Promote Potential Applications of Nanoparticles as Respiratory Drug Carrier: Insights from Molecular Dynamics Simulations

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ABSTRACT

Nanoparticles (NPs) show great promises in biomedical applications as the respiratory drug carrier system. Once reaching the alveolar region, NPs first interact with the pulmonary surfactant (PS) film, which serves as the first biological barrier and plays an important role in

maintaining the normal respiratory mechanics. Therefore, understanding the interactions between NPs and PS can help promote the NP-based respiratory drug carrier systems. Using coarse-grained molecular dynamics simulations, we studied the effect of rigid spherical NPs with different hydrophobicity and sizes on a dipalmitoylphosphatidylcholine (DPPC) monolayer at the air-water interface. Four different NPs were considered, including hydrophilic and hydrophobic NPs, each with two diameters of 3 nm and 5nm (The sizes are comparable to that of generation 3 and 5 PAMAM dendrimers, which have been widely used for nanoscale drug carrier systems.). Our simulations showed that hydrophilic NPs can readily penetrate into the aqueous phase with little or no disturbance on the DPPC monolayer. However, hydrophobic NPs tend to induce large structural disruptions, thus inhibiting the normal phase transition of the DPPC monolayer upon film compression. Our simulations also showed that this inhibitory effect of hydrophobic NPs can be mitigated through PEGylation. Our results provide useful guidelines for molecular design of NPs as carrier systems for pulmonary drug delivery.

KEYWORDS: nanoparticle, respiratory drug carrier, DPPC monolayer, penetration, molecular dynamics simulation

INTRODUCTION

Nanoparticles (NPs) have received intense interests for their advantages in broad biomedical applications such as drug delivery, bio-imaging, bio-sensing, specific targeting, etc.[1-6] For example, there have been extensive studies on the applications of NPs in respiratory therapeutics.[7-11] The human lungs are easily accessible due to its large surface area, thin epithelial barrier, abundant underlying vasculature, low proteolytic activity, low acidity and thin mucus layer. NPs as drug carriers have been shown to improve drug stability, bioavailability,

targeting, uptake and biological activity. Hence, using inhaled nanoparticles as drug carriers to the respiratory system shows great promises for treating lung diseases.

As mentioned above, NPs have easy access to the respiratory system. Thus, one of the key scientific issues in the applications of NPs as drug carriers in respiratory therapeutics is the balance between the penetration ability across the alveolar barrier and the relative side effects of the NPs.[12-13] In the present work, attention is focused on pulmonary surfactant (PS), which lines the entire alveolar surface and serves as the first biological barrier for particle translocation after inhalation. PS maintains normal respiratory mechanics by reducing alveolar surface tension at the air-liquid interface and thus prevents the lung from collapsing at the end of expiration.[14] PS consists of approximately 90% lipids, with dipalmitoylphosphatidylcholine (DPPC) being the most abundant single lipid component for most mammalian species, and 10% proteins. Both experiments[14-18] and computer simulations[19-21] have confirmed that the phospholipids of PS undergo surface phase transition during the respiratory cycles. During the expiration process (i.e., film compression), phospholipid monolayers undergo surface phase transitions from a "fluid-like" liquid-expanded (LE) phase to a "solid-like" liquid-condensed (LC) phase, which is opposite to the direction of phase transition in the inspiration process (i.e., film expansion). Phospholipid phase transition and separation have been proven to play an important role in regulating the biophysical function of PS film.[14, 17] When the lateral structure of the PS film is disrupted, lipid molecules may detach from the air-water interface, which affects PS homeostasis.[22]

In this work we used coarse-grained (CG) molecular dynamics simulations to probe the effects of NPs of different hydrophobicity and sizes on DPPC monolayers during the compression and expansion process (See Figure 1 for simulation setup). DPPC is the major component of PS

responsible for surface tension reduction.[14, 19-25] Hence, our simulations may provide useful insights into promoting NP-based pulmonary drug delivery.
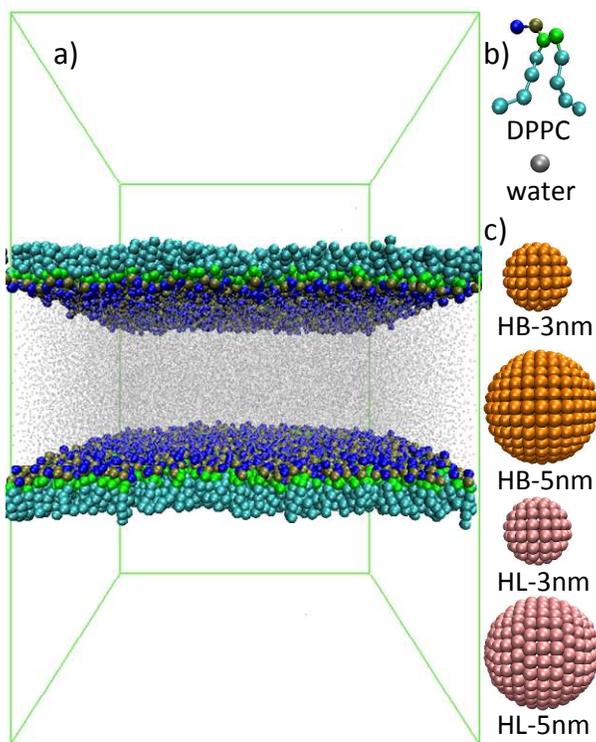
Figure 1. (a) System setup, (b) lipid, water and (c) nanoparticles in the MARTINI model. Color scheme: head-groups of DPPC in blue-tan-green, tail of DPPC in cyan, water in silver, hydrophobic NP (HB) in orange, hydrophilic NP (HL) in pink, simulation box edges in lime. Nanoparticles are named as HB-diameter or HL-diameter.

The rest of this work is organized as follows: Section 2 describes the model and the simulation details. In Section 3, four NPs will be considered: hydrophobic NP (diameter d=3nm, 5nm) and hydrophilic NP (d=3nm, 5nm). The respiratory cycle consists of two main processes: the compression process and the expansion process. Hence, we will study the interactions of NPs with the DPPC monolayer at the air-water interface during both the compression process and the expansion process, respectively. Structural disruptions by NPs and the effects on phase transition dynamics of the DPPC monolayer will be analyzed. Section 4 summarizes our main findings and concludes the paper.

SIMULATION METHODS

Coarse-grained Model.

Compared to atomistic models, coarse-grained (CG) models, which map several atoms into one interaction site and have near-atomic resolution, allow simulations to be performed with a longer time period and a larger length scale.[29-32] Maritni force field is one of the most popular coarse-grained models,[29, 30] which has been widely used to simulate biomolecules, such as lipids, etc. and is open to be used for NPs.

Martini CG model is based on a four-to-one mapping, i.e., on average four heavy atoms are represented by a single interaction center. Only four main types of interaction sites: polar (P), nonpolar (N), apolar (C), and charged (Q). Each particle type has a number of subtypes, which allow for a more accurate representation of the chemical nature of the underlying atomic structure. Within a main type, subtypes are either distinguished by a letter denoting the hydrogen-bonding capabilities (d donor, a acceptor, da both, 0 none), or by a number indicating the degree of polarity (from 1, low polarity, to 5, high polarity). A shifted Lennard-Jones (LJ) 12-6 potential energy function and a shifted Coulombic potential energy function are used to describe the non-bonded interactions. A weak harmonic potential is applied for the bonded interactions. More details can be found in the paper of Marrink et al.[29]

The CG DPPC and water force field parameters were given in details by Marrink et al.[29] and downloaded from http://md.chem.rug.nl/cgmartini/. For the CG spherical NPs, we used only one bead type to stack relative NP, Nda-type for hydrophilic NP and C1-type for hydrophobic NP (Nda and C1 are parameters in Martini force field.[29]). Spherical NP was stacked by beads that were evenly spaced on the surfaces of concentric spheres. Beads within 1nm were constrained by

a spring to confirm rigid NPs as reported by our previous work.[33] In total, four different kinds

of NPs were constructed with two sizes (d=3nm, 5nm) and hydrophobic/hydrophilic properties.

Simulation Details.

As shown in Figure 1, we used the bi-monolayer system, which has been validated by many

researchers,[19-21, 28] to probe the interactions between inhaled NPs and DPPC monolayer. The air

space was represented by vacuum and PS was modeled by a pure DPPC monolayer. Our bi-

monolayer system consisted of 2×1024 DPPC molecules and 82944 CG water molecules. The

normal of these two monolayers was set as the z-axis of the simulation system. After performing

compression and expansion simulations, we extracted two frames from the resulting trajectories:

one (averaged area per lipid Aav=0.64nm^2, LE phase according to Ref. 16, box: 25.58nm $\times$

25.58nm $\times$ 40nm) as the initial conformation of the compression simulations for NP-DPPC

monolayer systems; the other one (Aav=0.47nm^2, LC phase according to Ref. 16, box: 22.01nm

$\times$ 22.01nm $\times$ 40nm) as the initial conformation of the expansion simulations. NPs were placed in

the vacuum of these two frames near the DPPC monolayer separately to mimic the state of NP's

deposition onto the PS film from the air space, followed by the compression and expansion

simulations. For each of these simulations, time scale as long as 2.0μs was performed. As we

know, the time scale of respiration may be many orders of magnitude longer than μs. It is still

rather difficult to perform so longer time scale using CG model. Hence, larger lateral pressures

are often used for simulations in order to reproduce the normal phase transition process of the

interfacial lipid molecules on μs time scale.[19-21] Besides, we systematically study the system of

NP:DPPC=1:1024 (a relative high ratio) and do not focus on the concentration effects of NPs on

the DPPC monolayer at the present work. So, these treatments should be considered for insights

from the simulation results for designing nanoparticles as respiratory drug carriers.

For all simulations, a cutoff of 1.2 nm was used for van der Waals (vdW) interactions, and the Lennard–Jones potential was smoothly shifted to zero between 0.9 nm and 1.2 nm to reduce cutoff noise. For electrostatic interactions, the Coulombic potential, with a cutoff of 1.2 nm, was smoothly shifted to zero from 0 to 1.2 nm. The relative dielectric constant was 15, which was the default value of the force field.[29] Lipids, water and NPs were coupled separately to Berendsen heat baths[34] at T = 310 K, with a coupling constant τ = 1 ps. The monolayer compression was simulated using semiisotropic pressure coupling (Berendsen coupling scheme,[34] coupling constant of 4 ps, compressibility in the lateral direction of 5×10^{-5} bar^{-1} and in the normal direction of zero). Each of the simulations were performed for 2.0 μs with a time step of 20 fs. The neighbor list for non-bonded interactions was updated every 10 steps. Snapshots of the simulation system in this paper were all rendered by VMD.[35] All simulations were performed with the GROMACS simulation package.[36]

Two-dimensional phase map

Order parameter of the lipid's tail can represents the molecular orientation of the tail and can be calculated using the formula

$$S_{z,n} = \left\langle \frac{1}{2}\left(3\cos^2\theta_n - 1\right)\right\rangle$$

where θ_n is the angle between the vector connecting the n-1 and n+1 sites of the tail and the monolayer normal z.

DPPC monolayers at the LE, the LC-LE coexistence, and the LC phases have different order degrees of molecular orientations, which can be characterized by molecular imaging of monolayer thickness in experiments[14, 18, 37] or computing the order parameter in simulations.[21, 28] We have developed a two-dimensional (2D) phase map method to display the detailed phase behaviors of the DPPC monolayer.[28] In 2D phase map, each point represents the Center-of-

Mass (COM) of an interfacial DPPC molecule and is colored according to the order parameter of this molecule, thus mapping the molecular orientations of interfacial monolayers. These 2D phase maps show perfect consistency with monolayer thickness as shown in the Supplemental Materials (Figure S1).

RESULTS AND DISCUSSION

Monolayer penetrations and structural disruptions caused by NPs

To understand the effects of hydrophobicity/hydrophilicity and size of NPs on monolayer penetrations and structural disruptions, we first show the time evolution of the simulation system (Figure 2). As shown in Figure 2, we considered both the compression and expansion processes. We found that the hydrophobic NP tends to cause large structural disruptions of DPPC monolayer and form DPPC-coated NP structure during the compression process, which is consistent with the case of large fullerene nanoparticles reported by Chiu et al.[38] And the structure of smaller hydrophobic NP (d=3nm, HB-3nm) immerges into the water phase deeper than that of hydrophobic NP (d=5nm, HB-5nm). We did not observe that this DPPC-coated NP structure detaches from the DPPC monolayer completely in our compression simulations. This structural disruption disappeared in the next expansion simulations returning to the initial state (data not shown). During the expansion process, hydrophobic NPs just embed themselves in the hydrophobic tails of the DPPC molecules and show little impacts on the DPPC monolayer. In other words, hydrophobic NPs penetrate DPPC monolayer neither in compression process nor in expansion process.

Hydrophilic NP behaves quite differently from the hydrophobic NP. Hydrophilic NP can easily penetrate the DPPC monolayer in the compression process and nearly cross the DPPC monolayer

during the expansion process (Figure 2). Little or no structural disruptions appear. Considering the good monolayer penetration ability and little structural disruptions, our simulations suggests that hydrophilic NPs may serve as a potential carrier for respiratory drug delivery.
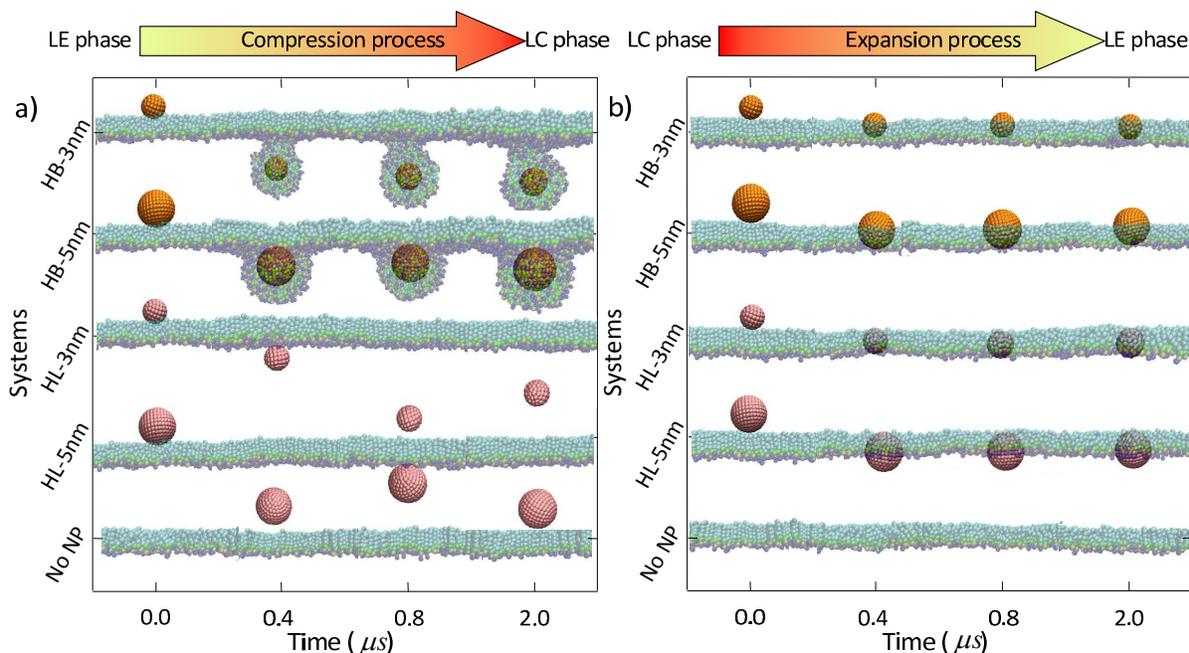
Figure 2. Structural disruptions by NPs and monolayer penetration ability of NPs both in compression (a) and expansion (b) processes. It is found that hydrophobic NP tends to induce large structural disruptions during compression process, while hydrophilic NP is easy to penetrate DPPC monolayer with little or no disruptions to DPPC monolayer. All NPs show little influences on the DPPC monolayer during the expansion process. The color for DPPC and NPs are the same as Figure 1. And water molecules are not shown for clarity.

As discussed above, hydrophobicity and hydrophilicity of NPs show an significant differences in monolayer penetration ability and relative structural disruptions. This is because that it is energy-favorable for hydrophobic NP to interact with the hydrophobic tails of DPPC molecules and for hydrophilic NP to interact with the hydrophilic head-groups of DPPC molecules and water molecules,[29-30,33,38] which modulates the interaction dynamics between NP and the DPPC monolayer. Besides, the disruption structure caused by the smaller hydrophobic NP (HB-3nm) can immerge into the water phase deeper than that structure caused by HB-5nm. The smaller hydrophobic NP corresponds to smaller increase of the in-plane rigidity of the DPPC monolayer

in this same concentration, which explains the size effects of NPs on structural disruptions of the monolayer.[39]

NP-induced phase behavior change of DPPC monolayer

DPPC molecules of different phases correspond to different molecular arrangements, which regulate the role of the DPPC monolayer in reducing the surface tension of the air-water interface and in the gas-exchange process.[16-21] During the compression process, the interfacial molecules of pure DPPC monolayer change from the LE phase to LC-LE coexistence and then to the LC phase, indicated by the increase of the order parameter of the DPPC molecules (Figure S1, Figure 3); the reverse process takes place upon film expansion (Figure S1, Figure 3), which is defined as normal phase transition.[28] Here, the interfacial DPPC molecules refer to the DPPC molecules that remain at the air-water interface and don't include the DPPC molecules from NP-induced disruption structures (Figure S2). For all simulations, NPs show little or no influence on the normal phase transition of interfacial DPPC molecules during the expansion process. And only hydrophobic NPs (B-3nm, B-5nm) tend to inhibit the normal phase transition of interfacial DPPC molecules during the compression process.
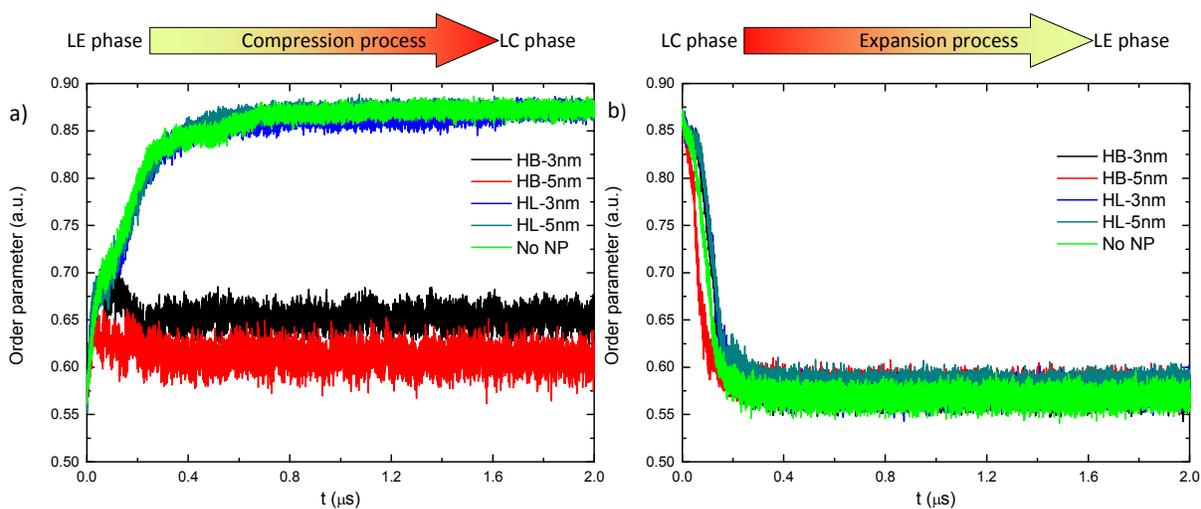
Figure 3. Time evolution of order parameter of DPPC monolayer for all the simulation systems both in the compression (a) and the expansion (b) processes. Hydrophobic NP tends to inhibit the normal phase transition of DPPC monolayer during the compression process, while hydrophilic NP shows little or no effects on this transition of DPPC monolayer.

As shown in Figure 3, both the compression and expansion simulations reach the equilibrium states after approximately 0.4μs. To obtain more information about how NP inhibited the normal phase transition of DPPC monolayer, the two-dimensional (2D) phase maps of the interfacial DPPC molecules and top-view snapshots of the systems (at t=0.8μs) during the compression and the expansion processes are shown in Figure 4. The points of the map represent the interfacial DPPC molecules and the blank regions of the map correspond to the situations that the large structural disruption is induced by NPs or the DPPC monolayer is embedded with NPs (Figure 4, Figure S2). Both the phase maps and snapshots validate that only hydrophobic NPs can inhibit the normal phase transition of interfacial DPPC molecules during the compression process. Besides, we choose an equilibrium state (t=0.8μs) to perform NVT simulations, in order to calculate the surface tension of the DPPC monolayer. The results show both hydrophobic NPs and hydrophilic NPs have little effects on the surface tension of the DPPC monolayer (Figure S3). Our simulation results are consistent with the experimental results reported by Tatur et al.,[40] whose experiments point out that hydrophobic NPs do not influence the π-A isotherm, but do alter the nucleation, growth, and morphology of the condensed domains in the DPPC monolayer.
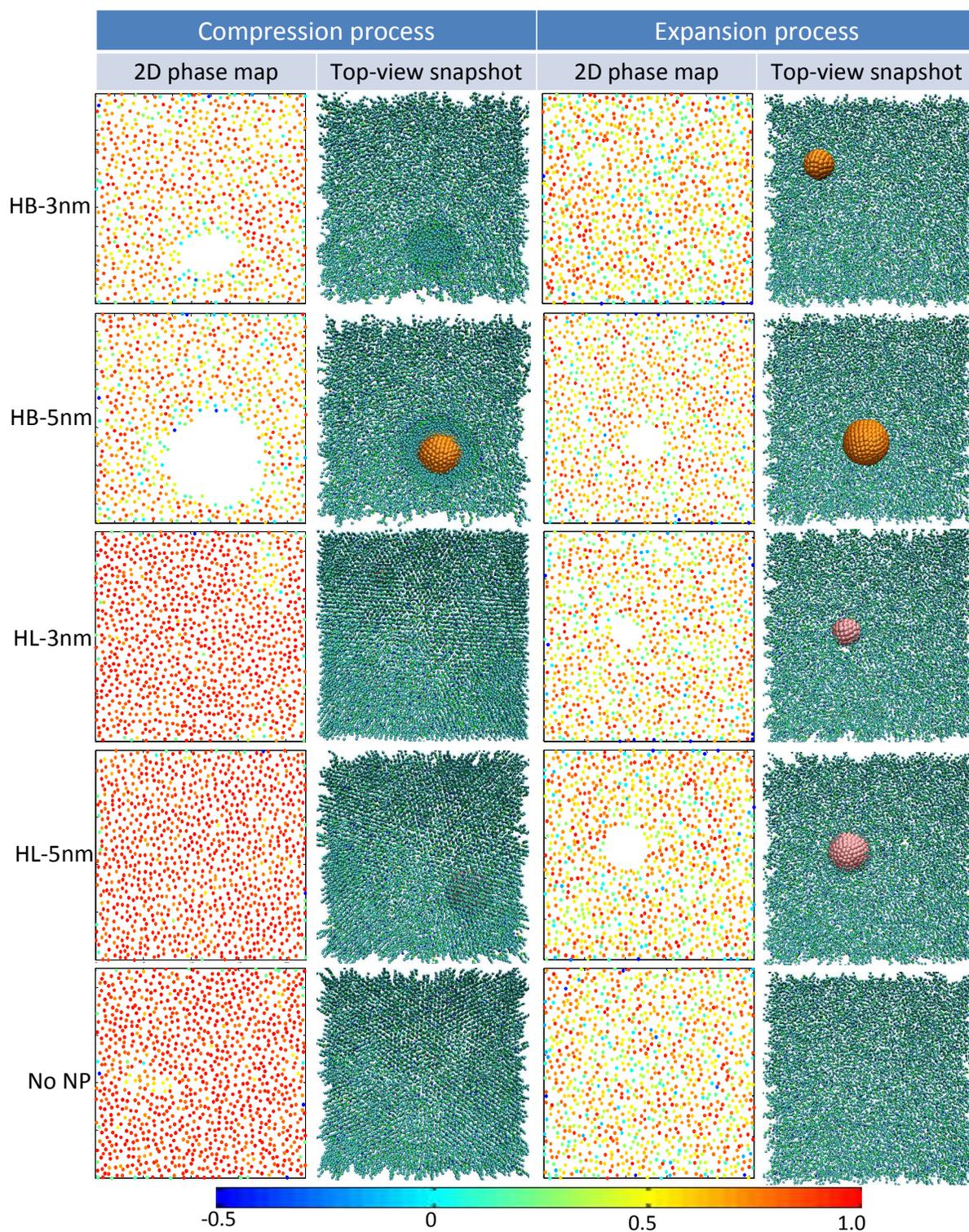
Figure 4. Two-dimensional (2D) phase maps and top-view snapshots for all the simulation systems at t=0.8μs. The left two columns are for compression process and the right two for expansion process. The points in the 2D phase maps represent the interfacial DPPC molecules at the air-water interface and are colored according to the values of order parameter of the relative DPPC molecules. According to the color bar at the bottom, the

redder color represents more order orientation of the interfacial DPPC molecules (more LC phase), and the bluer color represents more disorder orientation of the interfacial DPPC molecules (more LE phase). The blank regions of the map correspond to the situations that the large structural disruption is induced by NPs and the DPPC monolayer is embedded with NPs , which are further described in Figure S2. The color for the snapshots are the same as Figure 1.

On one hand, large structural disruptions of DPPC monolayer can make some DPPC molecules detach from the air-water interface, which may further affect PS homeostasis.[22] On the other hand, the normal phase transition of interfacial DPPC molecules plays an important role in regulating the mechanics of air-water interface and the inhibition of this normal phase transition may disturb the regulation of the mechanics and further destabilize the interface structure of alveolus.[16-21] In our simulations, we found that large structural disruptions of DPPC monolayer are always accompanied by normal phase transition inhibition of interfacial DPPC molecules. And only hydrophobic NPs caused large structural disruptions and inhibited the normal phase transition of the interfacial DPPC molecules. Hydrophilic NPs show excellent penetration ability and little structural disruptions to DPPC monolayer. Therefore, hydrophilic NPs are most suitable for respiratory drug delivery carriers. Along this line, surface modification of hydrophobic NPs with hydrophilic moieties, such as PEGylation, may help improve particle penetration across the DPPC monolayer,[41] which will be studied in the next section.
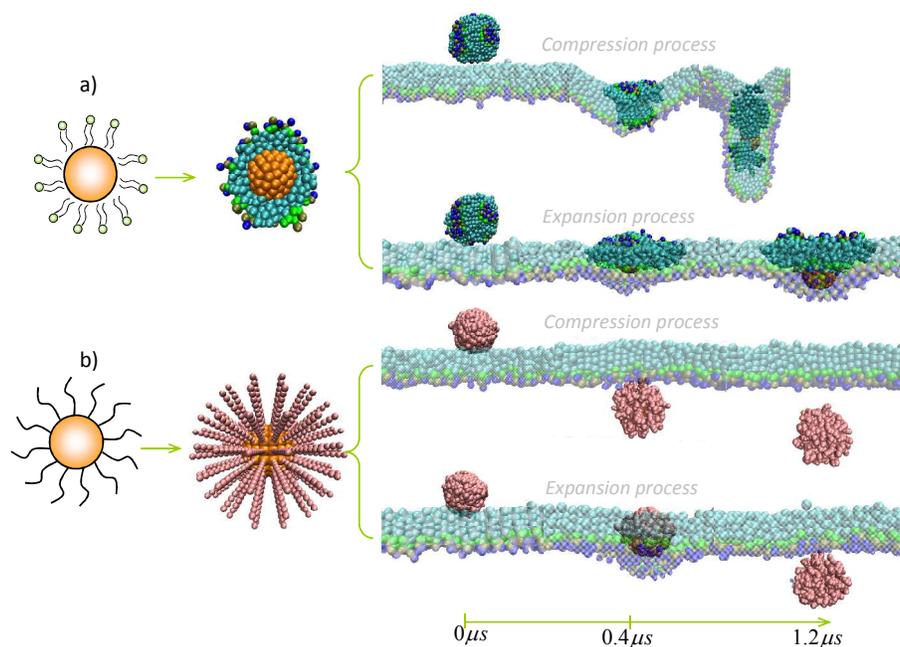
Figure 5. The interactions between DPPC-coated (a) or PEGylated (b) hydrophobic NP and the DPPC monolayer during the compression and expansion processes. PEGylated hydrophobic NP can easily penetrate the DPPC monolayer both in compression and expansion process. However, DPPC-coated hydrophobic NP not only cannot penetrate the DPPC monolayer, but also induce collapse of the DPPC monolayer. Water molecules are not shown for clarity.

Effects of hydrophilic modifications on interaction between hydrophobic NPs and the DPPC monolayer

Our simulation results showed that hydrophobic NPs tend to induce large structural disruption and inhibit the normal phase transition of the DPPC monolayer during the compression process, which suggests a potential side effect when using hydrophobic NPs for pulmonary delivery. Hence, we perform additional simulations to study the translocation ability of the hydrophobic NPs with hydrophilic surface modifications. We studied two widely used surface modification methods: non-covalent coating with DPPC molecules and covalent coating with PEG.[41]

For the non-covalent method, we firstly perform self-assembly simulation of a mixture of NP, DPPC and water molecules (Here we use DPPC as a surfactant to obtain NP-surfactant complex because this will not change the composition of the DPPC monolayer with the interactions of

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NP-surfactant complex). Due to hydrophobic interactions, DPPC molecules can spontaneously

adsorb onto the NP to form the complex with the hydrophilic head-group of DPPC exposing on

the surface (Figure 5a). After a pre-equilibrium simulation of the complex in the vacuum, the

complex is placed near the DPPC monolayer for compression and expansion simulation to model

the interactions between the inhaled complex and PS during respiratory process. The complex

interacts with the DPPC monolayer to firstly form a local DPPC bilayer with NP embedded in it,

and then the DPPC monolayer collapses quickly during the further compression process. The

collapsed conformation consists of a "fold" structure with NP and an aggregate of DPPC

molecules embedded in it (Figure 5).[20] And the source of the aggregate absolutely comes from

the NP-DPPC complex. The above results point to a conclusion that the DPPC-coated NP

obtained using the non-covalent method cannot effectively promote the translocation ability of

the hydrophobic NP and reduce its potential side effects.
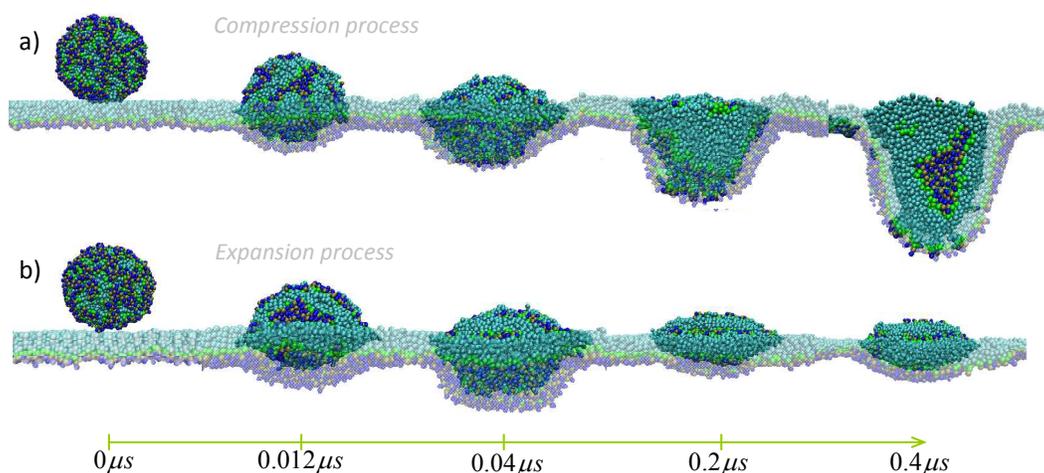
Figure 6. The snapshots for the interaction of a DPPC liposome (d=12nm) with the DPPC monolayer during the compression (a) and expansion (b) processes. The morphology of the liposome experiences severe changes during its interactions with the DPPC monolayer and is trapped by the DPPC monolayer. The liposome causes a large structural disruption of the DPPC monolayer during the compression process and promotes pore formation of the DPPC monolayer during the expansion process (Figure S4). Water molecules are not shown for clarity.

The inefficacy of DPPC-coated NP in penetrating the DPPC monolayer may be ascribed to the free amphiphilic molecules (DPPC) on its surface, which can easily flip-flop to form local bilayer structure and further promote the formation of large structural disruptions. In order to validate this hypothesis, we further probe the interactions between a DPPC liposome (i.e., closed DPPC bilayers self-assembled via non-covalent interactions) and a DPPC monolayer during the compression and expansion processes (Figure 6). Results show DPPC molecules in the liposome can easily flip-flop to keep their hydrophobic tails facing the gas phase (also see Figure S5), and further induce large structural disruptions of the DPPC monolayer during the compression process and promote pore formation of the DPPC monolayer during the expansion process. These results are consistence with the simulations proposed by Baoukina et al.[42] for the interactions between the lipid bilayer aggregate in the vacuum and the lipid monolayer. Hence, the drug carrier systems using amphiphilic molecules (e.g., DPPC) as building block via non-covalent interactions may not be a good choice for respiratory therapy.

For the covalent method, we choose the commonly used PEGylation. Poly-(ethylene glycol) (PEG) has broad applications in biomedical formulations because of its favorable properties, such as low toxicity, biocompatibility, and ease of excretion.[43] In order to compare with the DPPC-coated NP, we used PEG9, which has a similar length to the DPPC molecule. The force field for the PEG has recently been developed and is compatible with the Martini force field used for all our simulations.[44, 45] Using the similar simulation procedure as the DPPC-coated NP, we found that PEGylated NP can easily penetrate into the aqueous phase without provoking large structural disruption both in the compression and expansion processes (Figure 5b). In other words, PEGylated modification of hydrophobic NP may provide an effective way to promote the applicability of hydrophobic NPs as drug carriers in the respiratory therapy.
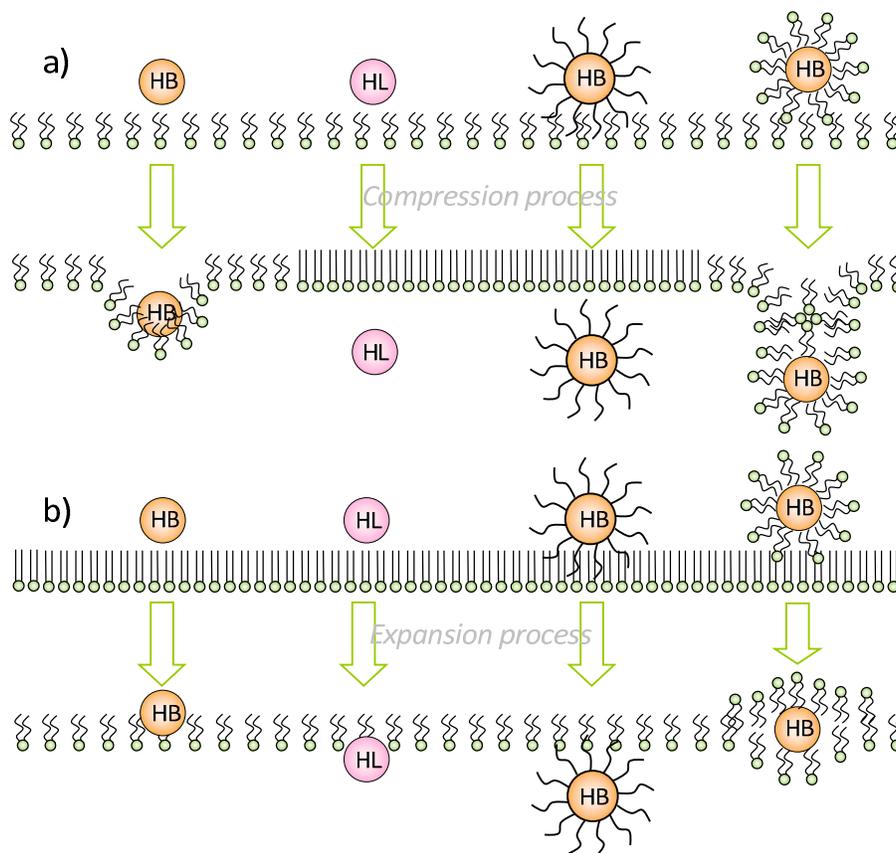
Scheme 1. Summary of the interactions between NPs (hydrophobic NP, hydrophilic NP, PEGylated hydrophobic NP, DPPC-coated hydrophobic NP) and the DPPC monolayer.

CONCLUSION

Pulmonary delivery using NPs as a drug carrier shows significant promises in respiratory therapy. It is critical to study the effects of NP on the pulmonary surfactant in order to promote its safer biomedical applications. Hence, we probe the interactions between NPs and the DPPC monolayer (as a simple model pulmonary surfactant) on molecular level using coarse-grained molecular dynamics simulations. As shown in Scheme 1, hydrophilic NP shows obvious advantages in translocation into the aqueous phase with little influence on the DPPC monolayer. However, hydrophobic NP tends to disrupt the DPPC monolayer and inhibit the normal phase transition during the compression process. Considering the hydrophobic NP's potential side

effect, we try two hydrophilic treatments to reduce the side effect. Results show that the inhaled DPPC-coated NP can easily absorb onto the DPPC monolayer, form local DPPC bilayer with NP embedded in it, and further induce collapse of the DPPC monolayer during the compression process. However, PEGylated NP can penetrate into the aqueous phase with little influence on the structure and properties of the DPPC monolayer. Our results may glean insights for designing proper drug carrier systems for respiratory therapy and help evaluate NP's side effects on pulmonary surfactant.

Conflict of Interest: The authors declare no competing financial interest.

Supporting Information Available: Additional figures. This material is available free of charge via the Internet at http://pubs.rsc.org.

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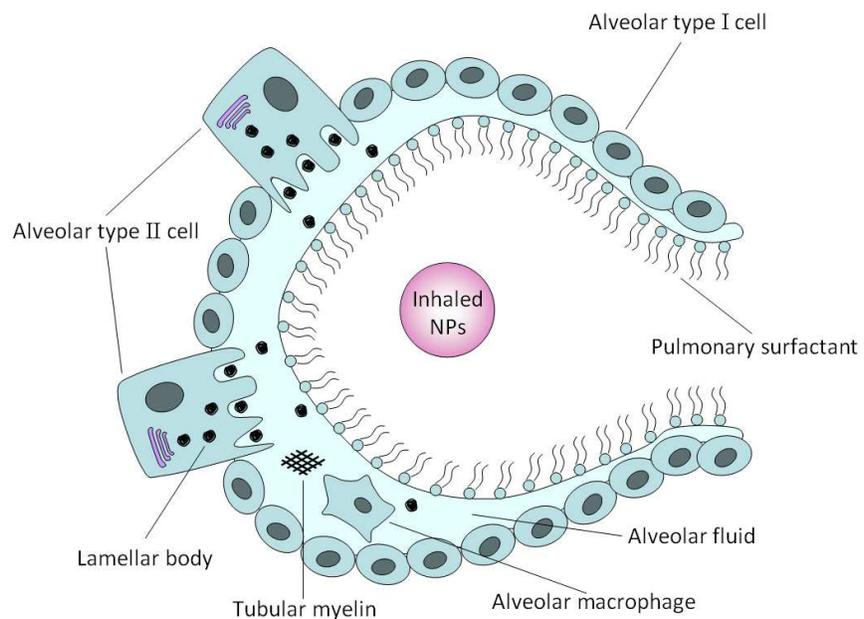
Understanding the interactions between nanoparticles and pulmonary surfactant can help promote the nanoparticle-based respiratory drug carrier systems.