Chemistry and Physics of Lipids 225 (2019) 104812

Contents lists available at ScienceDirect

Chemistry and Physics of Lipids

journal homepage: www.elsevier.com/locate/chemphyslip

Influence of temperature on dynamic surface properties of spread DPPC monolayers in a broad range of surface pressures

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ARTICLE INFO

Keywords:
Surface elasticity
Non-linear behavior
Lipids
DPPC
Pulmonary surfactants

ABSTRACT

This work is focused on the study of the dynamic surface properties of spread monolayers of 1,2-dipalmitoyl-sn-glycero-3-phosphocholine (DPPC), which is the main component of the pulmonary surfactant (PS), in the region of high surface pressures and at different temperatures. The increase of temperature from 25 to 35 °C led to a decrease of surface elasticity in the high surface pressure range corresponding to physiological conditions inside alveoli during breathing. Furthermore, the obtained results evidenced that the relaxation processes in spread DPPC monolayer were accelerated with the increase of temperature, which resulted in two different effects. On one hand, it led to the increase of hysteresis of surface pressure isotherms, which was an important condition for maximizing air penetration into alveoli; whereas on the other hand, it prevented reaching extremely high surface pressure, which could result in a premature alveolar collapse.

1. Introduction

Thin films of pulmonary surfactant (PS) overlay the inner surface of lung alveoli and play a very important role in breathing process (Clements, 1957). PS increases the surface pressure at the air/liquid surface to extremely high values (low values of the surface tension) under surface compression and prevents alveoli collapse during exhalation (Goerke, 1998; Hidalgo et al., 2017; Lopez-rodriguez and Pérez-gil, 2014; Parra and Pérez-gil, 2015; Piknova et al., 2002; Zasadzinski et al., 2010). It is generally accepted that this unique property is mainly due to the presence of 1,2-dipalmitoyl-sn-glycero-3-phosphocholine (DPPC), which is the main component of PS mixtures (Goerke, 1998; Hidalgo et al., 2017; Lopez-rodriguez and Pérez-gil, 2014; Parra and Pérez-gil, 2015; Piknova et al., 2002; Todorov et al., 2017, 2015; Wustneck et al., 2005; Zasadzinski et al., 2010; Zuo et al., 2008). This makes Langmuir monolayers of this lipid an appropriate model to shed light on the most fundamental physico-chemical basis underlying the physiological performance of PS during breathing. It worth mentioning that the real behavior of the inner surface of lung alveoli may be more complex because of the role of the different PS components: proteins, cholesterol and other lipids (Bykov et al., 2017; Guzmán and Santini, 2019; Hidalgo et al., 2017; Lopez-rodriguez and Pérez-gil, 2014; Parra and Pérez-gil, 2015; Wustneck et al., 2005; Zuo et al., 2008).The decrease of PS concentration in solution at the inner surface of lung or deviations from the optimal PS composition can lead to the neonatal respiratory distress syndrome for premature infants.

Although the surface pressure at the inner surface of lungs is higher than 50 mN/m, the majority of studies of spread DPPC monolayers or PS mixtures are focused on the region of surface pressure lower than 50 mN/m. This is due to experimental problems connected with the film leakage at high surface pressures (Arriaga, 2010; Banerjee and Belare, 2001; Bykov et al., 2017; Dunbar et al., 1997; Guzmán et al., 2013; Guzmán and Santini, 2019; Hidalgo et al., 2017; Lopez-rodriguez and Pérez-gil, 2014; Nino et al., 2008; Parra and Pérez-gil, 2015; Wustneck et al., 2000, 2005, 2002b, 2002a; Zuo et al., 2008), which limits the biophysical relevance of the results obtained in many of the aforementioned studies.

The dynamic surface properties proved to be important characteristic parameters of PS since the alveoli surface undergoes permanent compression and expansion cycles during the normal breathing process (Banerjee and Belare, 2001; Hidalgo et al., 2017; Lopez-rodriguez and Pérez-gil, 2014; Parra and Pérez-gil, 2015; Wustneck et al., 2005). The dilational surface elasticity characterizes the response to compression or expansion of the surface layer and can give additional information on the mechanism of PS action (Banerjee and Belare, 2001; Bykov et al., 2017; Guzmán and Santini, 2019; Todorov et al., 2015; Wustneck et al., 2005; Zuo et al., 2008). Measurements of the dilational surface elasticity of spread DPPC monolayers show that it can reach very high values

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https://doi.org/10.1016/j.chemphyslip.2019.104812
Received 30 April 2019; Received in revised form 20 June 2019; Accepted 17 August 2019
Available online 19 August 2019

with the increase of surface pressure up to 40 mN/m (Arriaga, 2010; Grigoriev et al., 2003; Guzmán et al., 2013; Nino et al., 2008; Wustneck et al., 2000, 2005, 2002a,b). It has been shown recently that the application of a modified Langmuir trough and the use of an approach based on large surface deformations give access to information on the dilational surface elasticity in the region of extremely high surface pressures, i.e. in the region of importance for the breathing process (Bykov et al., 2019, 2018; Bykov and Noskov, 2018). It is worth mentioning that additional components in PS adsorbed layers lead to a decrease of the dynamic surface elasticity as compared to the values of pure DPPC monolayers (Bykov et al., 2019). Moreover, the main relaxation time of surface stresses in the region of high surface pressures for spread DPPC monolayers is much longer than that for adsorbed layers of PS mixtures, which may be ascribed to an enhanced respreading of PS layers as result of the action of surface active proteins contained in PS, mainly of two of them: SP-B and SP-C (Bykov et al., 2019; Parra and Pérez-gil, 2015).

In our previous studies of PS adsorption layers the temperature of investigated solutions was 25 °C, and thereby being significantly different from the normal physiological temperature of human body. It is well known that temperature has strong influence on the properties of lipid monolayers; hence the extrapolation of previous results to the particular conditions inside lung alveoli should be done with caution (Sosnowski et al., 2017). Furthermore, the surface pressures corresponding to two-dimensional phase transitions in spread monolayers have been found to be temperature dependent (Wustneck et al., 2005). Moreover, the increase of temperature leads to a decrease of the surface elasticity in the region of surface pressures lower than 50 mN/m for spread DPPC monolayers (Wustneck et al., 2005, 2002a). In this work the dynamic surface elasticity and the rates of mechanical relaxation for spread DPPC monolayers are investigated at 30 and 35 °C in a broad region of surface pressures corresponding to physiological conditions inside alveoli.

2. Materials and methods

DPPC (Sigma-Aldrich, 99% of purity) and chloroform (Sigma Aldrich) were used as received. NaCl (Merck) was preliminary heated at about 750 °C for ensure that it is free of organic impurities. Phosphate buffer (Sigma-Aldrich) was used without additional purification. The solutions were prepared in water distillated three times.

DPPC solutions in chloroform with concentration 1 mg/mL were used for spreading. For preparation of monolayers a known volume of the DPPC solution was added drop by drop onto the aqueous subphase contained in the Langmuir trough with temperature control. The Langmuir trough was placed into a plexiglass box and the temperature was controlled during all the measurements. The aqueous subphase contained phosphate buffer and NaCl to control of pH (7.0) and ionic strength (0.15 M).

The dynamic dilational surface elasticity was measured by the oscillating barrier method using the ISR instrument (KSV NIMA, Finland). In this work, the Langmuir trough was modified and a specific design enabling for the exclusion of the undesirable lipid leakage from the monolayer below the barriers at the highest surface pressures. For this purpose, a flexible fluoroplastic ribbon was fixed along the cell perimeter (Bykov and Noskov, 2018). The use of a leakage-proof barrier enables for reaching extremely high surface pressures. The instrument had two barriers oscillating at given amplitudes and frequencies (from 0.005 to 0.03 Hz). This frequency range is slightly lower than the frequency corresponding to normal breathing, but it is limited by the used device. Changes of the surface tension were measured using a Wilhelmy plate. Thus, it is possible to obtain the surface pressure as $\Pi = \gamma - \gamma_0$ with γ and γ_0 being the surface tensions of the interface containing the monolayer and the bare interface respectively. The Wilhelmy plate was made from chromatography filter paper with a width of 1 cm. The plate was positioned parallel to the barriers in the middle of the trough for minimizing the influence of surface shear deformations (Mangiarotti et al., 2014; Petkov and Gurkov, 2000; Wilke et al., 2010).

In the case of a standard procedure and small amplitudes of the surface area oscillations the modulus of the dynamic surface elasticity ε is determined by the ratio of the surface tension amplitude and the amplitude of relative deformations, according to the following equation:

$$\varepsilon = \frac{\Delta\gamma}{\Delta A/A_0} \quad (1)$$

where ΔA is the surface area increment, A_0 is the initial surface area, $\Delta\gamma$ is the surface tension increment (Caruso et al., 2016; Cicuta and Terentjev, 2005; Noskov and Bykov, 2015).

One can apply a standard procedure, when the surface tension is relatively stable before the oscillations of surface area and the system response is reproducible for three periods of oscillations at least. In the case of an unstable system, when fast changes of the surface tension were observed before the oscillations, the standard procedure cannot be applied since the mean value of surface tension decreases with time (supporting information Fig. S1). In this case, the dynamic surface elasticity measurements are based on the modified stress decomposition method described in previous publications (Bykov et al., 2019, 2015; Ilyin et al., 2014; Yu et al., 2010). According to this approach the determination of the dynamic surface elasticity is based on the comparison of system responses (increments of the surface tension) at different deformations of the surface (Bykov et al., 2019, 2015). The difference in the system responses for two given deformations characterizes the efficient surface elasticity (ε_{ef}) in the compressed or expanded states (Bykov et al., 2019, 2015). Fig. 1 presents as an example Lissajous plots for a model system with the surface tension of 67.5 mN/m at the amplitude of surface area oscillations $\Delta A^1 = 40\%$ (blue open circles) and $\Delta A^2 = 50\%$ (black open squares). The corresponding segments for different deformations (red and magenta lines) have different slopes. One can use the slopes of these segments to characterize ε_{ef} in the region of maximal deformations. To determine these quantities, it is necessary to take a difference of the ordinates ($\Delta\gamma'$ or $\Delta\gamma''$) corresponding to maximal deformations ΔA^1 and ΔA^2 and to divide it by the corresponding relative deformations ($^{\Delta A'}/_{A_0'}$ or $^{\Delta A''}/_{A_0''}$). Note that the relative deformations equal the difference of abscises for the maximal deformations ΔA^1 and ΔA^2 divided by the area corresponding to the amplitude of deformation ($A_0 \pm \Delta A^1$) where different signs before ΔA^1 correspond to expansion and compression. It can be written in the following form for compressed (2) and expanded (3) states:

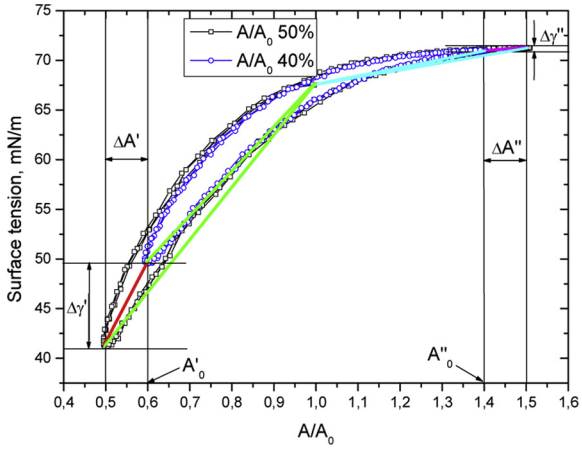

Fig. 1. Lissajous plots for a model system with initial surface tension of 67.5 mN/m at the amplitude of surface area oscillations of $\Delta A^1 = 0.4$ (blue open circles) and $\Delta A^2 = 0.5$ (black open squares). Green and cyan lines correspond to secants, red and magenta lines are segments connecting the points of maximal deformations.

$$\varepsilon_{ef}^{'} = \frac{\Delta\gamma^{'}}{\Delta A^{'}/_{A_0{'}}} = \frac{\Delta\gamma^{'}}{(\Delta A^2 - \Delta A^1)/_{(A_0 - \Delta A^1)}} \quad (2)$$

$$\varepsilon_{ef}^{''} = \frac{\Delta\gamma''}{\Delta A''/_{A_0{''}}} = \frac{\Delta\gamma^{''}}{(\Delta A^2 - \Delta A^1)/_{(A_0 + \Delta A^1)}} \quad (3)$$

For similar rates of relative deformations and for stable systems ε and ε_{ef} usually coincide. At large deformations, the system becomes unstable for a short period of time less than one cycle, and therefore one can obtain a reproducible response for many cycles. In this work it was sufficient to use five cycles of oscillations to estimate the efficient surface elasticity at the frequency 0.03 Hz. Although this method gives a possibility to determine the modulus of efficient surface elasticity for a system in an unstable state, it is difficult to estimate the retardation of the response and thereby to determine the real and imaginary parts of the dynamic surface elasticity separately, since the rate of relative deformation increases with the increase of deformation amplitude even at a constant frequency of oscillations.

The static surface elasticity E was estimated by differentiation of the quasi-equilibrium compression isotherms according to Eq. (1) at the barrier velocity of 1 mm/min, when one can assume that the deviations from equilibrium are negligible. In this case the surface tension and the surface area corresponded exactly to the point of differentiation. Note that E equals zero for solutions of conventional surfactants but can take high values for monolayers of insoluble surfactants. If the relative deformation rate increases, the elasticity modulus can deviate from the static elasticity. In this case, the elasticity was denoted as E_v, where the symbol *v* corresponds to the rate of compression.

3. Results and discussions

3.1. Low surface pressures

The surface properties of spread DPPC monolayers at 30 and 35 °C at low surface pressures (< 55 mN/m) resemble the properties at 25 °C investigated previously (Bykov et al., 2019; Bykov and Noskov, 2018; Wustneck et al., 2005, 2002a). Compression of DPPC monolayers leads to an initial increase of the dynamic surface elasticity up to 30 mN/m at surface pressures in the range 5–6 mN/m for all temperatures (Fig. 2). It corresponds to the formation of liquid expanded (LE) monolayers. A minimum of ε at the further compression is observed at surface pressures about 10, 20 and 30 mN/m at 25, 30 and 35 °C, respectively. This minimum corresponds to a transition between the LE and liquid condensed (LC) surface phases. The growth of the surface pressure

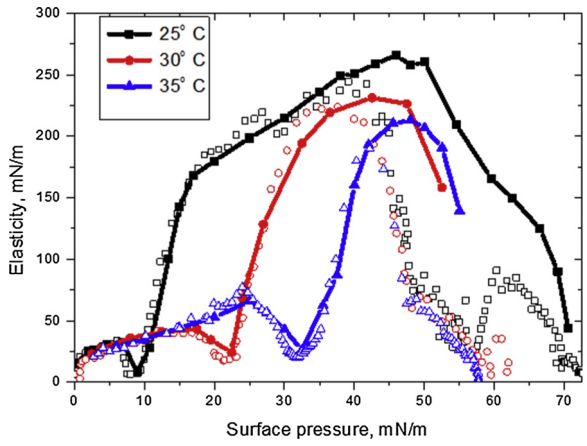

Fig. 2. Dependencies of static elasticity E (open symbols) and dynamic elasticity ε (closed symbols) measured at 0.03 Hz on the surface pressure for spread monolayers of DPPC at 25 °C (black squares), 30 °C (red circles) and 35 °C (blue triangles).

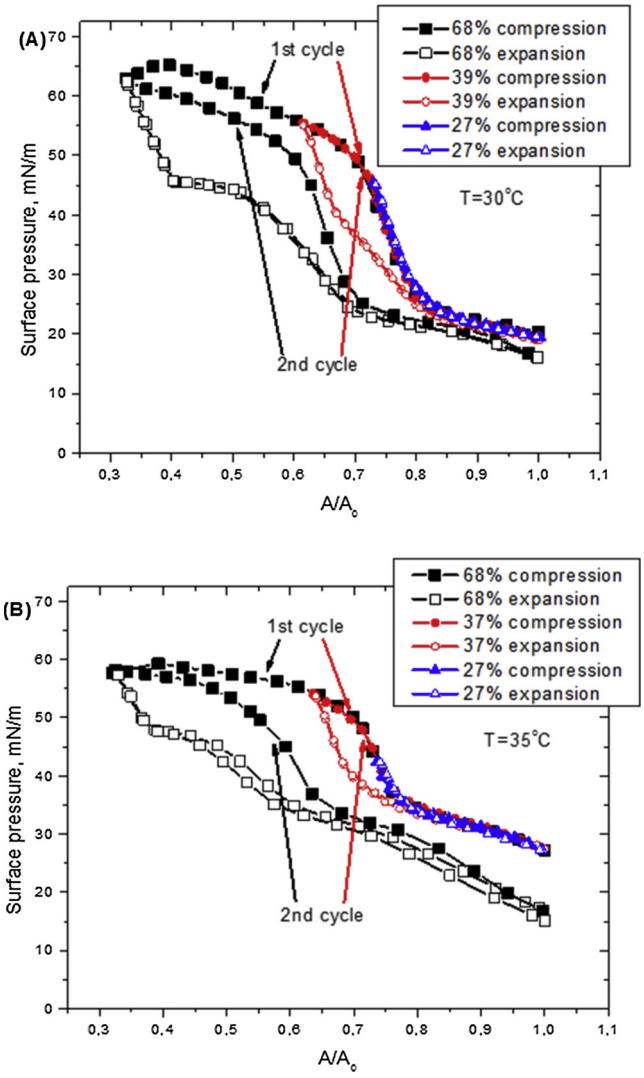

Fig. 3. Compression (closed symbols) and expansion (open symbols) isotherms for the first and second cycles at different relative deformations (68% - black squares, 37–39% - red circles, 27% - blue triangles, % - means degree of compression from initial surface area A_0) for spread DPPC monolayers at 30 °C (upper graph) and 35 °C (lower graph).The rate of deformation was 10% per minute.

corresponding to the phase transition with the increase of temperature agrees with the results of other studies and is connected with a disordering of the monolayer structure (Sosnowski et al., 2017; Wustneck et al., 2005, 2002a). Compression of LC monolayer results in an abrupt increase of ε over 200 mN/m for all the investigated temperatures indicating the formation of strongly packed monolayers (Fig. 2). The compression and expansion isotherms at surface pressures less than 40 mN/m almost coincide at a given temperature (blue triangles in Figs. 3 and S2). This means that the transition between LE and LC phases is reversible. Close values of E and ε indicate that there is no influence of relaxation processes on dynamic surface properties in this region of surface pressures at all investigated temperatures (Fig.2). Moreover, this conclusion is corroborated by the similarity of the ε values obtained in the frequency range from 0.005 to 0.03 Hz (Fig. S3a).

In the range of surface pressures from 40 to 55 mN/m ε passes through a maximum. Its value decreases slightly with the increase of temperature. The decrease of surface elasticity with temperature is in agreement with previous studies and can be connected with the above mentioned disordering effect of the temperature on the monolayer

packing (Wustneck et al., 2005, 2002a). Moreover, in this range of surface pressures E and ε differ significantly as the compression and expansion isotherms do (Figs. 2 and 3 and S2). This difference indicates some relaxation processes in the region of surface pressures 45–55 mN/m. Previously some changes in the state of lipid molecules in this region of surface pressures were observed by the infrared reflection adsorption spectroscopy and connected with a transition from LC to solid-like (S) surface phases (Hunt et al., 1989; Mendelsohn et al., 2010). One can assume that the discovered relaxation process also can be connected with a transition from LC to S surface phases (Bykov and Noskov, 2018). Note that previously discovered differences between the compression and expansion isotherms for DPPC monolayers can be also connected with the same phenomena (Nino et al., 2008). Note that the surface pressure corresponding to this transition does not show any significant dependence on the temperature. At the same time, in this region of surface pressures ε increases with the increase of the oscillation frequency from 0.001 to 0.01 Hz for all investigated temperatures (Fig. S3b). Therefore, the characteristic frequency of relaxation belongs to this range and the main relaxation time is between 200 to 500 s. The coincidence of compression (or expansion) isotherms for the first and the following deformation cycles confirms the reversibility of the transition (red circles in Figs. 3 and S2).

3.2. High surface pressures

In the region of high surface pressures (> 55 mN/m) the behavior of spread DPPC monolayers at 25 °C differs from the properties at 30 and 35 °C. At 25 °C the surface pressure of DPPC monolayers increases up to about 72 mN/m, i.e. corresponds to an almost vanishing surface tension, even at slow compression rates of 1 mm/min (Fig.S2). The further compression of the monolayer up to 32% of the initial area leads to irreversible collapse with squeezing-out DPPC from the monolayer in the form of 3D structures. This results in a shift of isotherms for the second and subsequent cycles of compression/expansion in relation to the first compression isotherm due to the absence of an efficient respreading of the expelled material from the interface during the expansion step (black squares in Fig. S2). At 30 and 35 °C the surface pressure does not reach 72 mN/m in the course of relatively slow compression rate of 1 mm/min (Fig.3). The compression isotherms for the second and subsequent cycles of compression/expansion are shifted to lower surface areas relative to the first compression isotherm indicating that the irreversible collapse of spread DPPC monolayers at 30 and 35 °C occurs at lower surface pressures than at 25 °C (black squares in Fig. 3). Although the maximal surface pressure for pure subphase decreases only to about 71 mM/m when the temperature increases, the decrease of collapse pressure for spread DPPC monolayers at the temperature of 35^0 C proved to be more significant. Moreover, it was shown that the maximal surface pressures at high temperatures and maximal strain depend on the rate of compression (Fig. S4). The decrease of deformation rate from 100 to 2 per cent per minute leads to a decrease of the maximal surface pressure from 72 to 68 and from 68 to 62 mN/m at 30 and 35 °C, respectively. The dependence of surface pressure on the rate of relative deformation also indicates some relaxation process in spread DPPC monolayer in the region of surface pressures from 60 to 72 mN/m at high temperatures.

At 25 °C the relaxation process in the region of surface pressures from 55 to 70 mN/m was extremely slow and the surface tension changed only slightly when the compression was stopped (Bykov et al., 2019). This allowed measurements of the dynamic surface elasticity using a standard procedure within this surface pressures range (Fig. 2) (Bykov et al., 2019). The results for ε_{ef} (Figs. 4 and S5a) were obtained by the modified stress decomposition method (Bykov et al., 2019, 2015; Ilyin et al., 2014; Yu et al., 2010), and agreed qualitatively with ε (Fig. 2). In the region of high surface pressures ε and ε_{ef} decreased from about 200 to 100 mN/m (Figs. 2 and 4). The decrease of the surface elasticity is a consequence of the monolayer collapse and formation of

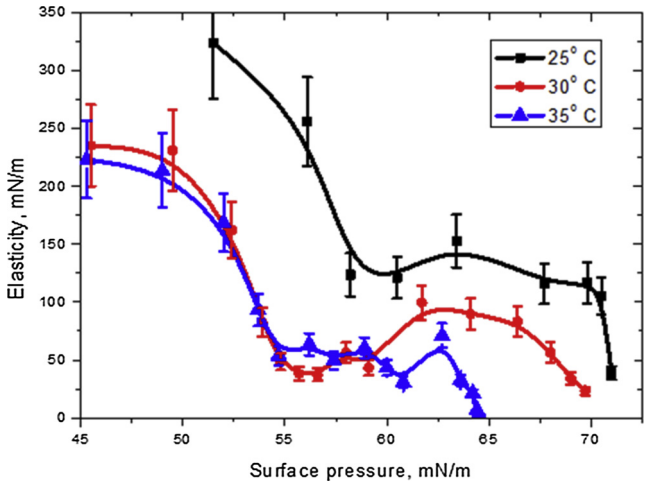

Fig. 4. Dependencies of efficient elasticity ε_{ef} on surface pressure for spread monolayers of DPPC at 25 °C (black squares), 30 °C (red circles) and 35 °C (blue triangles) determined by the modified stress decomposition method at high deformations.

3D structures, e.g. multilayers or vesicles (Bykov et al., 2019). However, unlike the collapse at 72 mN/m, the monolayer collapse in the region of surface pressures from 55 to 70 mN/m is reversible at 25 °C (Fig. S2). Note that formation of multilayer structures for the surface layers of pulmonary surfactants has been reported in numerous studies (Lopez-rodriguez and Pérez-gil, 2014; Parra and Pérez-gil, 2015; Zasadzinski et al., 2010). At 30 and 35 °C the decrease of surface pressure with time does not allow measuring of ε by a standard procedure due to the fast relaxation. Measurements of ε_{ef} show a similar dependence on surface pressure for all the temperatures (Figs. 4 and S5). The increase of surface pressure leads to a significant decrease of ε_{ef}. One can assume that similar changes in the structure of DPPC monolayer occur with the increase of surface pressure at different temperatures due to the transition between monolayer and multilayer structures. The increase of temperature decreases absolute values of ε_{ef} (Fig. 4) as a result of the loosening of the DPPC layer due to the increase of fluctuations. Moreover, at 35 °C ε_{ef} approaches zero at lower surface pressures than at other investigated temperatures because the collapse starts earlier. This occurs due to a relaxation process that does not allow reaching higher surface pressures.

The analysis of the system response to oscillations of the surface area at different amplitudes shows that the temperature increase leads to the changes of the shapes of Lissajous plots. Some Lissajous plots are presented for sake of example for the initial surface pressure of 41 mN/m (Fig. 5). At large deformations (± 30%), when the surface pressure of the monolayer exceeds 55 mN/m, one can observe noticeable hysteresis. The area between the compression and expansion branches of Lissajous plots (the area of hysteresis) increases significantly with the increase of temperature. It was previously shown that the hysteresis is an important condition for maximizing the air penetration into alveoli (Notter et al., 1982; Sosnowski et al., 2017). At 30 and 35 °C the increase of surface pressure above 60 mN/m leads to an increase of the hysteresis area, since the surface pressure decreases abruptly at the beginning of expansion. In these cases the surface layer structures are different at compression and expansion, probably, due to the layer destruction during the initial step of expansion. Note that at 25 °C the expansion and compression branches of Lissajous plots almost coincide at surface pressures between 60 and 70 mN/m due to the recovery of the layer structure during expansion. Moreover, at higher temperatures the monolayer surface pressure is relatively high during expansion due to LE/LC phase transition. This effect can decrease the energy of the expansion of lung surface during inspiration because of the high surface pressure.

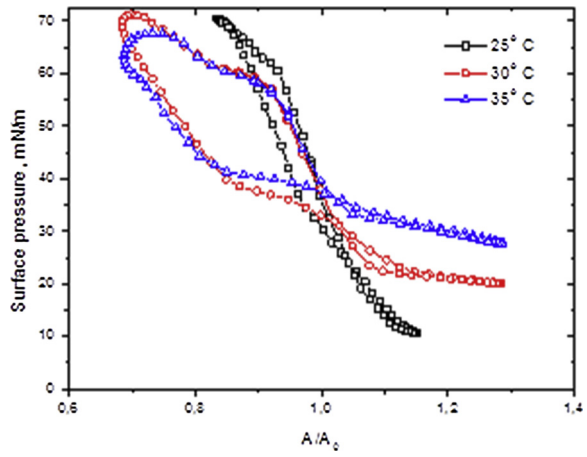

Fig. 5. Dependencies of the surface pressure on the relative deformation (Lissajous plots) measured at 25 °C (black squares), 30 °C (red circles) and 35 °C (blue triangles) and at frequency of surface area oscillations 0.03 Hz.

Measurements of ε at different oscillation frequencies using the standard procedure show that it depends slightly on the oscillation frequency and is close to E in the region of surface pressures from 60 to 70 mN/m at 25 °C (Bykov et al., 2019). These results agree with a negligible influence of the deformation rate on the compression isotherms (Figs. S2, S4 and S6). E_v is high and almost constant at compression rates in the range from 2 to 100 per cent per minute at a surface pressure of 65 mN/m and at 25 °C (Fig. S6). In this case, one can expect that the relaxation rate is much slower than the rate of relative surface deformations. Slow relaxation in the range of surface pressures from 60 to 70 mN/m is one of the reasons of the absence of a significant hysteresis even at low frequencies (Fig. S7a). At the same time, at 30 °C E_v decreases from 50 to 8 mN/m at the decrease of deformation rate from 100 to 2 per cent per minute when the surface pressure of DPPC monolayer is 65 mN/m (Fig. S6). This means that the relaxation time decreases with the increase of temperature. Acceleration of the relaxation process with temperature leads to the increase of the hysteresis area in Lissajous plots at oscillation frequencies from 0.03 to 0.005 Hz (Fig S7b). Therefore, the relaxation time at a surface pressure of 65 mN/m and at 30 °C becomes comparable with the period of oscillations. Moreover, the decrease of the maximal surface pressure with the decrease of deformation rate points at acceleration of the relaxation with the increase of surface pressure. Similar behavior is observed at 35 °C (Fig S6 and S7c). In this case, E_v at a surface pressure of 65 mN/m decreases from 20 to 0 mN/m with the decrease of deformation rate from 100 to 2 per cent per minute (Fig. S6).

The relaxation of surface pressure at different temperatures was also investigated with the aim to determine the relaxation time (Fig. 6).In this case, spread monolayers of DPPC were compressed with the rate of 1 mm/min up to the maximal values of surface pressure at 30 and 35 °C. These values decrease with the increase of temperature, and hence the relaxation curves starts from different values (Fig. 6). The experimental results were approximated by a single exponent:

$$\Pi = \Pi_t + \Delta\Pi * \exp(-t/\tau) \quad (4)$$

where t is the time, Π_t is the equilibrium surface pressure, $\Delta\Pi$ is the relaxation amplitude and τ is the relaxation time. Some deviations from experimental results at 35 °C can be connected with uncontrollable mechanical or thermal disturbances, which cannot be avoided at long measurements.

The fitting parameters are presented in Table 1. At surface pressures close to 66 mN/m and at temperature of 25 °C the relaxation time is close to 900 s. At higher temperatures, the relaxation time is lower than 900 s at surface pressures close to 60 mN/m. Because the relaxation time decreases with the increase of surface pressure, one can assume

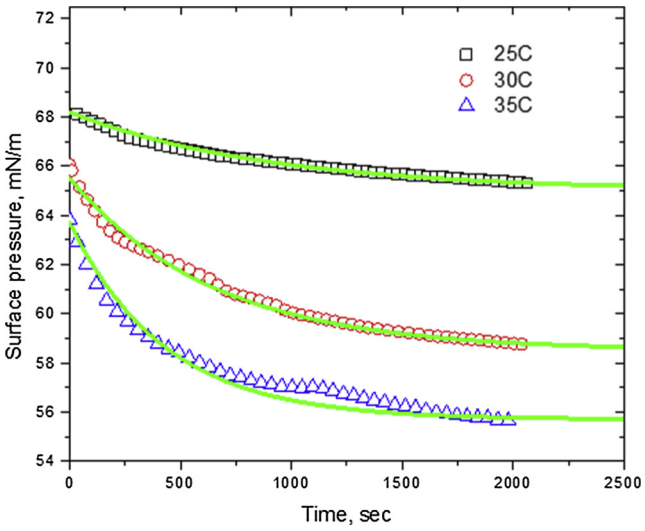

Fig. 6. Dependencies of the surface pressure on the time after compression of spread DPPC monolayers at 25 °C (black squares), 30 °C (red circles) and 35 °C (blue triangles). Zero time corresponds to the end of surface compression with the rate of 1 mm/min. Lines correspond to the exponential decay with the fitting parameters given in Table 1.

Table 1
Values of variable parameters for exponential decay function.

	Π_t, mN/m	$\Delta\Pi$, mN/m	τ, sec
25 °C	65	3.2	903
30 °C	58.5	7	648
35 °C	55.7	8	431

that the growth of temperature in the region of high surface pressures from 65 to 70 mN/m leads to a significant decrease of relaxation time. The obtained results corroborate the conclusions based on the measurements of the dilational surface elasticity.

The temperature has a strong influence on the dynamic surface properties of DPPC monolayers. In the region of low surface pressures the increase of temperature results in the increase of surface pressure corresponding to the LE/LC transition, thereby facilitating the preservation of low surface tension during expansion and the decrease of the energy required for inhalation. In the region of high surface pressures the increase of temperature leads to the acceleration of the relaxation, which is probably connected with a reversible transition between the monolayer and multilayer structures. This results in a more significant hysteresis. Comparing the results for low and high regions of surface pressures one can suppose that the main influence of temperature consists in the disordering of the monolayer structure. At 35 °C the behavior of spread DPPC monolayers proves to be close to that of adsorbed PS layers investigated in a previous work at 25 °C (Bykov et al., 2019) [24]. At the same time, there is a significant difference between these two systems because of the irreversible collapse of spread DPPC monolayers as a result of the fast relaxation processes in the latter system. At 35 °C and at the frequency of surface area oscillations of 0.03 Hz the irreversible collapse occurs already at the surface pressure close to 65 mN/m), while for adsorbed layers of PS the surface pressure increases up to about 72.5 mN/m, i.e. quasi-negligible values of surface tension. Note that the impossibility of reaching extremely high values of surface pressure can lead to premature alveoli collapse (Clements, 1957; Lopez-rodriguez and Pérez-gil, 2014; Parra and Pérez-gil, 2015; Zasadzinski et al., 2010).

4. Conclusion

In this work the dynamic surface properties of spread DPPC monolayers were investigated at different temperatures. The application of a modified Langmuir trough excluded the leakage of molecules from the surface between barriers, and the modified stress decomposition method gave a possibility to estimate the surface elasticity at extremely high surface pressures corresponding to the physiological conditions inside alveoli. The increase of temperature from 25 to 35 °C led to a decrease of the surface elasticity in the region of high surface presssure probably due to the disordering of the lipid monolayer structure. Moreover, the surface pressure relaxation and surface elasticity measurements at different frequencies of surface area oscillations showed the acceleration of the relaxation in spread DPPC monolayers with the temperature, which on one hand, leads to a more significant hysteresis of the surface pressure isotherms; whereas on the other hand, this leads to the impossibility of reaching extremely high values of surface pressure under surface compression.

Acknowledgement

The work was financially supported by the Russian Science Foundation (project 17-73-10171).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.chemphyslip.2019.104812.

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