Computational study of the effect of gradient magnetic field in navigation of spherical particles

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Abstract. The use of spherical magnetic nanoparticles that are coated with drugs and can be navigated in arteries to attack tumors is proposed as an alternative to chemotherapy. Navigation of particles is due to magnetic field gradients that may be produced in an MRI device. In the present work, a computational study for the evaluation of the magnitude of the gradient magnetic field for particles navigation in Y bifurcations is presented. For this purpose, the presented method solves for the fluid flow and includes all the important forces that act on the particles in their discrete motion. The method is based on an iteration algorithm that adjusts the gradient magnetic field to minimize the particles’ deviation from a desired trajectory. Using the above mentioned method, the appropriate range of the gradient magnetic field for optimum navigation of nanoparticles’s aggregation is found.

1. Introduction

Magnetic driving of the drug inside the human vessels is very important, because the drug can delivered to the desired area. The benefits of using this method are many; the quantity of the drug required is being reduced, while the drug concentration at targeted sites is increased. For the magnetic navigation of the drug, the use of magnetic nanoparticles is necessary. The anti-tumour agents are loaded on the surface of the magnetic nanoparticles. The magnetic field that is required in order to navigate the particles inside the human arteries is produced by a Magnetic resonance imaging (MRI) scanner.

Factors which influence the efficiency of magnetic nanoparticles’ usage for biomedical applications in the magnetic driving are the size and the magnetization of the biocompatible nanoparticles. Many of these particles are being trapped in the liver and spleen and are excreted via the kidneys. A small size of particles implies a small magnetic response, thus the use of huge magnets are imperative [1]. Using paramagnetic nanoparticles the magnetic response of the nanoparticles is maximized, as they are formed into chains under the influence of a steady magnetic field. The size of aggregates is very important and it depends on different parameters [2]. After the navigation in the infected area, the nanoparticles lose their magnetization in the absence of the magnetic field.

Previous studies [3,4] indicates the appropriate amount of changes of the gradient magnetic field for optimum navigation of particles into the desired direction. In this study, the ranges of the magnitude of the gradient magnetic field are evaluated.

2. Numerical Model

For the propulsion model of the particles seven major forces are considered; i.e. the magnetic force from MRIs main magnet static field, as well as the magnetic field gradient force from the special propulsion gradient coils. The contact forces are firstly developed between the aggregated
nanoparticles and secondly between nanoparticles and walls. The Stokes' drag force for each particle is considered, while only spherical particles are considered in this study. In addition, forces due to gravity and buoyancy, are included. Moreover, attractive forces, such as the Van der Walls forces, are included in the present model [4]. The numerical model for all the above mentioned forces as well as for the fluid flow is given in [5].

3. Numerical Method

The OpenFoam platform [6] has been used for the calculation of the flow field and the uncoupled equations of particles’ motion. The Covariance Matrix Adaptation Evolution Strategy (CMAES) algorithm [7] is used to adjust the gradient magnetic field in order to drive the particles through arteries. Initially, the CMAES algorithm provides the flow model with a random value of the gradient magnetic field. During the simulation, the computational platform evaluates the mean distance between particles and the desired trajectory. If all particles are in the desired trajectory, the simulation is completed. If not, the optimization platform provides new values of the gradient magnetic field in order to eliminate this distance. In this way, CMAES found the appropriate sequence of the gradient magnetic field in order to navigate efficiently the particles. The numerical method is explained in details in [4].

![Figure 1. Y-shaped geometry.](image1.png)

![Figure 2. Desired trajectory (Red line)](image2.png)

4. Results

For the evaluation of the effect of the magnitude of gradient magnetic field for navigation of particles, series of simulations with various ranges of the magnetic field gradient are performed. For this reason, the combined flow of particles and a Newtonian fluid solution in a Y-shaped geometry (2D) is simulated, as shown in Figure 1. The inlet of the fluid is in the left of the geometry and there are two outlet branches in the right side. Between the two outlet branches an angle of 60 degrees is selected. Both diameters of the main and outlet branches are kept constant at 2.5 mm. The overall length of the simulated geometry is 37 mm. The velocity of the fluid is 12.2 mm/s in the main branch of the geometry and 6.1 mm/s in the outlet branches. A desired trajectory is introduced for the navigation of nanoparticles as shown in Figure 2. The flow is under a uniform transverse magnetic field of magnitude $B_0 = 1T$. The formulation of nanoparticles’ into chains is a time consuming process [5]. In order to overcome this difficulty, ready-made aggregations from ref. [4] are used in the simulations. The range of magnetic gradient values is predefined in each simulation.
a) Peak magnetic gradient : +/- 100 mT/m

b) Peak magnetic gradient : +/- 200 mT/m
c) Peak magnetic gradient : +/- 300 mT/m
d) Peak magnetic gradient : +/- 400 mT/m
e) Peak magnetic gradient : +/- 500 mT/m

**Figure 3.** Navigation of particles (red circles) with different ranges of magnetic gradient

Five simulations are performed with range from +/-100 mT/m to +/-500 mT/m gradient of the magnetic field with increment of +/-100 mT/m. As is depicted in Figure 3 a,b for magnetic gradient ranges below +/-200 mT/m no sufficient navigation of particles is observed. On the other hand, ranges from +/-300 mT/m and above can effectively navigate particles through the desired direction, as shown in Figure 3 c,d,e. It is noted that the particle distribution in the flow is not uniform because of the parabolic flow.

Although the percentage of particles that follow the desired direction is increased as the range of the magnetic gradient is also increased, there is a small amount of them that stuck to the walls. The percentage of particles that found to follow the right path as the magnetic gradient range increases is depicted in Figure 4. It is observed that for magnetic gradient ranges less than +/-200 mT/m only a small increase above 50% is succeeded.

The increase is getting higher as larger magnetic gradient ranges are permitted, namely 80% for ranges of +/-300 mT/m, 93% for +/-400 mT/m and is maximized for +/-500 mT/m succeeded up to of 97% navigation. The increase in the percentage of particles that follow the desired direction is more steeper between magnetic gradients of +/-200 and +/-300 mT/m with growth of 17%. This percentage falling to 13% between +/-300 and +/-400 mT/m and is going to 4% at +/-500 mT/m. Higher ranges of the magnetic gradient can only increase by 3% with excess of cost and high probability of sticking some particles into the wall.
5. Conclusions
In this work, a computational study of the effect of the gradient magnetic field for the navigation of spherical particles into targeted areas is presented. Results indicate that as CMAES can adjust the magnetic gradient in ranges above +/-300 mT/m, navigation of particles with efficiency above 80% can be achieved. The computational method can simulate an MRI system working under experimental conditions and drive particles into the desired trajectory with efficiency 97% in the number of particles when the gradient magnetic field is 500 mT/m.

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