on the gas side can be neglected for oxygen absorbed in water. The solution of this simple differential equation leads to a known formula:

$$\ln\frac{c_i - \bar{c}_0}{c_i - \bar{c}} = Kt, \tag{6}$$

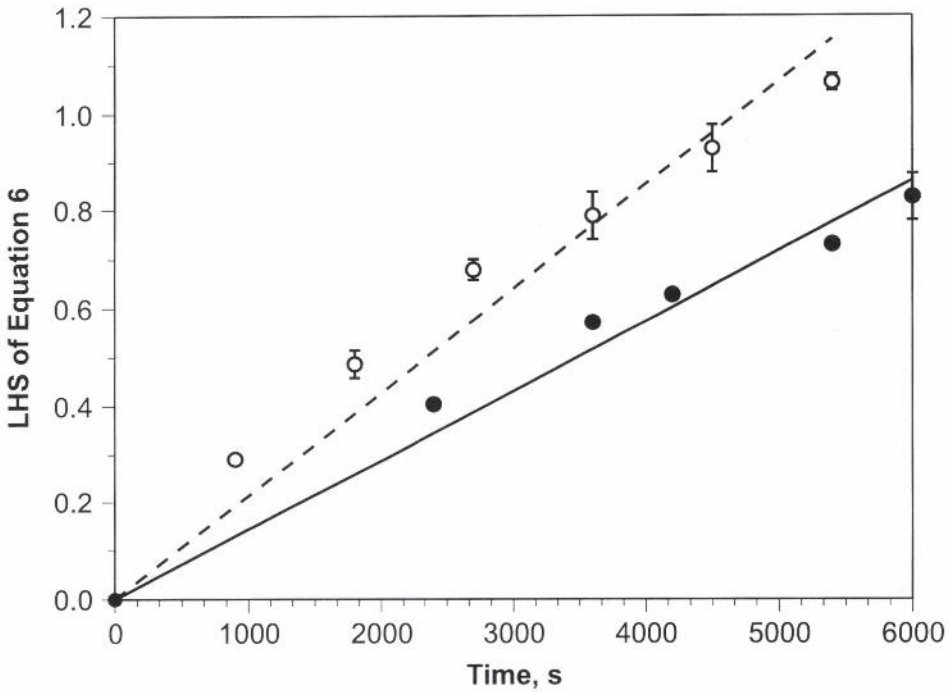

Figure 5. Graphic interpretation of Equation 6—determination of permeability coefficient. *Notes.* Empty circles—pure water, filled circles—water with DPPC monolayer, LHS—left hand side, DPPC—dipalmitoylphosphatidylcholine.

where $\bar{c}_0$(g m^{-3}) means average oxygen concentration at the beginning of the measurement ($t = 0$). A direct determination of K can be done by linear regression of a plot of the left hand side (LHS) of Equation 6 versus time. This procedure (Figure 5) led to the following values:

$K_w = 2.13 \cdot 10^{-4}$ s^{-1} for pure water,
$K_s = 1.43 \cdot 10^{-4}$ s^{-1} for water covered by a condensed DPPC monolayer.

Let us emphasize that K is not a universal physicochemical value, as it depends on the system configuration. However, it was introduced to compare rates of oxygen transfer in the same experimental system but for a different composition of the interface. Results of such a comparison suggest that oxygen absorption in the case of a stationary condensed DPPC monolayer can be approximately 30% slower than for a pure water interface.

3.2. Oxygen Transfer Under Dynamic Conditions

In the previous part of this paper, we analyzed the system that was closely related to PS but did not include its basic physiological feature, that is, motion due to breathing. The cyclic change of area of the gas-liquid interface in lungs is believed to lead to an essential modification of the hydrodynamic phenomena in the thin layer of alveolar lining (Podgórski & Gradoń, 1993; Sosnowski, 1997). The hydrodynamics of the PS system is very specific due to the presence of the surface active material. It is possible to model these phenomena with the Langmuir balance. As described in the previous section (see Equations 3–4), oxygen transfer rate in this laboratory system could be determined from the measurements of the electric current originated from the electrochemical processes. For the most interesting case from the physiological viewpoint, that is, for $T = 37$ °C, the study can be summarized by the results depicted in Figures 6 and 7.

Absorption enhancement ratio presented in Figure 6 is defined as

$$\Psi = \frac{\dot{n}_m}{\dot{n}_s}, \tag{7}$$

where $\dot{n}_m$ and $\dot{n}_s$ denote oxygen fluxes in the case of moving or stationary interface, respectively. Going back to Equation 4, it is clear that Ψ must be equal to the ratio of mass transfer coefficients in both

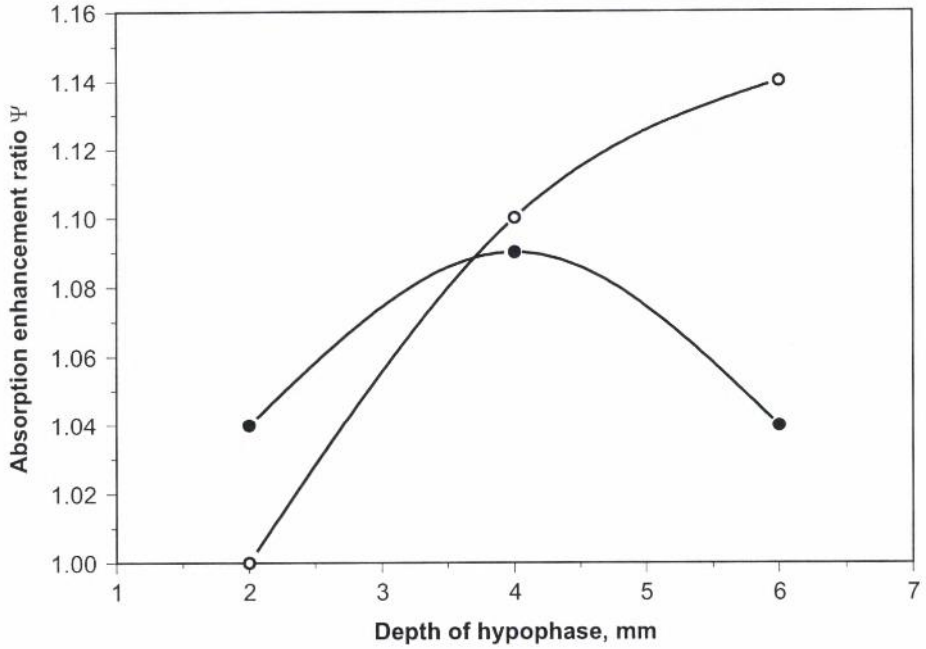

Figure 6. Oxygen absorption enhancement ratio for moving interface as a function of hypophase depth. *Notes.* Empty circles—pure water, filled circles—water with DPPC monolayer, $T = 37\,°C$, DPPC—dipalmitoylphosphatidylcholine.

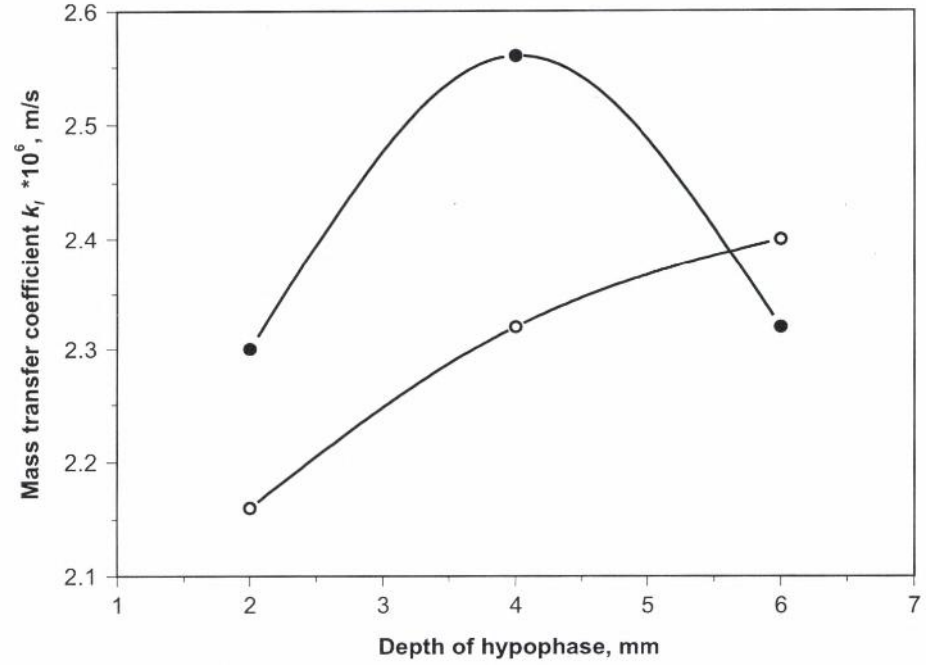

Figure 7. Mass transfer coefficient for oxygen as a function of hypophase depth for moving interface. *Notes.* Empty circles—pure water, filled circles—water with DPPC monolayer, $T = 37 \pm 0.5\,°C$, DPPC—dipalmitoylphosphatidylcholine.

cases, so in fact it indicates how many times the absorption rate increases when the interface is set in motion. Figure 6 demonstrates that a moving interface in general enhances the efficiency of oxygen absorption in the aqueous hypophase. It does not seem to be surprising in the case of pure water but for a model PS monolayer it is an interesting observation. It means that additional resistance for mass transfer, which was observed for a stationary condensed DPPC monolayer (Figure 5) is overlapped now by convective effects in the hypophase, and the net result elevates oxygen uptake. It is worth noticing that absorption enhancement depends on the thickness of the liquid layer. For the hypophase covered by the surfactant film, Ψ is highest for intermediate depth (4 mm). When compared to absorption enhancement promoted by compression and expansion of pure water interface, it is seen that similar Ψ values are obtained in both cases for a 4-mm hypophase. However, for a shallow hypophase (2 mm), oxygen is transferred to the liquid layer more efficiently when the surfactant is present at the moving interface. One may conclude that with decreasing hypophase depth, the absorption of oxygen will be strongly intensified by the presence of an active moving monolayer. This effect can be attributed to the mixing of the subsurface phase due to the surface tension gradient generated in the interface of the liquid film. The phenomenon is known as the Marangoni effect and is absent in the case of pure water, as $\nabla\sigma$ vanishes. When the depth of the hypophase increases, the subsurface flow under the DPPC monolayer can be supplemented by another convective effect appearing due to waves generated in the liquid. This explains the maxima on the DPPC curves in Figures 6 and 7. As monolayers are known to suppress waves at the interfaces and in a bulk liquid, this effect cannot be responsible for further absorption enhancement when hypophase is deeper (6 mm). Only for pure water does Ψ still increase with depth because "the wave effect" is much stronger in this system. A similar discussion can explain the influence of hypophase thickness on k_l (Figure 7). One can see that for shallow aqueous layers, oxygen is absorbed faster when the surfactant monolayer is present on a moving interface.

3.3. Measurements With the Use of PFC as a Laboratory Blood Model

The aim of this final study was to analyze oxygen transport in the most attainable realistic conditions, that is, taking into account consecutive

steps that compose its pathway from atmospheric air into blood. Physicochemical constants of FC43 had to be determined in the initial stage of this work and they are listed in Table 1.

TABLE 1. Physicochemical Constants of FC43 (Perfluorotributylamine) at 24 ± 0.5°C and Atmospheric Pressure

Property	Symbol	Units	Value	Deviation (%)
Density	ϱ	kg m^{-3}	1828	± 0.27
Surface tension	σ	N m^{-1}	0.02133	± 0.61
Henry's constant	H	Pa m^3 mol^{-1}	2773.5	± 4.41

From Henry's constant, H, oxygen solubility in FC43, s, can be calculated. It equals 25.27 ± 0.77 ml per 100 ml of the perfluorocarbon compound. Literature values of physicochemical data for a similar substance known as FC47 are at 25 °C as follows (Wesseler et al., 1977): $\rho = 1900$ kg m^{-3}, $\sigma = 0.016$ N m^{-1}, $s = 38.4$ ml O_2 per 100 ml. With the exception of oxygen absorption capacity, both sets of data are similar. However, even if the compound used in our study has lower oxygen solubility than FC47, it absorbs more than 40 times more oxygen than water. Kinetic studies on oxygen absorption rate in the stationary FC43 layer led to the permeability coefficient (see Equations 5–6) equal to $2.8 \cdot 10^{-4}$ ($\pm$ $7.5 \cdot 10^{-5}$) s^{-1}. Taking into account liquid volume and area of the gas-liquid interface in these studies, the equivalent mass transfer coefficient was estimated as $1.64 \cdot 10^{-5}$ ($\pm$ $4.4 \cdot 10^{-6}$) m s^{-1}, which suggests an over 7-fold faster oxygen absorption rate in FC43 than in water (both under stationary conditions). The rate of oxygen absorption in FC43 acting as a model of blood was measured in the LFB employing the complex laboratory procedure described earlier. The obtained results are summarized in Figure 8.

Figure 8 illustrates how function dc_{FC}/dt, that is, the rate of increase of oxygen concentration in PFC depends on c_{FC} (which denotes oxygen concentration in FC43, g m^{-3}) and the state of the air-water interface covered by a DPPC monolayer. The results demonstrate clearly that the moving interface covered by the phospholipid promotes faster oxygen uptake by FC43, so it must generate faster absorption of oxygen from the air to the hypophase. The explanation of this effect is the same as

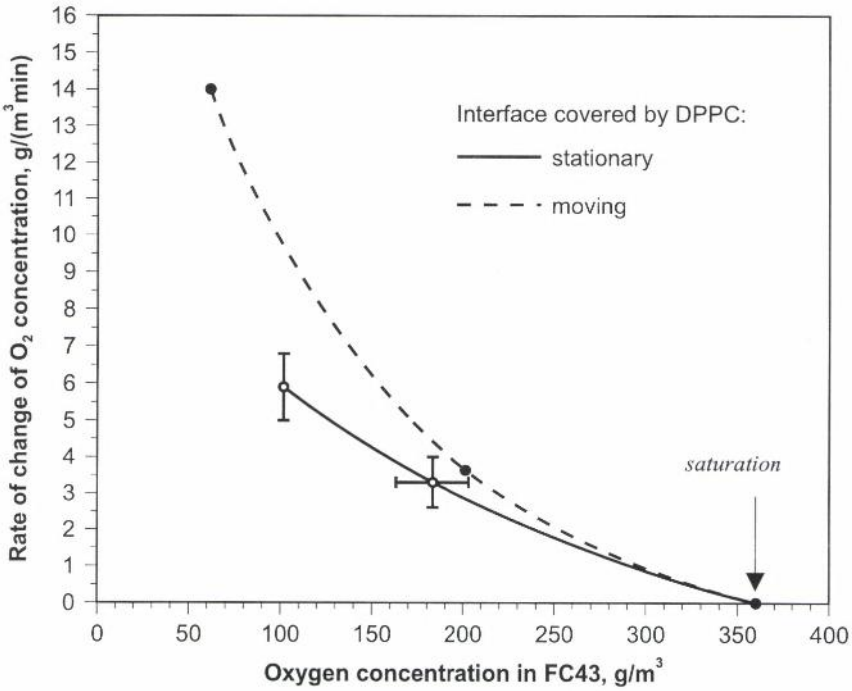

Figure 8. Rate of change of oxygen concentration in FC43 during uptake of the gas from aqueous hypophase absorbing oxygen from the air. Stationary or moving interface covered by DPPC monolayer. *Notes.* $T = 37 \pm 0.5\,^{\circ}C$, DPPC—dipalmitoylphosphatidylcholine.

discussed earlier. Cyclic compression and expansion of the monolayer-covered interface intensifies hydrodynamic processes in the hypophase and thus accelerates transport of dissolved oxygen from the interface to the receiver, that is, PFC. The dynamic properties of this system are also manifested by the π-A hysteresis measured in LFB during the experiment. This is depicted in Figure 9.

The aforementioned conclusion regarding gas absorption rate is very important from the physiological viewpoint. It confirms that oxygen transfer to the blood can be facilitated by interfacial and hydrodynamic phenomena occurring in the PS system undergoing motion during the breathing cycle. The essential consequence of this is that when the surfactant is inactive or destroyed (e.g., by inhaled toxic environmental pollutants), oxygen transport from breathing air into the blood can be significantly reduced. That will lead to oxygen deficiency in the whole organism. This important remark gives a new view on the pulmonary surfactant significance in the respiratory system.

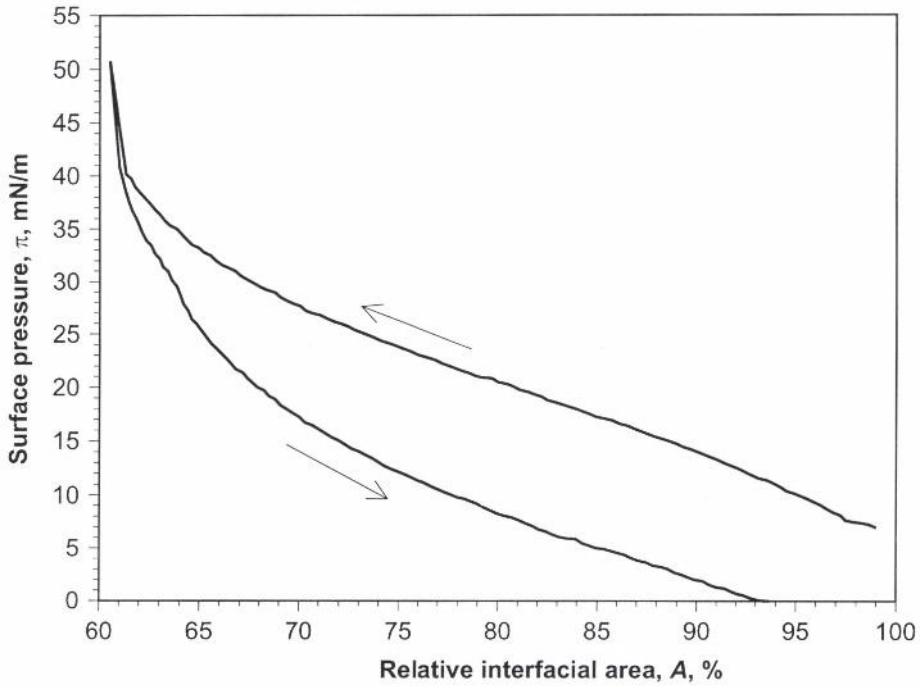

Figure 9. Surface pressure area (π-*A*) hysteresis during compression and expansion of DPPC monolayer on the aqueous hypophase in the LFB at 37 $\pm$ 0.5 °C. *Notes.* LFB—Langmuir film balance, DPPC—dipalmitoylphosphatidylcholine.

4. FINAL REMARKS

In this paper, several methods for determining the influence of pulmonary surfactant monolayer on oxygen uptake by blood system were proposed using laboratory models. In the studies, DPPC and PFC were used as the surfactant and blood models, respectively. The Langmuir balance was employed to mimic the area changes corresponding to breathing. As a result of the studies, it can be stated that

1. the atmospheric oxygen absorption rate depends on the composition and organization of the air-water interface. A slightly condensed static phospholipid monolayer does not change the permeability of the interface for oxygen, but a strongly compressed static DPPC monolayer can slow down this process even by 30%;
2. during the motion of the interface (compression-expansion corresponding to exhalation-inhalation in breathing), the mass transfer coefficient in general increases due to improved hydrodynamic conditions at the

interfacial region. The effect of the surfactant film is crucial for the thin layers of the aqueous hypophase—in those cases, the motion of the surfactant-free monolayer has little influence on oxygen absorption rate while DPPC-covered moving interface noticeably increases the rate of oxygen uptake, most probably due to Marangoni effects. As the hypophase is extremely thin in the physiological system, it may be expected that this result is significant for lungs in vivo;

3. perfluorocarbon compounds (e.g., FC43) can be used as a model of blood in laboratory studies on oxygen transport. In spite of the sophisticated and troublesome experimental procedure, it was possible to find a relationship between the effectiveness of oxygen uptake by PFC and hydrodynamic conditions of the hypophase. These experiments confirmed the important role of appropriate properties (composition and dynamics) of the PS system in the efficient delivery of oxygen to the circulation system.

Confirmation of the active role of the pulmonary surfactant in the gas exchange is the most important conclusion of the presented experimental work. A good understanding of the physicochemical processes occurring at the interfacial region of alveolar epithelium is important in the discussion of the functions of the breathing organ. Even if physicochemical studies cannot fully simulate physiological processes, they allow insight into the basic phenomena taking place in the lungs. As stated earlier, the impact of PS activity on oxygen delivery should be emphasized in the case of its dysfunction, for example, due to breathing in a toxic environment, which can be a common event at a workplace. It is possible that in those conditions oxygenation of organs will be impaired, giving harmful health effects. This topic certainly needs further investigations using animal models of induced surfactant inactivation.

ABBREVIATIONS AND SYMBOLS

ARDS — adult respiratory distress syndrome
DPPC — dipalmitoylphosphatidylcholine
FC43 — perfluorotributylamine: $(CF_3CF_2CF_2CF_2)_3N$
HMD — hyaline membrane disease
IRDS — infant respiratory distress syndrome
ŁFB — Langmuir film balance

NO_x — nitrogen oxides
PFC — perfluorocarbon compound
PS — pulmonary surfactant
A — relative area of a gas-liquid interface, %
A_c — area of the silver cathode of electrochemical measuring system, m^2
$\bar{c}$ — instantaneous average oxygen concentration in the hypophase, g m^{-3}
$\bar{c}_0$ — average oxygen concentration in the hypophase at $t = 0$. g m^{-3}
c_{FC} — oxygen concentration in FC43, g m^{-3}
c_i — oxygen concentration at the gas-liquid interface, mol m^{-3}
F — Faraday constant (= 96848 C mol^{-1})
H — Henry's constant for FC43/air system, Pa m^3 mol^{-1}
i — electric current
k_l — mass transfer coefficient, m s^{-1}
K_s — permeation coefficient for stationary interface covered with condensed DPPC film, s^{-1}
K_w — permeation coefficient for stationary pure water interface, s^{-1}
$\dot{n}$ — molar flux of dissolved oxygen, mol s^{-1}
$\dot{n}_m$ — oxygen flux for moving interface, mol s^{-1}
$\dot{n}_s$ — oxygen flux for stationary interface, mol s^{-1}
s — oxygen solubility in FC43, ml per 100 ml
T — temperature, °C
t — time, s
z — valence
π — surface pressure, N m^{-1}
ρ — density, kg m^{-3}
σ — surface tension, N m^{-1}
$\nabla\sigma$ — surface tension gradient, N m^{-2}
Ψ — ratio of absorption enhancement by motion of the interface

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