

# Influence of Biogenic Magnetic Nanoparticles on the Vesicular Transport

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In this paper, the interaction forces are calculated between chains of BMNs on the cell membrane and vesicles (granules) inside the cell to identify the role of BMNs in vesicular transport in cell. For the first time, the forces arising between the vesicle and BMNs inside the cell were calculated, with vesicles being considered as effectively paramagnetic, paramagnetic and vesicles containing magnetic nanoparticles. The comparison was carried out of the forces arising between the vesicle and BMNs with the forces of the antigen-antibody, with the force necessary for the functioning of the magnetic tweezers and with the forces that molecular motors develop. It was determined that the forces of magnetic-dipole interaction of BMN with vesicles can significantly affect vesicular transport in cells.

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## 1. Introduction

It is known that biogenic magnetic nanoparticles (BMNs) were experimentally found in representatives of all three kingdoms of living organisms of eukaryotes, prokaryotes and archaea [1]. BMNs create in their vicinity inhomogeneous magnetic fields [2] and BMNs are strong natural micro- and nanomagnets, around which a magnetic field is created four orders of magnitude greater than the Earth's magnetic field [3]. BMNs of bacteria accumulate vesicles and granules with compounds of oxygen, phosphorus, sulfur, polyphosphate granules, granules rich in lipids in the vicinity of the chains and individual clusters according to several investigations [4].

BMNs in human are connected in linear chains containing from tens to hundreds of particles bound to the membrane of cells [5, 6] with the size in the range from 10 nm to 250 nm [7, 8].

Taking into account the unique genetic mechanism of biomineralization of BMNs for representatives of all the kingdoms of living organisms [3, 9], similarity of localization, size, magnetic properties of crystals BMNs it is important to find out the impact of stray magnetostatic fields on vesicular transport in cells of living organisms.

## 2. Material and equipment

In this paper, the interaction forces are calculated between chains of BMNs on the cell membrane and vesicles (granules) inside the cell to identify the role of BMNs

in vesicular transport in cell. A model is considered in which BMNs on the membrane cells can be located both in the chain and separately while vesicles can accumulate in their vicinity [4]. The model of a linear chain of BMNs with radius  $r_0$ , the distance between the BMNs in the chain  $\Delta$ , distance from the tip of the chain to the vesicles  $\Delta_0$ , radius of vesicles  $R_0$ , is considered to calculate the interaction forces of the chain BMNs with vesicle as shown in Fig. 1.

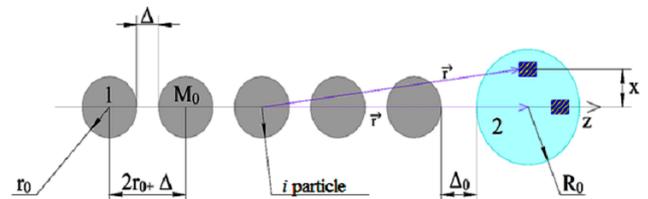


Fig. 1. Schematic representation of the interaction of vesicles and biogenic magnetic nanoparticles in a cell. 1 — BMNs in the cell, 2 - vesicles (granules),  $\Delta$  — the distance between nanoparticles,  $\Delta_0$  — distance from nanoparticles to vesicles,  $M_0$  — magnetization of the magnetic nanoparticles.

The magnetic field which is formed by the  $i$ -th BMN in a chain with magnetization  $M_0$  can be written as:

$$\mathbf{H}_i^{(m)} = \frac{4}{3}\pi r_0^3 \left[ \frac{3(M_0 \mathbf{n}_i) \mathbf{n}_i - M_0}{r_i^3} \right]. \quad (1)$$

It is assumed in equation 1 that all the particles in the chain are identical, the particles are magnetized along the chains, the magnetic moment of every particle is

$$\mathbf{m}_i = \mathbf{m}, \quad (2)$$

and the magnetic moment of the  $i$ -th particle is described

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by the equation:

$$\mathbf{m}_i = 4/3\pi r_0^3 \mathbf{M}_0, \quad (3)$$

where  $V = 4/3\pi r_0^3$  is the volume of a particle.

The coordinates of the vector from the center of the  $i$ -th particle to the volume element of the vesicle have the form:

$$\mathbf{r}_i = (x, y, z_i), \quad (4)$$

where

$$z_i = [r_0 + R_0 + \Delta_0 + (2r_0 + \Delta)(i - 1)] + z, \quad (5)$$

in the case if the vesicle is located on the axis of the BMNs chain at its tip, namely such an arrangement of vesicles was found experimentally as typical for magnetotactic bacteria [4].

The unit vector specifying the direction of the radius vector has the following components:

$$\mathbf{n}_i = \frac{1}{\sqrt{x^2 + y^2 + z_i^2}} (x, y, z_i). \quad (6)$$

The magnetic field projections formed by a magnetic nanoparticle with a magnetic moment  $\mathbf{m}$  on the axis of the Cartesian coordinate system have the form:

$$H_{ix}^{(m)} = \frac{4}{3}\pi r_0^3 \frac{3M_0 z_i x}{(x^2 + y^2 + z_i^2)^{5/2}}, \quad (7)$$

$$H_{iy}^{(m)} = \frac{4}{3}\pi r_0^3 \frac{3M_0 z_i y}{(x^2 + y^2 + z_i^2)^{5/2}}, \quad (8)$$

$$H_{iz}^{(m)} = \frac{4}{3}\pi r_0^3 \times \left[ \frac{3M_0 z_i^2}{(x^2 + y^2 + z_i^2)^{5/2}} - \frac{M_0}{(x^2 + y^2 + z_i^2)^{3/2}} \right]. \quad (9)$$

The interaction energy of the vesicle with the magnetization  $\mathbf{M}$  with the magnetic field, created by a chain of magnetic particles can be written as:

$$U = - \sum_{i=1}^n \int \mathbf{M} \mathbf{H}_i^{(m)} dV, \quad (10)$$

where the integration is carried out over the volume of the vesicle.

After substituting the magnetic field, created by a chain of magnetic particles, in the equation 10 we obtain:

$$U = - \sum_{i=1}^n \int \chi \left( \mathbf{H}_i^{(m)} \right)^2 dV, \quad (11)$$

where is the effective magnetic susceptibility of the vesicle which is equal to the difference between the magnetic susceptibility of the vesicle and the medium in which it is located.

We write the total energy of the magnetic nanoparticles:

$$F_z = - \frac{dU}{dz}, \quad (12)$$

as a result, we get:

$$F_z = \chi \sum_{i=1}^n \int_V \frac{d \left( H_i^{(m)} \right)^2}{dz_i} dx dy dz. \quad (13)$$

When calculating the value  $F_z$  the value of the magnetization for magnetite was taken into account:  $M_0 = 477$  CGS unit [10] and information about size, location and quantity  $R_0 = 100\text{--}800$  nm,  $r_0 = 20\text{--}250$  nm,  $N = 100$  particles [11], as well as the radius of the vesicles, the value of which varies in a wide range from several tens of nanometers to more than 800 nm.

### 3. Results and discussion

The performed calculations have shown that the forces of magnetic-dipole interaction between BMNs and the vesicles (granules) inside the cell depend on their size, but these forces are almost independent of the amount of nanoparticles in the chain for long chains, for example, if the quantity of BMNs in a chain is about 20 nanoparticles, then a further increase in the number of nanoparticles practically would not change the magnetic-dipole interaction forces.

It is necessary to compare the vesicle energy in a magnetic field (Eq. 11) with the energy of its thermal motion in order to assert, that vesicles with appropriate sizes and magnetic properties can accumulate in the vicinity of chains BMNs.

Calculations showed that energy of paramagnetic vesicles ( $\chi = 2 \times 10^{-4}$ ) and effectively paramagnetic vesicles ( $\chi = 2 \times 10^{-6}$ ) in a magnetic field BMNs exceeds the energy of thermal motion for certain parameters radius BMNs  $r_0$  from 40 nm to 250 nm and the radius of the vesicle  $R_0$  from 100 nm to 800 nm, this energy is sufficient to retain vesicles. However, the magnetic-dipole interaction of the vesicle with the BMN chain is two orders of magnitude less than the strength of the interaction of the antigen-antibody [12–14]. The strength of the magnetic-dipole interaction of the vesicle with the BMN chain slowly decreases with distance (proportionally to  $1/r^4$ ), so that the magnetic forces cover almost the entire volume of the cell in contrast to the interaction forces of the antigen-antibody.

The vesicles interacting with a chain of BMNs were considered for calculation of the forces of the magnetic-dipole interaction according to the equation 13 as paramagnetic vesicles ( $\chi = 2 \times 10^{-4}$ ), and diamagnetic vesicles, which are effectively paramagnetic ( $\chi = 2 \times 10^{-6}$ ). If the vesicle is paramagnetic, then even with the radius of the magnetic particle  $r_0 = 20$  nm, they attract paramagnetic vesicles larger than 100 nm. If the vesicle is diamagnetic with positive effective magnetic susceptibility then the corresponding minimum radius of the magnetic nanoparticle in this case would be 50 nm.

The forces of magnetic-dipole interaction of the chain of BMN with the vesicle are compared with forces that are used for the functioning of magnetic tweezers *in vivo* and *in vitro*. It is known that the forces necessary for the functioning of magnetic tweezers which used to manipulate the movement of controlled DNA inside a living cell are equal to  $5 \times 10^{-14}$  N [15]. Also, a comparison of forces of magnetic-dipole interaction of the chain of BMN with the vesicle is carried out with forces that are necessary for the operation of molecular motors which

range from  $5 \times 10^{-15}$  N to  $6 \times 10^{-14}$  N [16, 17]. Calculations showed that these forces are slightly larger than the forces necessary for the operation of the magnetic tweezers and molecular motors at certain sizes of nanoparticles and vesicles. Thus, the magnetic-dipole interaction forces BMNs with vesicles in cells vary in the range from  $6 \times 10^{-16}$  N to  $7 \times 10^{-14}$  N for paramagnetic vesicles with the following parameters of the system (BMNs radius  $r_0 > 20$  nm and vesicles radius  $R_0$  from 100 nm to 800 nm), for diamagnetic vesicles with the parameters of the system (BMNs radius  $r_0$  from 100 nm to 150 nm and vesicles radius  $R_0$  from 100 nm to 800 nm).

Since the calculations show that magnetic forces have a sufficient value for a significant effect on vesicular transport, they can affect metabolism in tissues and organs containing BMNs in norm [7, 18, 19], as well as in pathologically altered organs and tissues in which the biomineralization of BMN is observed [19, 20].

#### 4. Conclusion

The energy of effectively paramagnetic vesicles in the magnetic field of chain of BMNs exceeds the energy of their thermal motion for BMNs of sizes greater than 50 nm and sizes of vesicles greater than 100 nm. And the energy of paramagnetic vesicles exceeds the energy of their thermal motion for BMNs of sizes greater than 20 nm and sizes of vesicles greater than 100 nm. Thus, the energy of the magnetic-dipole interaction of BMN with vesicles in the cell is sufficient to retain vesicles with a positive effective magnetic susceptibility in the vicinity of the chain of BMNs that is, near the cell membrane.

Forces of magnetic-dipole interaction which arise inside the cell between BMNs and effectively paramagnetic vesicles range from  $10^{-16}$  N to  $10^{-13}$  N, paramagnetic vesicles range from  $10^{-14}$  N to  $10^{-13}$  N and vesicles containing magnetite nanoparticles range from  $10^{-12}$  N to  $10^{-9}$  N.

Magnetic-dipole force in the vicinity of the chain BMNs for effectively paramagnetic and paramagnetic vesicles is significantly less than the forces of a specific interaction of the "antigen-antibody" type and are greater or the same order that the above specific binding forces for vesicles containing magnetic nanoparticles.

Magnetic-dipole force is of the same order of magnitude as the forces necessary for the functioning of the magnetic tweezers for effectively paramagnetic vesicles with dimensions of BMNs from 20 nm to 150 nm and sizes of vesicles exceeding 100 nm, for paramagnetic vesicles with dimensions of BMNs from 20 nm and sizes of vesicles exceeding 100 nm.

Forces required for functioning molecular motors range from  $5 \times 10^{-15}$  N to  $6 \times 10^{-14}$  N [16, 17]. Therefore, the magnetic interaction forces for paramagnetic vesicles with a BMNs size of 20 nm and the sizes of vesicles exceeding 100 nm cannot be used to move the vesicles but only to keep them near the membrane. This significantly increases the probability of fusion of vesicles, paired processes of interaction of vesicles with receptors on the membrane and also interaction of contents of vesicles

with other bioactive substances which are transported through the cell membrane.

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