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Chain length and pressure dependence of lipid translational diffusion

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Abstract. The translational diffusion of pyrene, pyrene butyric acid and pyrene decanoic acid has been determined in phosphatidylcholine bilayers of different chain length and under pressure up to 200 bars. In the liquid crystalline phase and at a given temperature the diffusion decreases with increasing chain length. At a constant reduced temperature, T_{red} (about 10 K above the transition temperature), long chain lipids exhibit the fastest diffusion which is in disagreement with hydrodynamic models but favours free volume models for diffusion in lipid bilayers. The volume of activation, V_{act}, calculated from the decrease of the diffusion coefficient with pressure, $\partial \ln D / \partial P$, depends on lipid chain length. V_{act} decreases with decreasing lipid chain length at a given temperature, $T = 65\,^{\circ}\mathrm{C}$, and increases at the reduced temperature. These results are again in agreement with the dependence of the diffusion on lipid chain length and therefore with the free volume model.

Key words: Lipid diffusion, free volume, excimers, pressure, model membranes

Introduction

The translational diffusion of lipids and proteins has been the subject of numerous studies. A critical review comparing experiments and theory has been published recently (Clegg and Vaz 1985). Two models for the theoretical treatment of lateral transport in lipid bilayers have been developed. One is the continuum hydrodynamic model of Saffman and Delbrück (1975); Saffman (1976) which describes the diffusion by the Brownian motion of a particle in a viscous sheet. The second is the free volume model of Cohen and Turnbull (1959) which has been successfully applied to describe the transport properties of liquids (Vogel and Weiss 1981 a, b). Galla et al. (1979) were the first who adapted this model for the diffusion in lipid bilayers in connection with the excimer technique (Galla and Hartmann 1980).

The applicability of these models is not yet clear, however there is striking evidence that the Saffman-Delbrück model is valid for diffusants with diameters larger than that of the matrix molecules. This has been clearly demonstrated by Vaz et al. (1982) who investigated the diffusion of integral membrane proteins as a function of their size. Experimental evidence against the applicability of this model to lipid diffusion has been presented from a study using the fluorescence recovery after photobleaching technique. The diffusion of a lipid probe at a given temperature was found to be independent of chain length (Vaz and Hallmann 1983; Vaz et al. 1985) which was interpreted to be against the prediction of the hydrodynamic model but in agreement with the free volume model. Very recently Peters and Beck (1983) reported further evidence for the free volume model from diffusion measurements in lipid monolayers at the air-water interface. Further support was obtained from the pressure dependence of the lateral diffusion in dipalmitoylphosphatidylcholine membranes (Müller and Galla 1983). In addition to the description of the lateral diffusion in the fluid L_{α}-phase the free volume theory my also be applied to model the diffusion in fluidized channels of the crystalline $P_{\beta'}$-phase (Kapitza et al. 1984; Müller et al. 1986). However, further experimental work is needed for a concrete distinction from the hydrodynamic model.

Here we present further evidence against the applicability of the Saffman-Delbrück model for lipid

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Abbreviations: DLPC, Dilauroylphosphatidylcholine; DMPC, Dimyristoylphosphatidylcholine; DPPC, Dipalmitoylphosphatidylcholine; DSPC, Distearoylphosphatidylcholine; LUV, Large unilamellar vesicles; SUV, Small unilamellar vesicles; Tris, Tris(hydroxymethyl)aminomethan diffusion using the excimer formation technique. Jump frequencies instead of diffusion coefficients were determined in phosphatidylcholine bilayer membranes of different chain length and under pressure. The volume of activation for the diffusional step was calculated from the pressure dependence. The results fit the free volume model.

Materials and methods

DLPC, DMPC, DPPC and DSPC were obtained from Fluka (Neu-Ulm, FRG) checked by T. L. C. and used without further purification. Pyrene from Fluka was highly purified by repetitive zone melting. Pyrene butyric acid was from Serva (Heidelberg, FRG). Pyrene decanoic acid was synthesized as described (Galla and Hartmann 1981).

Vesicle preparation

Large unilamellar vesicles (LUV) used throughout the paper were prepared by a modification of the method of Szoka and Papahadjopoulos (1978). A 20 m*M* solution of phosphatidylcholine in chloroform/buffer (2 : 1, v/v) was briefly sonicated (Branson sonifier equipped with a microtip) until the mixture became a homogenous dispersion. The buffer solution was 1 m*M* *Tris*/HCl, pH 7.0. The organic solvent was then removed at a temperature about 10 K above the corresponding phase transition temperature and under reduced pressure in a rotary evaporator. The aqueous suspension obtained was washed three times by centrifugation at $12{,}000 \times g$ for 10 min. The final pellet was resuspended in 10–30 ml buffer solution to make a lipid concentration of 0.2–1.0 mg/ml. The typical vesicle size was between 1,000 and 2,000 Å.

Small unilamellar vesicles (SUV) were only used for comparison. 300–400 Å sized vesicles were obtained by sonification of the LUVs for 4 min with the Branson sonifier at 40 W.

Spectroscopic methods

Fluorescence measurements were performed with a fluorescence spectrometer equipped with two sets of monochromator/photomultiplier systems arranged perpendicular to the irradiation beam. The excitation wavelength was 335 nm for pyrene and 338 nm for pyrene butyric acid and pyrene decanoic acid. The monomer emission (I) and the excimer emission (I') were measured simultaneously at 394 and 470 nm for pyrene and at 396 and 470 nm for pyrene butyric acid and pyrene decanoic acid. Samples were kept in 1 cm quartz cuvettes in a specially constructed thermostatically controlled metal block equipped with pressure resistent quartz windows. Temperature was measured by a thermocouple in the sample.

Pressure was attained from a helium source pressurized to 200 bars. Air was removed from the system by pressurizing and venting several times.

The diffusion coefficients can be determined from the fluorescence intensities of the excimer, I', and the monomer, I, of pyrene derivatives incorporated into the membrane. The intensity ratio I'/I is a measure of the diffusion controlled excimer formation of the pyrene derivatives (Galla and Sackmann 1974a). The jump frequency, ν_j, in a lipid matrix is directly related to the intensity ratio by $\nu_j \sim \mathrm{const} \cdot I'/(I \cdot \tau_0')$ where τ_0' is the excimer life time which has to be measured separately. The coefficient of the lateral diffusion, D, is related to ν_j by $D = \nu_j \lambda^2/4$, where λ is the length of one diffusional step which is given by the average distance of two neighbouring lipid molecules ($\lambda \approx 0.8$ nm). In this paper translational diffusion is characterized by the jump frequency. For further details see Galla and Hartmann (1980); Galla et al. (1979).

It is important to note that pyrene butyric acid does not quantitatively incorporate into bilayer vesicles. We determined a partition coefficient between the lipid and the aqueous phase of $k_p \approx 2{,}500$. This made it necessary to analyze the vesicles and to quantify the amount of pyrene butyric acid from the absorption coefficient. Vesicles were centrifuged at $100{,}000 \times g$ and the pellet was dissolved in chloroform/methanol (1 : 1, v/v). Absorption spectra were measured by a Beckmann DU 50 spectrometer.

Results

The lipid chain length dependence and the pressure dependence of the lateral diffusion in phosphatidylcholine bilayer vesicles have been investigated by the excimer formation technique. Pyrene, pyrene butyric acid and pyrene decanoic acid have been used as probe molecules to monitor different regions of the hydrophobic membrane interior (Luisetti et al. 1979).

The effect of chain length

The chain length dependence of the translational diffusion at a given temperature, $T = 65$ °C, and at a reduced temperature, $T_{\mathrm{red}} = (T_s - T_t)/T_t$ where T_s is the sample temperature and T_t is the lipid phase transition temperature, is given in Fig. 1A–C and

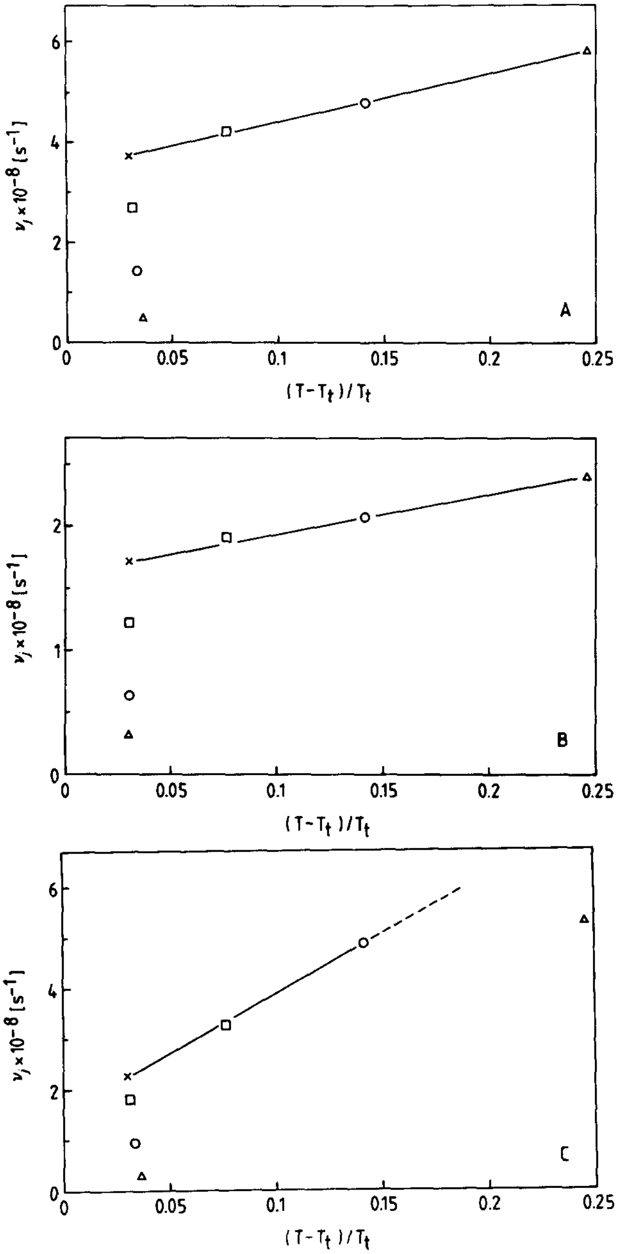

Fig. 1A–C. The jump frequency ν_j calculated from the excimer/monomer ratio of pyrene, pyrene butyric acid and pyrene decanoic acid is shown on a reduced temperature scale with $T_{\text{red}} = (T - T_t)/T_t$ to characterize the chain length dependence. Two sets of measurements were performed at $T = 65\,°\text{C}$ and at a temperature $T = T_t + 10\,\text{K}$ which corresponds to a constant reduced temperature of about 3.05×10^{-2} (vertically points). The straight lines stand for the measurements at $T = 65\,°\text{C}$. The different lipids are marked by the following symbols: x DSPC, □ DPPC, ○ DMPC, △ DLPC. **A** Pyrene as probe molecule, **B** pyrene butyric acid as probe molecule, **C** pyrene decanoic acid as probe molecule

in Table 1. The reduced temperature was chosen in order to consider the different lipid phase transition temperatures. Note that each point on the straight lines stands for a lipid of a given chain length. Pyrene, pyrene butyric acid and pyrene decanoic acid were used as probe molecules.

Table 1. Chain length dependence of the translational diffusion represented by the jump frequency, ν_j, of pyrene, pyrene butyric acid and pyrene decanoic acid in phosphatidylcholine bilayer membranes at $T = 65\,°\text{C}$ and at a reduced temperature $T_{\text{red}} = 3.05 \times 10^{-2}$ which is about $T = T_t + 10\,\text{K}$. Values for the phase transition temperature are taken from Szoka and Papahadjopoulos (1980). Large unilamellar vesicles and small unilamellar vesicles yield identical results within the experimental deviation

	Lipid	DLPC	DMPC	DPPC	DSPC
	T_t [°C]	−1.8	23	41	55
Pyrene	$\nu_j \times 10^{-8}$ [s^{-1}] at $T = 65\,°\text{C}$	5.8	4.8	4.2	3.8
	$\nu_j \times 10^{-8}$ [s^{-1}] at $T = T_{\text{red}}$	0.5	1.5	2.7	3.8
Pyrene butyric acid	$\nu_j \times 10^{-8}$ [s^{-1}] at $T = 65\,°\text{C}$	2.4	2.1	1.9	1.7
	$\nu_j \times 10^{-8}$ [s^{-1}] at $T = T_{\text{red}}$	0.3	0.6	1.2	1.7
Pyrene decanoic acid	$\nu_j \times 10^{-8}$ [s^{-1}] at $T = 65\,°\text{C}$	4.7	4.3	2.9	2.0
	$\nu_j \times 10^{-8}$ [s^{-1}] at $T = T_{\text{red}}$	0.3	0.9	1.6	2.0

At a given temperature of $T = 65\,°\text{C}$ where all membranes under investigation are in the fluid phase the jump frequency ν_j calculated for the translational diffusion decreases with increasing chain length for all probes (see Fig. 1A–C and Table 1 for calculated values). At a constant reduced temperature which is at about $T = T_t + 10\,\text{K}$ the situation is reversed and the order for the jump frequency is $\nu_j^{\text{DSPC}} > \nu_j^{\text{DPPC}} > \nu_j^{\text{DMPC}} > \nu_j^{\text{DLPC}}$. The effect is independent of the vesicle diameter. SUVs and LUVs yield identical results within the error of investigation. As illustrated in Fig. 1A–C for the different excimer probes we obtained a linear increase of the diffusion with decreasing chain length at a constant temperature of $T = 65\,°\text{C}$. The slope of the observed straight line is smaller for pyrene and pyrene butyric acid compared to pyrene decanoic acid. Measurements performed at $T = T_t + 10\,\text{K}$ which means a comparable reduced temperature as already shown in Table 1 yield a decrease of D_{diff} with decreasing chain length. Only the jump frequency of pyrene decanoic acid in DLPC-membranes measured at $T = 65\,°\text{C}$ deviates from a straight line, in contrast to the results obtained with pyrene and pyrene butyric acid.

Pressure dependence

The effect of pressure up to 200 bars on the lateral diffusion of pyrene, pyrene butyric acid and pyrene

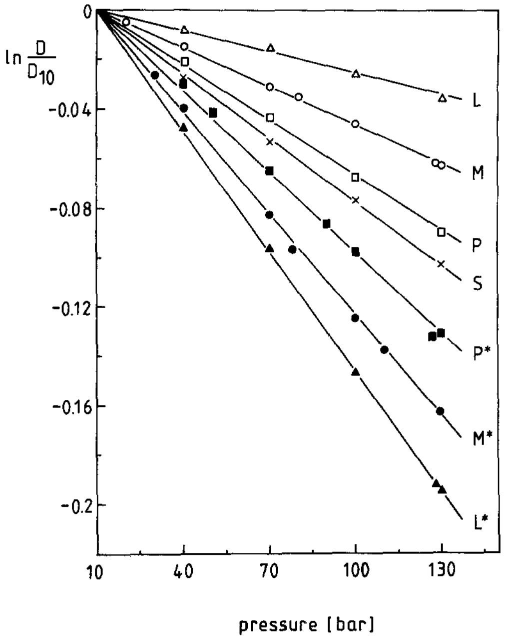

Fig. 2. The relative change of the lateral diffusion coefficient $\ln(D/D_{10})$ is given as function of pressure. D is the measured diffusion coefficient at a given pressure, D_{10} is the reference at 10 bars. The relative change is normalized to 10 bars (D_{10}). D is the measured diffusion coefficient at a given pressure. Measurements at $T = 65$ °C are marked with L, M, P and S for DLPC, DMPC, DPPC and DSPC. The corresponding values at $T \approx T_t + 10$ K are marked by L^*, M^* and P^*

decanoic acid in phosphatidylcholine membranes of different chain length is demonstrated in Figs. 2–4. The pressure dependence was again investigated at a constant temperature $T = 65$ °C and at a temperature, which corresponds for all lipids to an identical reduced temperature $T_{\mathrm{red}} = 3.05 \times 10^{-2}$ ($\approx 10\,\mathrm{K}/T_t$). Figure 2 shows the pressure dependence of the diffusion coefficient of pyrene in DLPC, DMPC, DPPC and DSPC-membranes. The ordinate gives the relative change with respect to the value of D_{diff} at 10 bars on a logarithmic scale. Normalization to 10 bars instead of 1 bar was performed for technical reasons. All pressure dependent measurements were started at 10 bars to avoid oxygen influx. At $T = 65$ °C (symbols S, P, M, L) and at $T_{\mathrm{red}} = 3.05 \times 10^{-2}$ (symbols S, P^*, M^* and L^*) we obtained straight lines for the decrease of $\ln D/D_{10}$ with pressure. The error bars correspond to the size of the symbols. Measurements were performed at probe concentrations between molar fractions of $x = 0.03$ and 0.05.

The change in diffusion coefficient with pressure at $T = 65$ °C has the largest slope for DSPC and the smallest for DLPC. At the reduced temperature ($T \approx T_t + 10$ K) the order of the slope is reversed: DLPC > DMPC > DPPC > DSPC. The pressure effect is smallest for the long chain lipid. Comparing measurements at $T = 65$ °C and $T \approx T_t + 10$ K we

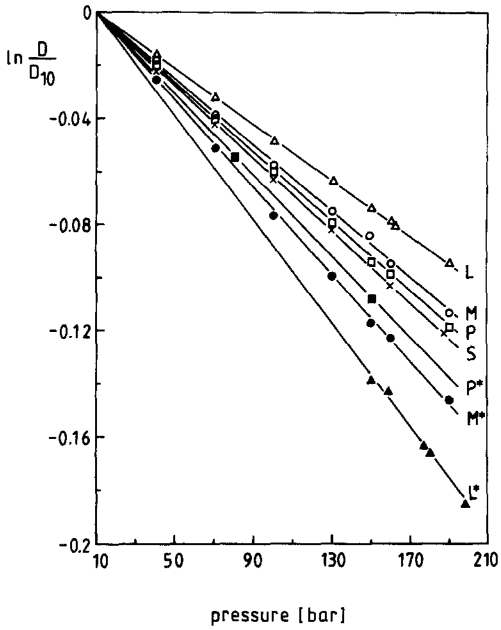

Fig. 3. The same as Fig. 2 but pyrene butyric acid was used as probe molecule

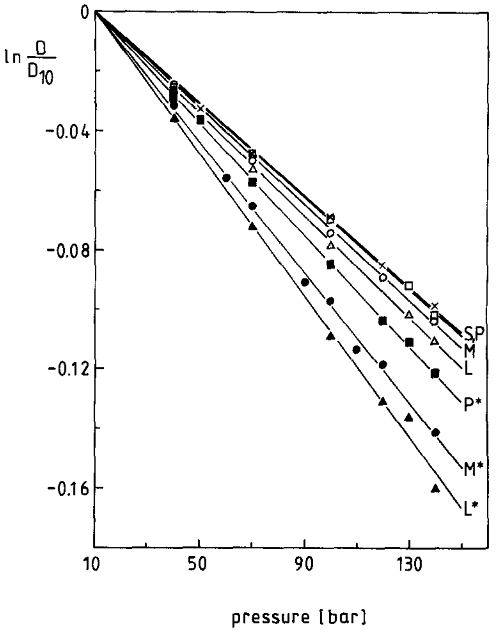

Fig. 4. The same as Fig. 2 but pyrene decanoic acid was used as probe molecule

always obtain a smaller pressure dependence at the higher temperature.

Qualitatively we obtained the same results with pyrene butyric acid (Fig. 3). The pressure decrease of the translational diffusion is maximal for the long chain lipid at $T = 65$ °C and minimal at the reduced temperature. Using pyrene decanoic acid the pressure effect at $T = 65$ °C becomes indistinguishable for DSPC, DPPC and DMPC membranes. The slope is slightly increased for DPLC. At the reduced tem-

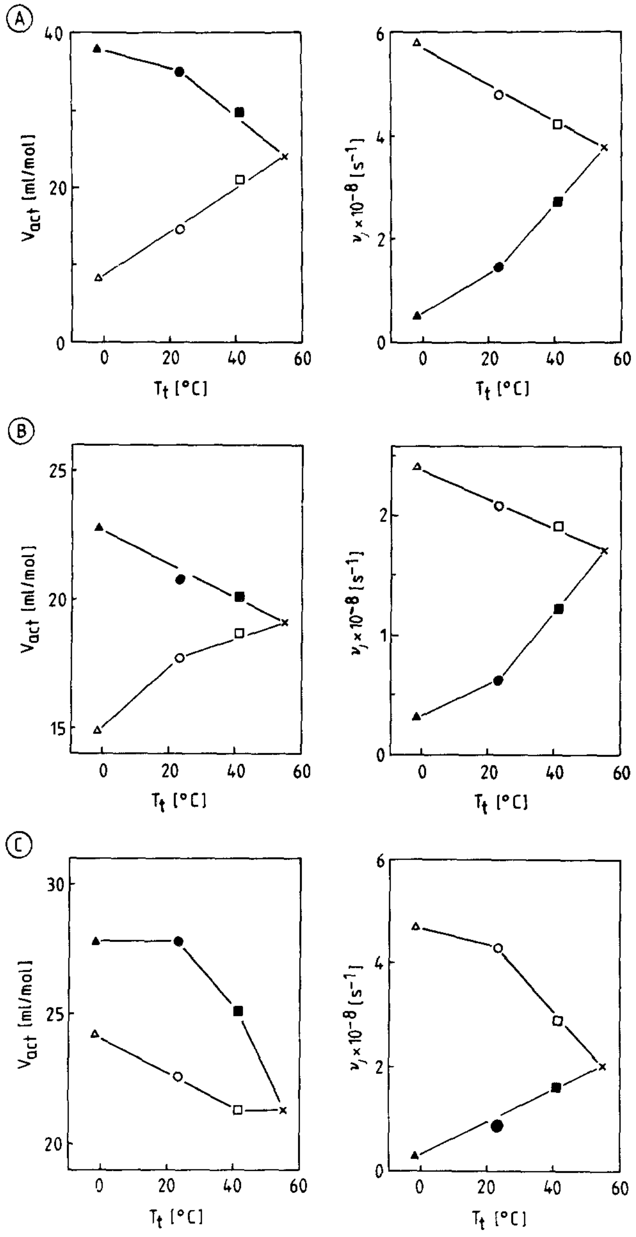

Fig. 5A–C. The volume of activation and the jump frequencies, ν_j, given as function of the corresponding lipid phase transition temperature. The different lipids are marked by the following symbols: × DSPC, □ DPPC, ○ DMPC, △ DLPC. *Open symbols:* $T = 65\,°C$; *filled symbols:* $T = T_t + 10\,K$; **A** pyrene as probe molecule, **B** pyrene butyric acid as probe molecule, **C** pyrene decanoic acid as probe molecule

Table 2. The volume of activation $V_{act} = -RT(\partial \ln D/\partial P)_T$ is calculated from the slopes of the straight lines in Figs. 2–4 for pyrene, pyrene butyric acid and pyrene decanoic acid. Values are given at $T = 65\,°C$ and at T_{red}. The volume of activation decreases with increasing chain length at the reduced temperature and increases at $T = 65\,°C$. This is not observable by the use of pyrene decanoic acid at 65 °C

	Lipid	DLPC	DMPC	DPPC	DSPC
Pyrene	V_{act} [ml/Mol] at $T = 65\,°C$	8.3	14.6	21.0	24.0
	V_{act} [ml/Mol] at $T = T_{red}$	37.9	34.9	29.8	24.0
Pyrene butyric acid	V_{act} [ml/Mol] at $T = 65\,°C$	14.9	17.7	18.7	19.1
	V_{act} [ml/Mol] at $T = T_{red}$	22.8	20.8	20.1	19.1
Pyrene decanoic acid	V_{act} [ml/Mol] at $T = 65\,°C$	24.2	22.6	21.3	21.3
	V_{act} [ml/Mol] at $T = T_{red}$	27.8	27.8	25.1	21.3

perature the order is again DLPC > DMPC > DPPC > DSPC. The differences in the slopes however are smaller compared to pyrene used as probe molecule.

From the slopes of the straight lines we are able to calculate the volume of activation for the diffusion according to $V_{act} = -RT(\partial \ln D/\partial P)_T$ (McCall et al. 1959). The values are given in Table 2 again for $T = 65\,°C$ and for the reduced temperature, $T_{red} = 3.05 \times 10^{-2}$. Figure 5 illustrates the dependence of the volumes of activation and the jump frequencies on the phase transition temperature. Values for $T = 65\,°C$ (open symbols) and for T_{red} (filled symbols) are compared. Again pyrene, pyrene butyric acid and pyrene decanoic acid were used as probe molecules. At $T_{red} \approx T_t + 10\,K$ the volume of activation decreases and the diffusion increases with increasing phase transition temperature, that is with increasing lipid chain length. At $T = 65\,°C$ the dependence is reversed. The only exception is the dependence of the V_{act} of pyrene decanoic acid which decreases with increasing lipid chain length at $T = 65\,°C$.

Discussion

As was shown earlier (Galla and Sackmann 1974a; Galla et al. 1979; Galla and Hartmann 1980) it is possible to determine the excimer formation rate from the fluorescence spectra of pyrene derivatives. The excimer formation rate on the other hand yields the jump frequency of the probe molecules which characterizes the lateral diffusion of the probe. From the relation $D = 0.25\,\nu_j \lambda^2$ where λ is the average jump distance, a diffusion coefficient may be estimated if λ is known. The average jump distance has been considered as the average distance between lipid molecules, occupying neighbouring lattice places in a lipid layer (e.g. Galla and Hartmann 1980). Here we used the excimer formation technique to investigate the lipid chain length dependence and the pressure dependence of the lateral diffusion.

Our results shown in Fig. 1 clearly demonstrate that the lateral diffusion measured at a given temperature above the lipid phase transition temperature increases with decreasing lipid chain length. We have chosen a temperature of $T = 65\,^{\circ}\mathrm{C}$ for these experiments which is above the phase transition temperature of all lipids used. DSPC, the lipid with longest chains melts at $T = 55\,^{\circ}\mathrm{C}$. In Fig. 1 the jump frequency is plotted as function of the reduced temperature to illustrate the chain length dependence. Each point stands for a different lipid. We obtained straight lines if pyrene or pyrene butyric acid were used as probe molecules (Fig. 1A and B). If pyrene decanoic acid was used as probe molecule ν_j increases linearly in the order DSPC > DPPC > DMPC. The jump frequency measured in the short chain lipid DLPC is only slightly increased compared to DMPC and a deviation from the extrapolated straight line was found.

This is explainable by the misfitting of the probe. Pyrene decanoic acid exerts the lauroyl chain and therefore has to bend back or has to protrude into the second monolayer of the bilayer which reduces the lateral diffusion due to disturbance of membrane structure. Pyrene or pyrene butyric acid fit even into the short chain DLPC and consequently the observed jump frequency is further increased with respect to DMPC.

Derzko and Jacobson (1980) used fluorescence labels of different chain length and different number of chains which all showed the same lateral diffusion. This supports the interpretation that probe diffusion is determined by the self diffusion of the lipid matrix. However, within the error bars their photobleaching data are comparable to the present work. We clearly observe a difference with different excimer probes. The jump frequency of pyrene decanoic acid falls consistently between ν_j for pyrene and pyrene butyric acid. This result is true for all bilayers examined. Obviously the position of the pyrene moiety and its influence upon the bilayer order plays a considerable role at least for hydrophobic probes.

The improved experiments shown in Fig. 1 clearly demonstrate that the lateral diffusion of pyrene or pyrene derivatives is dependent on the lipid chain length and is not a universal function of temperature as assumed earlier (Galla et al. 1979). Consequently the kink formation (Galla and Sackmann 1974b) may not be the only parameter that determines lateral diffusion. Van der Waal's interaction between the lipid chains seem to play an important role beside chain dynamics.

From dilatometric and densitometric measurements (Nagle and Wilkinson 1978; Schmidt and Knoll 1985) we know that phosphatidylcholines of different chain lengths exhibit an increase of their specific volumes with increasing chain length at all temperatures. The temperature dependent volume change is identical for all lipids. Consequently the volume per lipid molecule is largest in DSPC-membranes at a given sample temperature, e.g. at $T = 65\,^{\circ}\mathrm{C}$. The free volume of a lipid molecule, is given by $V_f \sim V \cdot \alpha \cdot (T - T_t)$ (Galla et al. 1979) where V is the average volume just above the phase transition temperature and α is the thermal expansion coefficient. If α is constant for all lipids used then $T - T_t$ determines the free volume, which is then largest for DLPC and smallest for DSPC-membranes due to the smallest temperature difference with respect to the phase transition temperature. This result fits the free volume model but also the continuum fluid hydrodynamic model, which predicts a decrease of the lateral diffusion with increasing chain length but also with increasing viscosity. The theory predicts $D_{\mathrm{diff}} \sim \mathrm{kT}/4\pi\eta h$, where η is the viscosity and h is the thickness of the bilayer and also the heigth of the diffusing particle (Saffman and Delbrück 1975).

At a constant reduced temperature $T_{\mathrm{red}} = (T - T_t)/T_t = 3.05 \times 10^{-2}$ the situation changes. The volume per lipid acyl chain $\mathrm{CH_2}$-group increases with increasing chain length (Cornell and Separovicz 1983; Vaz et al. 1985) which corresponds to a larger free volume for a long chain lipid. The theoretically expected decrease of the lateral diffusion with decreasing chain length is in excellent agreement with our excimer data (Fig. 1) but in contradiction to the expectation of the Saffman-model. Photobleaching experiments studying long range diffusion led to the same results (Vaz et al. 1985). In agreement with these authors we conclude that the free volume model appropriately describes the lateral diffusion of molecules which are of equal size or smaller than lipid molecules.

The pressure dependence of the lateral diffusion again fits the free volume model which predicts an exponential decrease with increasing pressure (Müller and Galla 1983). From the slopes of the straight lines in Figs. 2–4 we calculated the volume of activation, V_{act} (Table 2). A large volume of activation must correspond to a low excimer formation rate. The calculated values of V_{act} are consistent with the results presented in Fig. 1. All data are summarized in Fig. 5. At a reduced temperature, the volume of activation decreases with increasing chain length whereas the diffusion coefficient increases. At a constant temperature $T = 65\,^{\circ}\mathrm{C}$ V_{act} increases drastically with lipid chain length if pyrene or pyrene butyric acid were used as probes. The increase of V_{act} corresponds to the decrease of the diffusion coefficient with increasing lipid chain length. The effect predicted by the diffusion measurements is best observable by pyrene which incorporates into the interior of the lipid bilayer. Figure 5 demonstrates the change in the volume of activation and the corresponding change in the lateral diffusion with lipid phase transition temperature and therefore with lipid chain length.

Pyrene decanoic acid is the only probe that behaves anomalously at $T = 65\,^{\circ}\mathrm{C}$ (Fig. 5c, open symbols). The volume of activation in DLPC and DMPC is higher compared to DPPC. However, the jump frequency increases with decreasing chain length. This effect is less pronounced between DMPC and DLPC. A possible interpretation of this behaviour is the misfit between probe and lipid matrix. As already mentioned pyrene decanoic acid may, because of its chain length, protrude into the hydrophobic part of the second monolayer of a lipid bilayer. This may lead to an increase in the observed volume of activation. If this interpretation holds pyrene moieties from probes being incorporated in either monolayer of the bilayer will be able to occupy the space between the two monolayers and to form excimers which yield an artifactually increased jump frequency due to an increased concentration of pyrene moieties in the middle part of the bilayer. In long chain lipids excimers can only be formed between probes within one monolayer. The overlap of probe molecules is larger in DLPC than in DMPC and should not occur in DPPC membranes. This assumption can only be proven by a systematic change of the chain length of the pyrene fatty acid derivatives.

However, this discrepancy should not vitiate the conclusion of the present study: the pressure dependence as well as the chain length dependence support the thesis that lipid translational diffusion is appropriately described by the free volume model.

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References

Clegg RM, Vaz WLC (1985) Translational diffusion of proteins and lipids in artificial lipid bilayer membranes. A comparison of experiment with theory. In: Watts A, De Pont JJHHM (eds) Progress in protein-lipid interactions. Elsevier, Amsterdam, pp 173–229

Cohen MH, Turnbull D (1959) Molecular transport in liquids and glasses. J Chem Phys 31:1164–1169

Cornell BA, Separovicz F (1983) Membrane thickness and acyl chain length. Biochim Biophys Acta 733:189–193

Derzko Z, Jacobson K (1980) Comparative lateral diffusion of fluorescent lipid analogues in phospholipid multibilayers. Biochemistry 19:6050–6057

Galla HJ, Hartmann W (1980) Excimer-forming lipids in membrane research. Chem Phys Lipids 27:199–219

Galla HJ, Hartmann W (1981) Pyrene decanoic acid and pyrene lecithin. Methods Enzymol 72:471–479

Galla HJ, Sackmann E (1974a) Lateral diffusion in the hydrophobic region of membranes: Use of pyrene excimers as optical probes. Biochim Biophys Acta 339:103–115

Galla HJ, Sackmann E (1974b) Lateral mobility of pyrene in model membranes of phospholipids with different chain length. Ber Bunsenges Phys Chem 78:949–953

Galla HJ, Hartmann W, Theilen U, Sackmann E (1979) On two-dimensional passive random walk in lipid-bilayers and fluid channels of biomembranes. J Membr Biol 48:215–236

Kapitza HG, Rüppel D, Galla HJ, Sackmann E (1984) Lateral diffusion of lipids and proteins in solid phosphatidylcholine bilayers: The role of structural defects. Biophys J 45:577–587

Luisetti J, Möhwald H, Galla HJ (1979) Monitoring the location profile of fluorophores in phosphatidylcholine bilayers by the use of paramagnetic quenching. Biochim Biophys Acta 552:519–530

McCall DW, Douglass DC, Anderson EW (1959) Self-diffusion in liquids: Paraffin hydrocarbons. Phys Fluids 2:87–91

Müller HJ, Galla HJ (1983) Pressure variation of the lateral diffusion in lipid bilayer membranes. Biochim Biophys Acta 733:291–294

Müller HJ, Luxnat M, Galla HJ (1986) Lateral diffusion of small solutes and partition of amphipaths in defect structures of lipid bilayers. Biochim Biophys Acta 856:283–289

Nagle JF, Wilkinson DA (1978) Lecithin bilayers. Density measurements and molecular interactions. Biophys J 23:159–175

Peters R, Beck K (1983) Translational diffusion in phospholipid monolayers measured by fluorescence microphotolysis. Proc Natl Acad Sci USA 80:7183–7187

Saffman PG (1976) Brownian motion in thin sheets of viscous fluid. J Fluid Mech 73:593–602

Saffman PG, Delbrück M (1975) Brownian motion in biological membranes. Proc Natl Acad Sci USA 72:3111–3113

Schmidt G, Knoll W (1985) Densitometric characterization of aqueous lipid dispersions. Ber Bunsenges Phys Chem 89:36–43

Szoka F Jr, Papahadjopoulos D (1978) Procedure for preparation of liposomes with large internal aqueous space and high capture by reverse-phase evaporation. Biochemistry 75:4194–4198

Szoka F Jr, Papahadjopoulos D (1980) Comparative properties and methods of preparation of lipid vesicles (liposomes). Annu Rev Biophys Bioeng 9:467–508

Vaz WLC, Hallmann D (1983) Experimental evidence against the applicability of the Saffman-Delbrück model to the translational diffusion of lipids in phosphatidylcholine bilayer membranes. FEBS Lett 152:287–290

Vaz WLC, Criado M, Madeira VMC, Schoellmann G, Jovin TM (1982) Size dependence of the translational diffusion of large integral membrane proteins in liquid-crystalline phase lipid bilayers. A study using fluorescence recovery after photobleaching. Biochemistry 21:5608–5612

Vaz WLC, Clegg RM, Hallmann D (1985) Translational diffusion of lipids in liquid crystalline phase phosphatidylcholine multibilayers. A comparison of experiment with theory. Biochemistry 24:781–786

Vogel H, Weiss A (1981a) Transport properties of liquids. I. Self-diffusion, viscosity and density of nearly spherical and disk like molecules in the pure liquid phase. Ber Bunsenges Phys Chem 85:539–548

Vogel H, Weiss A (1981b) Transport properties of liquids. II. Self-diffusion of almost spherical molecules in athermal liquid mixtures. Ber Bunsenges Phys Chem 85:1022–1026