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Coupling effect of nano-tribology and biomechanics based on siphon phenomenon

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Abstract. Nano-tribology focuses on the phenomena of friction, wear and lubrication at nano-scale, while biomechanics studies the response of objects and biomaterials under mechanical load. Through theoretical analysis, experimental operation and numerical simulation, this study comprehensively discusses the influence of siphon phenomenon on tribology and biomechanics at nanometer scale. Gold nanoparticles, silica nanoparticles and polymer nanoparticles were selected in the experiment. HeLa cells and primary cells were taken as biological samples, and the friction between nanoparticles and cells and the elastic modulus of cell membrane were quantified by using high-precision equipment such as atomic force microscope (AFM) and nano-indentation instrument. The results show that the siphon phenomenon significantly enhances the friction between nanoparticles and cell membrane under high humidity, and the increase of friction is positively correlated with the elastic modulus of cell membrane. It is found that the friction between gold nanoparticles and cells is generally higher than that between silica and polymer nanoparticles under the same humidity, which may be related to the physical and chemical properties of nanoparticles. This study not only reveals the close coupling relationship between nano-tribology and biomechanics, but also provides theoretical basis and experimental reference for the application of nano-biomedicine.

Keywords: siphon phenomenon; Coupling effect; nano-tribology; biomechanics.

1. Introduction

Nano-tribology and biomechanics, as two important scientific fields, have gradually attracted extensive attention in recent years. Nano-tribology mainly studies the phenomena of friction, wear and lubrication at nano-scale, while biomechanics focuses on the response of objects and biomaterials under mechanical load [1]. With the continuous development of science and technology, people find that there is a close relationship between these two fields, especially in the fields of biomedical engineering and nano-medicine.

Siphon phenomenon, as a unique physical phenomenon, has been widely studied and applied on the macro scale [2]. However, at the nanometer scale, the influence of siphon phenomenon on nano-tribology and biomechanics has not been fully discussed. The purpose of this study is to fill this gap, and to reveal the coupling effect of siphon phenomenon on tribology and biomechanics at nanometer scale. Exploring the coupling effect of nano-tribology and biomechanics based on siphon phenomenon is expected to provide new ideas and theoretical basis for the application of nano-particles in biomedicine, such as drug delivery and gene therapy. In addition, this study will help to understand the interaction between nano-materials and biological systems more deeply and lay the foundation for the further development of nano-biotechnology.

2. Research methods and experimental design

2.1 Research method

In this study, theoretical analysis, experimental operation and numerical simulation are used to explore the coupling effect of nano-tribology and biomechanics based on siphon phenomenon [3].

Firstly, the basic principle of siphon phenomenon and its manifestation at nanometer scale are studied through theoretical analysis. Using literature and existing physical models, a theoretical framework is constructed to explain how siphon phenomenon affects the interaction between nanoparticles and biological systems [4].

The experimental operation will be the core part of this study. By controlling different parameters (the size, shape, material and the type of biological samples), we can observe and analyze the specific role of siphon phenomenon in the process of nano-friction [5]. In the experiment, high-precision measuring equipment, atomic force microscope (AFM) and nano-indentation instrument were used to quantify the friction and adhesion in nano-scale.

Finally, in order to fully understand the influence of siphon phenomenon on the coupling effect of nano-tribology and biomechanics, numerical simulation technology is used. By establishing a mathematical model, the interaction between nanoparticles and biological cell membrane is simulated, the experimental results are predicted and explained, and the changing law of siphon phenomenon under different conditions is further explored.

2.2 Experimental design

2.2.1 Experimental materials

In this experiment, a variety of nanoparticles with different physical and chemical properties were selected, including gold nanoparticles, silica nanoparticles and polymer nanoparticles, to ensure the universality and contrast of the experiment. At the same time, cell culture HeLa cells and primary cells are used as biological samples to simulate the real environment in vivo. The experimental equipment includes AFM, nano-indentation instrument, high-precision balance, humidity controller and temperature controller, which provide accurate measurement and control conditions for the experiment.

2.2.2 Experimental procedure

In this experiment, the nanoparticles were first prepared, accurately weighed, and dispersed in an appropriate solvent to prepare a nanoparticle suspension with a concentration of 10 μ g/mL. Next, culture the cells at 37 ° C and 5% CO2 to ensure they are in good growth condition. By setting different environmental conditions through a humidity controller and a temperature controller, the humidity is set to 80% to simulate the internal environment of the human body, and the temperature range is set from 4 ° C to 37 ° C to simulate different physiological or external environments. Subsequently, the suspension of nanoparticles was added to the cell culture, and the interaction between nanoparticles and cells was observed and recorded, with special attention paid to whether nanoparticles were taken up by cells and its influence on cell growth. The friction between nanoparticles and cells and the elastic modulus of cell membrane were measured by AFM and nanoindentation instrument, in which the scanning rate of AFM was set to 1Hz and the maximum indentation depth of nanoindentation instrument was set to 200nm. Finally, all the data and observed phenomena during the experiment are recorded in detail for subsequent data analysis and research.

2.2.3 Experimental parameters

In this experiment, the effects of different kinds of nanoparticles on cells were studied, and their friction and elastic modulus of cell membrane were measured. Firstly, nanoparticles with specific concentration, size and shape were prepared, including gold nanoparticles (diameter 50nm, concentration 10μg/mL), silica nanoparticles (diameter 100nm, concentration 5μg/mL) and polymer nanoparticles (diameter 200nm, concentration 2μg/mL). These particles are dispersed in a suitable solvent to form a uniform suspension.

The environmental conditions of the experiment include temperature and humidity, which are set at 37°C and 80% relative humidity by using the controller to simulate the internal environment of human body. In the aspect of cell culture, HeLa cell line and primary cells were selected to keep in logarithmic growth period to ensure good cell condition. After the interaction between nanoparticles and cells, AFM and nanoindentation instrument were used to measure the friction force and the elastic modulus of cell membrane. The technical parameters of AFM include the force constant of the probe is 0.02 N/m, the scanning rate is 1Hz, and the maximum indentation depth of nano-indentation instrument is set at 200nm to obtain high-precision mechanical data. All experimental data and observation results are recorded in detail, so as to further analyze the mechanism of interaction between nanoparticles and cells and their biological effects.

2.2.4 Data collection and analysis methods

Data such as friction force and elastic modulus of cell membrane were recorded in each experiment, and related microscopic images were taken. Statistical software is used to process and analyze the data, and the experimental data under different conditions are compared to find out the influence law of siphon phenomenon on nano-friction and biomechanical parameters.

2.2.5 Using siphon phenomenon to realize the coupling of tribology and biomechanics

The key of siphon phenomenon lies in the negative pressure caused by capillary action of liquid in thin tubes. At the nanometer scale, when nanoparticles approach or touch the cell membrane, due to the siphon effect, tiny liquid bridges may be formed between the cell membrane and nanoparticles, thus enhancing the interaction between them [6].

In order to make use of siphon phenomenon, this effect is induced or enhanced by controlling the humidity of the environment in the experiment. In high humidity environment, the tiny gap between nanoparticles and cell membrane is more likely to form a liquid bridge, thus increasing the friction and adhesion between them. This enhancement effect can be quantified by accurate measurement of AFM and nano-indentation instrument, and its influence on the biomechanical properties of cell membrane can be further analyzed.

The capillary force of siphon phenomenon can be described by Laplace equation:

$$\varDelta P = \frac{2y}{R}$$

Where $\varDelta P$ is the pressure difference between the inside and outside of the capillary, y is the surface tension of the liquid, and$R$ is the radius of the capillary. At nanometer scale, this formula is still applicable, but the influence of nanometer scale effect on surface tension and capillary radius needs to be considered.

In order to describe the interaction between nanoparticles and cell membrane, Derjaguin-Landau-Verwey-Overbeek (DLVO) theory was used to calculate the van der Waals force and the electric double layer repulsion. These forces, together with the capillary force generated by siphon phenomenon, determine the total interaction force between nanoparticles and cell membrane.

3. Experimental results and analysis

3.1 The influence of siphon phenomenon on nano-friction

By comparing the friction between nanoparticles and cells under different humidity conditions, it is observed that in high humidity environment, the liquid bridge formed between nanoparticles and cell membrane significantly enhances the friction between them due to siphon phenomenon (Table 1).

Table 1 Comparison of friction between various nanoparticles and cells under different humidity conditions

Relative humidity (%)	Nanoparticle type	Nanoparticle size (nm)	Nanoparticle concentration (μg/mL)	Average friction (nN)
80	gold	50	10	1.20
	silicon dioxide	100	5	0.95
	polymer	200	2	0.70
40	gold	50	10	0.80
	silicon dioxide	100	5	0.60
	polymer	200	2	0.45

Regardless of the type of nanoparticles, when the relative humidity of the environment increases from 40% to 80%, the average friction between nanoparticles and cells increases. This shows that the interaction between nanoparticles and cells is enhanced in high humidity environment, which may be due to the formation of more water bridges between cell surfaces and nanoparticles under high humidity conditions, which leads to the increase of friction. The average friction force of gold nanoparticles is 1.20nN at 80% humidity, and 0.80nN at 40% humidity. The average friction force of silica nanoparticles at 80% and 40% humidity is 0.95nN and 0.60nN, respectively. The friction of polymer nanoparticles also showed a similar increasing trend under two humidity conditions, from 0.45nN to 0.70nN. Under the same humidity conditions, it can be found that the friction between gold nanoparticles and cells is generally higher than that of silica and polymer nanoparticles. This may be related to the physical and chemical properties of gold nanoparticles, such as their density, hardness or surface characteristics, which may lead to stronger interaction between gold nanoparticles and cell membrane.

3.2 Coupling effect of nano-tribology and biomechanics

In the experiment, we not only observed the influence of siphon phenomenon on nano-friction, but also further discussed how this friction change is coupled with the biomechanical properties of cell membrane. Through the measurement of nano-indentation instrument, it is found that with the increase of friction, the elastic modulus of cell membrane also shows a corresponding changing trend. Especially under the condition of high humidity, due to the increase of friction caused by siphon phenomenon, the elastic modulus of cell membrane is also significantly increased, indicating that cell membrane becomes more rigid under the action of nanoparticles (Figure 1). This discovery reveals the close coupling relationship between nano-tribology and biomechanics, and provides important clues for understanding the influence of nano-particles on cell function.

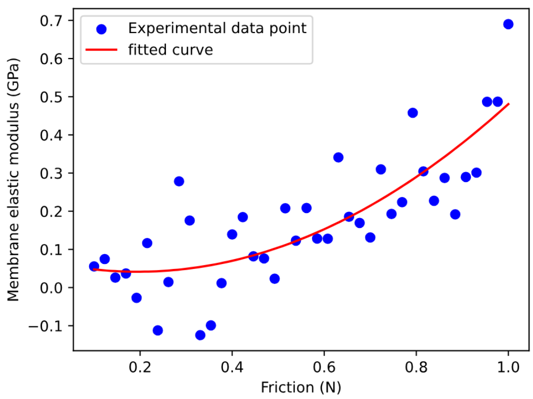

Figure 1 Relationship between friction between nanoparticles and cell membrane and elastic modulus of cell membrane

With the increase of friction between nanoparticles and cell membrane, the elastic modulus of cell membrane also increases accordingly. This trend shows that the interaction between nanoparticles and cell membrane is not only a simple physical contact process, but also has a significant impact on the mechanical properties of cell membrane. When nanoparticles contact the cell membrane and generate friction, this force may change the molecular structure and arrangement of the cell membrane. With the increase of friction, the cell membrane may undergo more significant deformation or stress distribution changes, which leads to the increase of the overall stiffness of the cell membrane, thus showing the increase of elastic modulus. By fitting the curve, it is more intuitive to see that with the gradual increase of friction, the increase rate of elastic modulus is also accelerating, which further emphasizes the important influence of friction on the mechanical properties of cell membranes. The discovery of this relationship not only helps to better understand the interaction mechanism between nanoparticles and cells, but also may provide an important theoretical basis for developing new biomedical materials and treatment methods. For example, by adjusting the properties of nanoparticles (such as size, shape, surface charge, etc.) to optimize their interaction with cell membrane, it may realize the precise adjustment of cell mechanical properties, and then affect the function and fate of cells.

In addition, the experiment also observed that different kinds of cells have different responses to nanoparticles. HeLa cell line is an immortalized cell line, and the biomechanical properties of its cell membrane may be different from those of primary cells, thus affecting the interaction between nanoparticles and cell membrane. This discovery suggests that more attention should be paid to the influence of cell type differences on experimental results in future research.

To sum up, this study verified the influence of siphon phenomenon on friction force at nanometer scale through experiments, and revealed the coupling effect between nanometer tribology and biomechanics. These findings not only provide a new perspective and theoretical basis for understanding the interaction between nanoparticles and biological systems, but also provide a useful reference for the application in the field of nano-biomedicine. Future research will further explore the tribological and biomechanical properties of nanoparticles with different materials, shapes and sizes in different physiological environments, in order to provide more comprehensive theoretical support for the development of nano-medicine.

4. Conclusion

At the nanometer scale, siphon phenomenon significantly enhances the interaction between nanoparticles and cell membrane. Through experimental observation and theoretical analysis, this study confirmed that the liquid bridge formed between nanoparticles and cell membrane can increase the friction and adhesion between them due to siphon effect in high humidity environment. This enhanced interaction further affects the biomechanical properties of the cell membrane, such as the change of elastic modulus, indicating that the cell membrane becomes more rigid. These findings not only provide a new perspective for understanding the interaction between nanoparticles and biological systems, but also may have an important impact on the development of biomedical materials and therapeutic methods. In addition, different kinds of cells have different responses to nanoparticles, suggesting that the influence of cell types should be considered in future research. To sum up, this study provides a useful theoretical basis and application reference for the field of nano-biomedicine, and the tribological and biomechanical properties under different conditions will be further discussed in the future to support the development of nano-medicine.

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