The study of the interaction of quantum dots with phosphatidylcholine to create hybrid functional materials

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Abstract. Quantum dots (QDs) are widely used as biomarkers that has both fundamental and applied importance. Since cell membranes are mainly composed of lipids such as phosphatidylcholine (PC) and its derivatives, it is important to investigate the interaction of QDs with PC in monolayers to understand the penetration mechanism. This work is devoted to the study of the interaction of QDs with PC by determining their surface-active properties at various interfaces by dynamic surface tension. The isotherms of the surface tension of 5 μg/L QDs solution or 0.17 mM (0.86 mM) PC solutions, as well as the solutions of the mixtures of QDs and PC: 0.17 mM (0.86 mM) PC and 5 μg/L QDs or 0.17 mM (0.86 mM) PC and 15 μg/L QDs were obtained. The mixed QDs/PC monolayers (at low content of QDs equal to 1:100) were characterized by the formation of a stable domain structures. An adsorption of PC at QDs allows to vary the degree of surface modification by changing the amount of the lipid. Such nanoparticles have dimensions not very different from the sizes of the initial QDs, due to the small size of lipids and are well suited for incorporation into biomembrane models.

1. Introduction

Currently, quantum dots (QDs) are widely used as biomarkers that has both fundamental and applied importance [1–5]. This is a rapidly growing field at the interface of materials and life sciences in particular, as nanomaterials with special properties for nanotechnology, biotechnology, bioelectronic, biophotonic, etc. [1–5]. The synthesis and properties of various QDs (with and without covering surfactant layer) have been described earlier [2, 3]. However, the mechanism of QDs penetration through biological membranes has not yet been studied in details. Since cell membranes are mainly composed of lipids such as phosphatidylcholine (PC) and its derivatives [6–8], it is important to understand the interaction of quantum dots with such individual lipids as well as with lipid monolayers and other models of biological membranes [6–8] to understand the mechanism of penetration. This fundamental model based on some geometrical assumption for a lipid monolayer deformation and suggested the transition between QD–lipid liposomes and micelles depending on the QD parameters, mainly, charge [9] and size [10, 11].

In addition, a preparation of the hybrid functional materials based on membrane components and models is of considerable interest. One approach is to incorporate nanoparticles into a lipid layers at the interfaces.
This work is devoted to the study of the interaction of quantum dots with one of the most common lipids – phosphatidylcholine by determining the surface-active properties of the resulting systems at the interfaces.

2. Materials and methods

2.1. Materials
To study the interaction and surface modification the following materials were used:
1) phosphatidylcholine (1,2-Diacyl-sn-glycero-3-phosphocholine or L-α-Lecithin) isolated from egg yolk (Sigma-Aldrich), Type XVI-E, ≥99% (TLC), lyophilized powder (cat. number P3556-100MG) was dissolved in chloroform (final PC concentration in solution was 1.04 mM);
2) CdSe/ZnS alloyed quantum dots (Sigma-Aldrich, Fluorescent Nanocrystals, Trilite™), fluorescence λem 575 nm, 6 nm diameter, concentration 1 mg/mL in toluene (cat. number 753785).
All solvents were used without further purification. The water was cleaned with a Milli-Q filtration unit of “Millipore Corp.” and distilled (resistance is 18 MOm, surface tension 72.7 mN/m at 20°C).

2.2. Methods
The surface-active properties of quantum dot nanosystems with phosphatidylcholine were studied by measuring the dynamic surface tension (DST) by the maximum bubble pressure method on a BPA-1P instrument from Synterface, Germany. This method allows one to obtain not only the equilibrium values of the surface tension, but also the DST values at very short “bubble lifetimes” (0.01–10 min.) at the liquid/air interface. The size of the particles with a modified surface was determined by dynamic light scattering on a highly-sensitive device “Zetasizer Nano ZS” (“Malvern Instruments”, UK).

The QD monolayers were prepared by spreading of precise amount (between 10 and 20 μl) of QD solutions onto distilled water (20°C). The PC monolayers were prepared by spreading of 70 μl of PC solution in chloroform (1.04 mM). The PC-QD solutions were prepared by mixing of these PC and QD solutions in the particular ratios (v/v) in chloroform and the mixed monolayers - by spreading from 50 to 100 μl of PC-QD solutions (90:10 or 99:1). The surface pressure (π) - molecular area (A) and surface potential (∆V) – molecular area (A) isotherms were recorded on a rectangular trough (dimensions 11.0 cm x 38.0 cm x 0.8 cm) made from polytetrafluoroethylene provided with a 2 cm wide filter paper Wilhelmy balance and vibrating plate condenser (with Pt plate, 1.5 cm diameter, operating at 400 Hz) [8]. The monolayers were compressed by moving the barrier with a constant speed of about 25 cm²/min.

3. Discussion and results
Based on the previously obtained data [6–8], it is known that phosphatidylcholine has strong surface-active properties and does not lead to aggregation of nanoparticles to submicron sizes, unlike a number of other surfactants. To assess the effect of these properties of phosphatidylcholine on the DST of colloidal solutions of the studied systems, PC was taken in two concentrations: at concentrations close to or above CMC of phosphatidylcholine – 0.17 mM and 0.86 mM, respectively. To assess the effect of the concentration of quantum dots, nanoparticles were also taken in two concentrations – 5 and 15 μg/L. This range of the concentrations is the most representative and, at the same time, sufficient to evaluate the interaction of nanoparticles with surfactants.
Colloidal solutions of quantum dots in the concentrations used do not affect the surface tension - the surface tension isotherm is similar to the water isotherm (figure 1 curve). The presence of PC is known to reduce the surface tension (figure 1, curve 2). Moreover, at a concentration of PC about 0.17 mM its effect on the surface tension is noticeable only at large “bubble lifetimes”. The addition of quantum dots at a concentration of about 5 μg/l slightly affects the surface tension of the system (figure 1, curves 3, 4), while an increase in the concentration of QDs about 15 μg/l leads to a rapid and significant change in surface tension (figure 1 curve 5). This indicates the interaction of QDs with PC which at high concentrations of QDs have a significant effect on the surface properties at the interfaces.

The presence of PC at a concentration of 0.86 mM in a colloidal solution significantly reduces the surface tension (figure 2, curve 2). The addition of QDs at a concentration of 5 μg/L does not significantly affect the surface tension of the system (figure 2, curve 3). An increase in the concentration of QDs at 15 μg/L also does not lead to a significant change in the surface tension in comparison with the PC solution (figure 2, curve 4).
It should be canceled that the final state of the QDs / PC systems (at concentrations of “0.17 / 15” and “0.86 / 15”) is the same. In the first case, it is achieved more smoothly, which indicates a shorter response time of the system – even at short “bubble lifetimes”. It is reasonable to assume that this effect is associated with the time of diffusion of particles to the surface of the bubble from the solution and requires further study.

In addition, the structural features of the interaction of phosphatidylcholine with quantum dots at the water/air interface were investigated. The studies were carried out using surface spectroscopy and microscopy methods, which make it possible to evaluate the organization and interaction of the formed supramolecular structures. Phosphatidylcholine immediately after application to the phase boundary a monolayer is formed in a liquid-stretched state, which is a uniform film with small “open” sections of water. After the start of compression of the monolayer, i.e. decreasing the surface area, the PC forms domains, which upon further compression disappear and pass into the liquid-condensed state of the monolayer. An increase in surface pressure leads to the collapse of the monolayer. The behavior of a monolayer of PC with integrated QDs is different from the behavior of a monolayer of an individual PC. The most indicative is a mixed monolayer with a QDs content of 1: 100 to PC by weight. When applying the QDs / PC mixture, an inhomogeneous layer is immediately formed at the phase boundary. Two types of structures are observed in the monolayer, the first of which relates to submicron-sized QDs aggregates; the second type of structures are homogeneous sections. With further compression of the liquid-stretched state monolayer, the PC and QDs sections are separated for an insignificant time. Almost immediately after separation, the QDs aggregates mix with the PC and form a more uniform layer in the liquid-condensed state. Subsequent compression of the mixed monolayer leads to the formation of an almost uniform monolayer having a “granular” structure. In general, mixed QDs / PC monolayers even with such a low content of quantum dots (equal to QDs / PC of 1: 100 to physical mass fraction) are characterized by the formation of a stable domain structure with preservation of the sharp boundaries between aggregates of these substances.

4. Conclusion
The most interesting for further study of the interaction of quantum dots with individual lipids and promising from the point of view of creating hybrid functional materials based on in membrane models are systems with a QDs concentration of at least 15 μg/L and phosphatidylcholine concentrations equal to CMC and higher.

An additional result of this study is the development of the simplest method for modifying the surface of quantum dots - sorption of surface-active substances (or surfactants) on the surface of quantum dots, which combines both classical approaches: replacing the original surfactants used during the synthesis of quantum dots with hydrophilic or other ligands; interaction with amphiphilic polymers - building a shell around the original surfactants. An adsorption of PC at QDs allows to vary the degree of surface modification by changing the amount of the lipid. Such nanoparticles have dimensions not very different from the sizes of the initial QDs, due to the small size of lipids and are well suited for incorporation into biomembrane models.

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