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Q1 Mathematical model for drug molecules encapsulated in lipid nanotube

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HIGHLIGHTS

- Interaction energy between three shapes of DOX and lipid nanotube is studied.
- Lennard-Jones potential and continuous approximation are utilized to determine such energy.
- We find that a thin cylindrical DOX gives a maximum suction energy among other cases.
- The main results are mathematical expressions.

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ABSTRACT

Lipid nanotube is considered as a nanocontainer for drug and gene delivery. It is important to understand a basic idea of the encapsulation process. In this paper, we use the Lennard-Jones potential function and the continuous approximation to explain the energy behaviour of three hollow shapes of Doxorubicin (DOX) clusters that are a sphere, a cylinder, and an ellipsoid interacting with the lipid nanotube. On assuming that the surface areas of the three structures are equal, we can find the minimum size of the lipid nanotube that encapsulates DOX inside by determining the suction energy. Moreover, we find that a long cylindrical drug provides the largest suction energy among other structures studied here due to the perfect fit between the cylindrical drug and the cylindrical tube. This investigation is the first step to develop the design of nanocapsule for medical application.

1. Introduction

One of the health problems occurring around the world is cancer, and there are a number of people who suffer and die from this disease [1,2]. Although cancer is currently cured by chemotherapy, the normal cells of human body are damaged by this treatment. With the emerging of technological innovation, drug delivery application has expensively been developed [3], where nanocarriers can carry drug to targeted cells. There are some advantages of nanocarriers such as to reduce the harmful and to decrease the toxic on healthy cells. In this paper, we employ the lipid nanotube as a carrier to deliver Doxorubicin to the targeted cells.

Doxorubicin (DOX) is used as a chemotherapy drug. Due to the fact that treating by DOX causes damage to human tissue, many researchers attempt to transport DOX to the targeted cells without the side effect. Meng et al. [4] employ mesoporous silica nanoparticle as a drug carrier to deliver DOX and Pgp siRNA to a drug-resistant cancer cell line (KB-V1 cells).

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Lu et al. [5] use the multi-walled carbon nanotubes (MWCNTs) and iron oxide magnetic nanoparticles to transport DOX to the cancer cells. Their results indicate that DOX encapsulated in MWCNTs can destroy cancer cells more efficient than free DOX. Moreover, Meng et al. [6] utilize single-walled carbon nanotubes (SWNTs) as a drug vehicle to carry DOX to cancer tissue, and they find the highly efficient DOX loading onto SWNTs.

Zhou et al. [7] describe that the lipid nanotube is an open-ended and hollow cylinder consisting of rolled-up bilayer membrane due to the self-assembling of lipid molecules in lipid media. The lipid nanotube has several template-synthesized such as nanotubes [8], concentric tubular hybrids [9], complex helical architectures [10] as well as one-dimensional arrays of quantum dots where its diameter and length can be controlled. Besides, Shimizu [8] finds that dimensions including inner and outer diameters of the lipid nanotube can be controlled by the self-assembly of amphiphilic lipid monomers. Consequently, it may be used as a nanocarrier for the encapsulation of nanomaterials and biomolecules.

Another important topic on the drug delivery system is the drug release. Leo et al. [11] utilize the dynamic dialysis technique to evaluate the drug unload for the doxorubicin (DXR)-gelatin nanoparticle conjugates. Further, Liu et al. [12] study the system of DOX contained inside single-walled carbon nanotube with the poly(ethylene glycol) (PEG) decoration. They report that the complex nanocontainer is sensitive to the acidic solution and the drug can release rapidly. Dali et al. [13] synthesis the supramolecular amphiphilic block copolymers by the formation of multiple hydrogen interactions between adenine-terminated poly(ε-caprolactone) (PCL-A) and uracil-terminated poly(ethylene glycol) (PEG-U) so that the constructed copolymers can self-assemble into the water-stable micelles. These micelles can unload DOX at the pH of 5.0 that is faster than physiological pH. Here as a first step to study the drug delivery system, we focus on the uptake behaviour of the lipid nanotube containing the DOX molecule.

In terms of mathematical model, Baowan et al. [14] study the toxicity of a C_{60} fullerene by investigating the penetration of C_{60} through the lipid bilayer. They use the Lennard-Jones potential function and the continuous approximation to calculate the total energy of the system. In addition, Baowan et al. [15] compute the interaction energy between either gold or silver spherical nanoparticle and the lipid nanotube. Cox et al. [16,17] study the energy behaviour of the spherical and spheroidal fullerenes interacting with the carbon nanotube, and their results demonstrate that those nanoparticles can be encapsulated in the tube.

Here, we employ the same concept proposed by Baowan et al. [14] to investigate the encapsulation of three hollow shapes of the DOX which are a sphere, a cylinder and an ellipsoid entering the lipid nanotube. Further, we focus on the interaction energy between the nanotube and those three shapes with the hollow structure, and determine the optimal radius of the lipid nanotube encapsulating the different shapes of the DOX drug molecule. We comment that due to the complicated chemical structure of the DOX, more sophisticated mathematical derivation is required.

In the following section, the Lennard-Jones potential function and the continuous approximation used to calculate the interaction energy between the DOX and the lipid nanotube are described. The mathematical derivation and the interaction energy of the DOX and the lipid nanotube are presented in Section 3. Finally, the numerical results are reported and the findings are summarized.

2. Interaction energy and continuous approximation

The Lennard-Jones potential function is widely used to approximate the interaction energy between two non-bonded atoms. The Lennard-Jones function is of the form

$$\Phi = -\frac{A}{\rho^6} + \frac{B}{\rho^{12}}, \tag{1}$$

where ρ represents the distance between two typical non-bonded atoms, A and B denote attractive and repulsive Lennard-Jones constants, respectively. Since $A = 4\epsilon\sigma^6$ and $B = 4\epsilon\sigma^{12}$ where ϵ is the well depth and σ is the van der Waals diameter, then (1) can be rewritten as

$$\Phi = 4\epsilon\left[-\left(\frac{\sigma}{\rho}\right)^6 + \left(\frac{\sigma}{\rho}\right)^{12}\right].$$

The interaction energy between two non-bonded molecules may be determined by using the continuous approximation where atoms at discrete locations on the molecule are assumed to be uniformly distributed over the surface or the volume of the molecule. Therefore, the total interaction energy can be written as

$$E = \eta_1\eta_2\int_{\Sigma_1}\int_{\Sigma_2}\left(-\frac{A}{\rho^6} + \frac{B}{\rho^{12}}\right)\mathrm{d}\Sigma_2\mathrm{d}\Sigma_1,$$

where η_1 and η_2 denote the mean surface or the mean volume densities of atoms on each molecule and ρ is the distance between two typical surface or two typical volume elements $\mathrm{d}\Sigma_1$ and $\mathrm{d}\Sigma_2$. Moreover, we define the integral I_n as

$$I_n = \int_{\Sigma_1}\int_{\Sigma_2}\rho^{-2n}\mathrm{d}\Sigma_2\mathrm{d}\Sigma_1, \quad n = 3, 6,$$

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