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Simulation Study on Forward Problem of Magnetoacoustic Tomography with Magnetic Induction Based on Magnetic Nanoparticles

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Abstract—Magnetoacoustic tomography with magnetic induction (MAT-MI) is a multiphysics imaging technique that combines electrical impedance imaging with ultrasound imaging. In order to study the influence of parameters on the source of MAT-MI, such as radius and permeability of magnetic nanoparticle clusters, the paper is divided into the following stages. Firstly, this paper analyzes the electromagnetic and acoustic properties of MAT-MI after adding magnetic nanoparticles. Secondly, to determine suitable simulation conditions, a two-dimensional model is constructed. Thirdly, use the finite element method to solve physical processes of electromagnetic field and acoustic field under conditions of different magnetic nanoparticle clusters' radii and permeabilities, then obtain the magnetic flux density image. Consequently, make the qualitative and quantitative analysis according to the theory and simulation results. The results show that magnetic nanoparticle clusters interact with each other and distort the magnetic field to different degrees; its radius increases with the degree of flux density distortion around it, so does its permeability and magnetoacoustic signal intensity. The research results can play a guiding role in the parameter selection of magnetic nanoparticle clusters in practical applications to a certain extent.

1. INTRODUCTION

In recent years, magnetic nanoparticles (MNPs) have been widely used as contrast agents in clinical and molecular imaging [1–3]. The detection of drug therapy imaging by combining antibody-carrying MNPs with tumor-specific markers is a hotspot of current research [4–8]. As early as in 2006, Oh et al. demonstrated the feasibility of image reconstruction by using MNPs embedded in tissues under the changing magnetic field to generate ultrasonic signals [9]. Although Xu and He proposed magnetoacoustic tomography with magnetic induction (MAT-MI) in 2005 [10], it was not until 2012 that the team first applied MNPs to magnetoacoustic imaging. Experiments obtained clear boundary images containing MNPs, which proved the feasibility of using MNPs for magnetoacoustic imaging [11]. In 2016, Mariappan and others successfully detected and reconstructed the MNPs distribution in mice with MNPs in vivo using MAT-MI. The experiment proved that the MAT-MI based on MNPs had good resolution and imaging depth [12]. In 2018, Yan and other researchers studied the influence of MNPs on MAT-MI from a theoretical point of view and determined that MNPs can make the reconstruction of sound sources more convenient because MNPs can produce more sound pressure signals and more uniform sound pressure distribution than traditional MAT-MI. The research made clear that the sound pressure signal carried rich MNPs information [13].

However, most of the current researches focus on the detection of magnetoacoustic signals and the acquisition of tissue boundary images after adding MNPs. So far, there is no report on the influence

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of cluster parameters of magnetic nanoparticles on the acoustic source of magnetoacoustic imaging. In view of this, this paper carries out research on electromagnetic and acoustic fields under different radius and permeability conditions of magnetic nanoparticle clusters, establishes a two-dimensional model of imaging target body, and analyses the influence of two parameters on magnetic flux density amplitude and magnetic field gradient from theoretical and simulation aspects. Consequently, make a preliminary qualitative and quantitative analysis for the influence of magnetic nanoparticle cluster parameters on the physical process of MAT-MI.

2. THEORETICAL ANALYSIS

In MAT-MI, the object is located in a static magnetic field $\boldsymbol{B}_0$ and a time-varying (μs) magnetic field $\boldsymbol{B}$. $\boldsymbol{B}$ is generated by applying pulsed current to coils. Eddy current $\boldsymbol{J}$ is induced in the object, which interacts with static magnetic field and alternating magnetic field to generate Lorentz force, thus exciting ultrasonic wave. When MNPs are introduced, the source of force changes from Lorentz force to electromagnetic force $\boldsymbol{f}$ of magnetic nanoparticles under the action of alternating magnetic field. At this point, the ultrasonic wave satisfies the following formula

$$\nabla^2 p - \frac{1}{c_s^2}\frac{\partial^2 p}{\partial t} = \boldsymbol{f} \tag{1}$$

where p is the sound pressure, C_s the sound velocity in the object, and the electromagnetic force f is [9]

$$\boldsymbol{f} = -\frac{x_{np} v_{np} f_m}{\mu_0}\nabla|\boldsymbol{B}|^2 \tag{2}$$

where x_{np} is the susceptibility of MNPs, v_{np} the volume of MNPs, f_m the volume fraction of MNPs, and μ_0 the permeability in vacuum. Assuming that only the x-direction magnetic field is considered, Eq. (2) can be expressed as [9]

$$\boldsymbol{f} = -\frac{x_{np} v_{np} f_m}{\mu_0} B_x \frac{\partial B_x}{\partial x}\boldsymbol{e}_x \tag{3}$$

3. NUMERICAL SIMULATION

In this paper, a finite element model is established by using the numerical simulation software COMSOL Multiphysics, and the electromagnetic-acoustic multi-field coupling analysis is carried out. The model is shown in Fig. 1. Considering the concentric circle model, the center of the circle is set at the origin of the coordinate, and the outer circle represents the normal biological tissue with a radius of 400 nm. The relative permeability is set to 1; the inner circle is a magnetic anomaly; and the relative permeability is set according to the simulation problems.

In this study, the magnetic anomaly model in Fig. 1 is a nanoscale cluster of targeted drug-loaded magnetic nanoparticles with a nuclear structure. It consists of superparamagnetic nanoparticles with an average diameter of 3–4 nm embedded in biocompatible polymers, coated with antineoplastic drugs

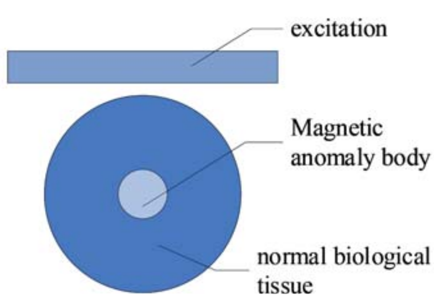


Figure 1. Two-dimensional simulation model.

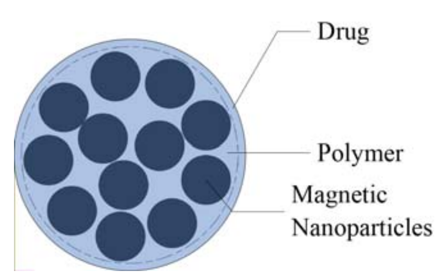
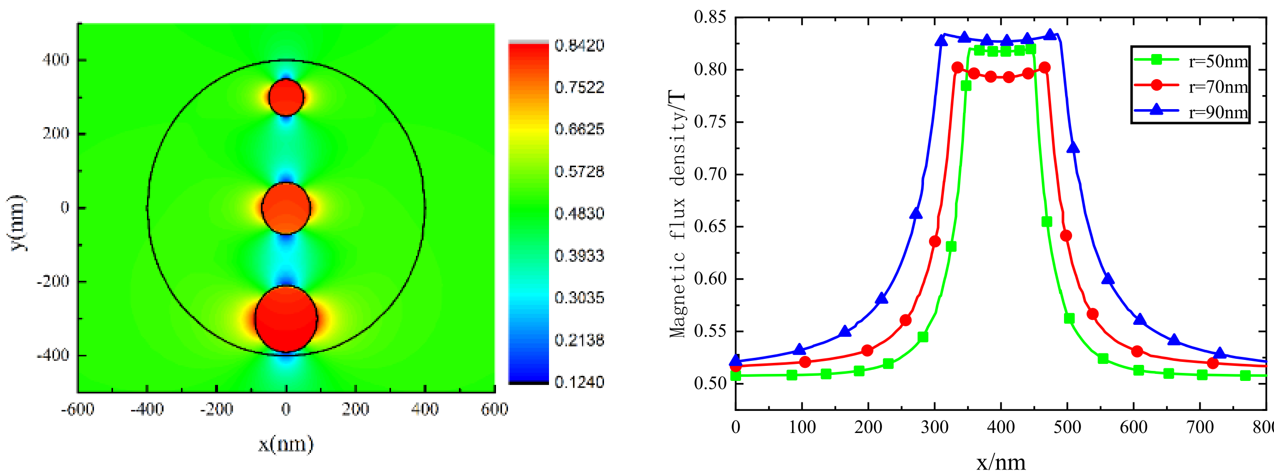


Figure 2. Superparamagnetic nanoparticles stable cluster.

and synthesized by chemical methods, as shown in Fig. 2. The combined diameter of the stable clusters of superparamagnetic nanoparticles is usually between 40 and 100 nm [14].

3.1. The Influence of Radius of Magnetic Nanoparticle Clusters

The different radii of magnetic nanoparticle clusters cause various surface curvatures, and in this case, the effect of changing the direction of the original magnetic field magnetic line is also different. As a result, different magnetic field characteristics will be produced. Based on this principle, a magnetic nanoparticle cluster with radius of 50 (SA-BiotinModifiedFe_3O_4 Microspheres by Beijing Zhongkeleiming Daojin Technology Co, Ltd), 70 (PLL coated Fe_2O_3 nanoparticles) and 90 nm (SA-BiotinModifiedFe_3O_4 Microspheres) is placed in a uniform background magnetic field with magnetic field intensity of 4×10^5 A/m. The central positions of the three clusters are (0, 300), (0, 0), (0, -300) (nm), respectively, and their relative permeability is set to 6. The simulation is simplified to a two-dimensional field, and the magnetic field distribution around the magnetic nanoparticles cluster is simulated based on the uniform medium and static magnetic field distribution. The simulation results are shown in Fig. 3.



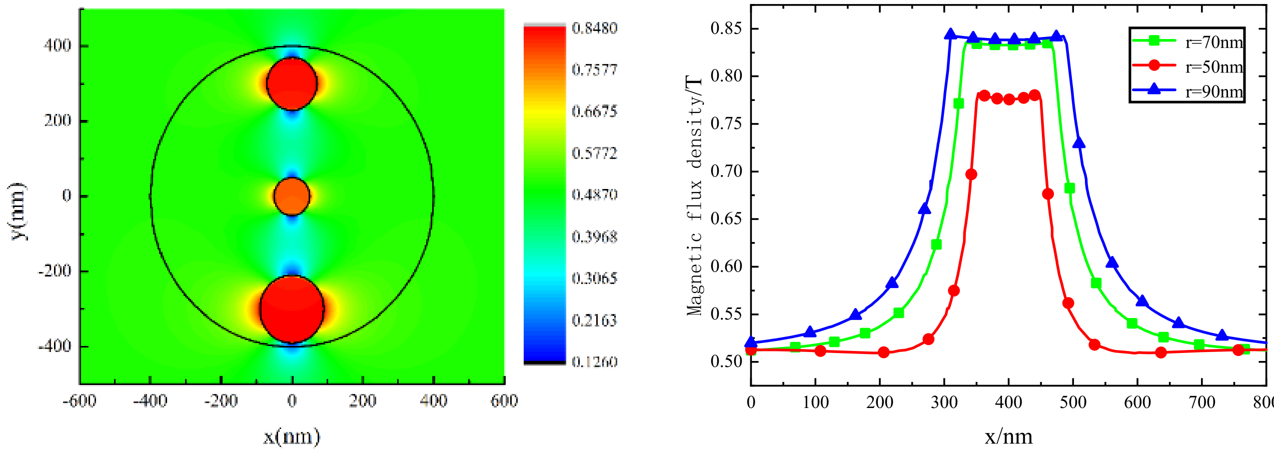
(a) (b)

Figure 3. Flux density distribution of MNPs with different radii. (a) Flux density two-dimensional distribution. (b) Flux density one-dimensional curve.

However, due to the limitation of the simulation model, there is not enough distance between the three clusters of magnetic nanoparticles. Besides, the influence of magnetic field on each other cannot be neglected. Therefore, the results in Fig. 3 may have errors caused by such reasons. In order to ensure the accuracy of the results in Fig. 3 and not affected by the factors of alignment position, the comparative simulation as shown in Fig. 4 shows that different alignment positions will affect the magnitude of magnetic field around MNPs.

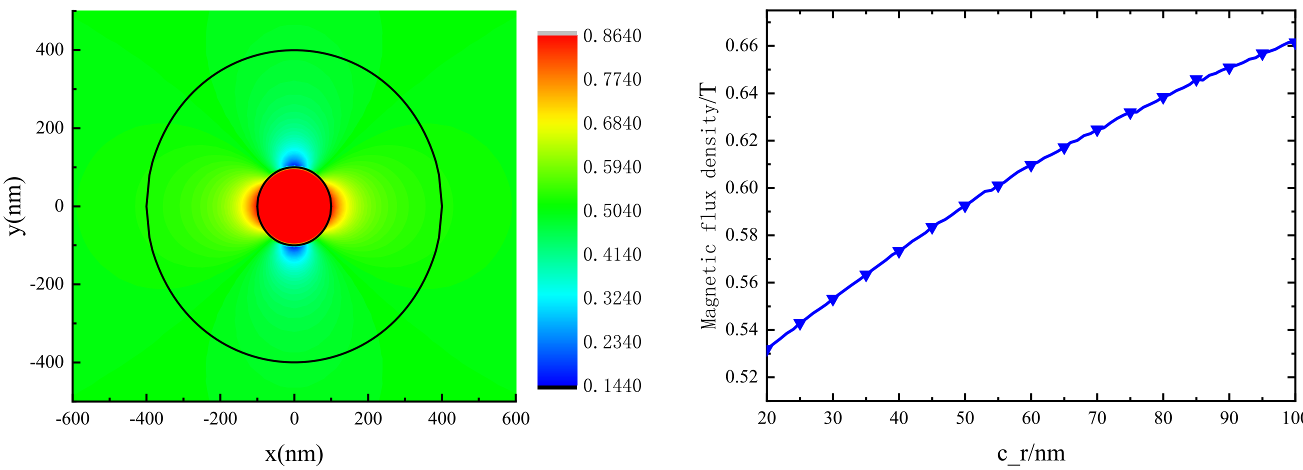
In addition, the regions with high magnetic field intensity mainly exist near the left and right surfaces of magnetic nanoparticles clusters. With the increase of the radius of magnetic nanoparticles cluster, the range of action in the strong magnetic field region increases. With the decrease of the radius of magnetic nanoparticles cluster, the flux density decays faster, and the magnetic field gradient increases. These are all because of the smaller radius of magnetic nanoparticles cluster, larger curvature surface, more obvious sharp angle effect, larger distortion of the background magnetic field, and higher magnetic field gradient.

From the above results, we can see that the simulation needs to be further improved. Therefore, a parametric scanning of the radius of a magnetic nanoparticle cluster is carried out in this paper. In a reasonable range, the particle model with radius between 20 and 100 nm is proposed, and the step length is set to 1 nm. The results are shown in Fig. 5. Fig. 5(a) shows a planar map of flux density



(a) (b)

Figure 4. Contrastive analysis of position effects. (a) Two-dimensional distribution of magnetic flux density. (b) One-dimensional curve of magnetic flux density.



(a) (b)

Figure 5. The influence of magnetic nanoparticle radius on magnetic flux density. (a) $r = 100$ nm magnetic flux density distribution plan. (b) The relationship between magnetic flux density and radius.

distribution at a radius of 100 nm. A point 5 nm away from the inner circle is selected as the test point, and the position of the test point varies with the radius of the inner circle. The relationship between the flux density at the test point and the radius of the inner circle is shown in Fig. 5(b).

As can be seen from Fig. 5, the flux density modulus at the test point increases with the increase of radius, but the growth rate decreases, which can be approximately regarded as a linear proportional relationship. With the change of radius of magnetic nanoparticles cluster, the magnetic field gradient will be different due to the difference of radius and curvature of particles and the distortion of magnetic field. Therefore, the distribution of sound field with different radii of particles cannot be determined only by the magnitude of magnetic flux density, and further calculation of $B_x \frac{\partial B_x}{\partial x}$ in Eq. (3) is needed. The value of $B_x \frac{\partial B_x}{\partial x}$ is also needed when studying the effect of magnetic nanoparticle clusters with different radii on the acoustic signal characteristics of MAT-MI.

3.2. The Influence of Permeability of MNPs

The radius of magnetic nanoparticles is 50 nm; the relative permeability is 6, 11, and 16 on the basis of the susceptibility $x = 7.8 \pm 0.5$ calculated in [15]; and the central positions are (0, 300), (0, 0), (0, -300) (nm), respectively. The magnetic field distribution around MNPs is simulated by a uniform background magnetic field of 4×10^5 A/m. The simulation results are shown in Fig. 6.

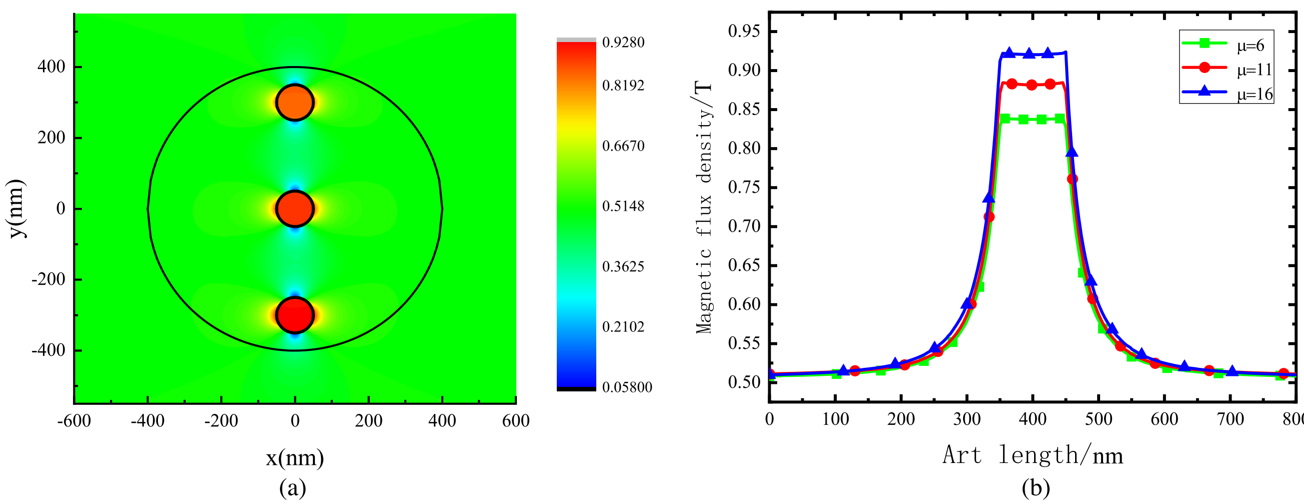


Figure 6. The influence of permeability of magnetic nanoparticles on flux density. (a) 2-D distribution of flux density. (b) 1-D curve of flux density.

Figure 6 shows that the magnitude of magnetic flux density around MNPs increases with the permeability of magnetic nanoparticles. Because of the same radius, the electromagnetic force produced by each magnetic nanoparticle increases with the magnitude of magnetic flux density. Obviously, the higher the permeability of magnetic nanoparticles is, the greater the acoustic pressure amplitude is produced by MAT-MI.

Although the acoustic pressure amplitude of MAT-MI increases with the increase of magnetic permeability of magnetic nanoparticles, it does not mean that the magnetic permeability of magnetic nanoparticles can be increased indefinitely to enhance the imaging effect. Also, the impact of MNPs should be taken into account on human body when they are subjected to the action of magnetic field. The impact of targeted therapeutic drugs encapsulated in them and a series of other factors also need to be considered.

4. CONCLUSIONS AND PERSPECTIVES

In this paper, two parameters, the radius of magnetic nanoparticles cluster and the permeability of magnetic nanoparticles, have been studied. We have done researches to find the effects of two parameters on the magnetic flux density amplitude and magnetic field gradient. The influence of the position of magnetic nanoparticle clusters on each other is preliminarily analyzed. The radius of magnetic nanoparticle clusters is scanned in a certain range, and the influence of magnetic nanoparticle clusters on magnetic flux density is analyzed in this range. In the process of simulation and analysis, the following conclusions are obtained. The simulation results show that:

(1) The magnetic field is distorted due to the influence of magnetic nanoparticles cluster on each other. In view of this characteristic, the influence of MNPs arrangement on the imaging effect of MAT-MI can be further studied. If the influence is positive, another way to enhance the imaging effect can be considered.

(2) The intensity of magnetoacoustic signal increases with the permeability of MNPs. Each magnetic nanoparticle has an effect on the magnetic field around it, and this effect is also related

to the radius. Therefore, the influence of the arrangement of magnetic nanoparticles on the magnetic field, including magnetic field gradient and superimposed magnetic field intensity, should be further studied in order to further enhance the magnetoacoustic signal.

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