Application of Halbach-like Magnet Arrays to Magnetic Drug Targeting

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***Abstract* — Among the proposed techniques for delivering drugs to specific locations within the human body, magnetic drug targeting (MDT) surpasses due to its non-invasive character and its high targeting efficiency. In this study, we developed a principle of design and evaluation for MDT magnets, which was based on three parameters, gradient of energy density,** evaluation variable, **and homogeneity. In distance of 3cm of application from magnetic field source, we calculated and compared these parameters of four magnet arrays. Results presented that parameters value of Halbach-like magnet arrays have an order of magnitude increase.**

I. Introduction

Ideal medical treatment would require options for disease intervention with high specificity and efficacy excluding unwanted side effects. The concept of drug targeting stems from the very idea of minimizing the risk-to-benefit ratio.

Certain advantages of magnetic micro/nanoparticles employed in MDT offer some attractive possibilities to achieve this aim in biomedicine [1]-[2]. One advantage is that they can 'get close' to a biological entity of interest as they are smaller than or comparable to those of a cell, a virus [3]. Another advantage is that particles are magnetic, which means that they obey Coulomb's law, and can be manipulated by an external magnetic field. Also, particles in the magnetic fluid interact strongly with each other, which facilitate the delivery of high concentrations of drug to targeted areas.

Previous attempts to use magnetic micro/nanoparticles for MDT give us a vision that the main obstacle is that externally generated magnetic fields apply relatively small and insufficiently local forces on deeper magnetic particles[4]-[5]. This means that the depth to the general magnetic guidance systems may function is not enough. As a result, there has been great interest in devising external magnet arrays systems that produce strong and highly localized magnetic field force in the interior of the body. Therefore, in this paper we propose an efficient method based on the differential of the magnetostatic field energy density, $1/2(\boldsymbol{B}\cdot\boldsymbol{H})$, to develop a novel arrangement of permanent magnets, Halbach array, for magnetic drug delivery. This type of array has so-called one-sided flux characteristics. Simulation results of Halbach array indicated the array could generate higher magnetic field force than classical magnets with simple geometry.

II. Magnetic Force Modeling

Magnetic force acting on an individual magnetic nanoparticle is determined by using method of "effective" dipole moment, in which a magnetic particle is replaced by "equivalent" point dipole moment $\boldsymbol{m}$ localized at the center of particle. For a magnetic dipole we recognize that a uniform field gives rise to a torque, but no translational action. This magnetic force is governed by the equation:

$$\boldsymbol{F}_m = (\boldsymbol{m}\bullet\nabla)\boldsymbol{B} \tag{1}$$

where $\boldsymbol{m}$ depends on externally applied magnetic field intensity $\boldsymbol{B}$ at the center of particle, where the dipole moment is localized. In the case of a magnetic particle suspended in water, the total moment on the particle can be written

$$\boldsymbol{m} = \boldsymbol{V}_p \frac{\Delta\chi}{\mu_0}\boldsymbol{B}, \tag{2}$$

where V_p is the volume of the particle and $\Delta\chi$ is the effective susceptibility of the particle relative to the water. Applying equation (2), equation (4) becomes:

$$\boldsymbol{F}_m = \frac{V_p\Delta\chi}{\mu_0}(\boldsymbol{B}\bullet\nabla)\boldsymbol{B} \tag{3}$$

For a definite magnetic micro-and nanoparticle, it is clear from this equation that the force exerted on a magnetic particle is directly proportional to both the strength and the gradient of the magnetic field. This means that we need to consider two factors meanwhile. In order to facilitate the design of magnet array, provided there are no time-varying electric fields or currents in the medium, we can apply the Maxwell equation $\nabla\times\boldsymbol{B}=0$ to the following mathematical identity:

$$\nabla(\boldsymbol{B}\bullet\boldsymbol{B}) = 2\boldsymbol{B}\times(\nabla\times\boldsymbol{B}) + 2(\boldsymbol{B}\bullet\nabla)\boldsymbol{B} = 2(\boldsymbol{B}\bullet\nabla)\boldsymbol{B} \tag{4}$$

to obtain a more intuitive form of equation (3):

$$\boldsymbol{F}_m = V_m\Delta\chi\nabla\left(\frac{B^2}{2\mu_0}\right) \quad \text{Or} \quad \boldsymbol{F}_m = V_m\Delta\chi\nabla\left(\frac{1}{2}\boldsymbol{B}\bullet\boldsymbol{H}\right) \tag{5}$$

Therefore the magnetic force is related to the differential of the magnetostatic field energy density (direct ratio). Thus, the gradient of the magnetostatic field energy density can be used as an only parameter for evaluating force derived by magnet array.

III. Magnet Arrays

The force that would be exerted on the nanoparticles described above if it were placed in the vicinity of various magnet arrays was calculated for four distinct geometries. The first two belong to classical single square NdFeB permanent magnet(4cm×4cm×5cm) and the latter two belong to Halbach arrays, which consist of three components the same size permanent magnet(4cm×4cm×5cm) magnetized perpendicular to the 4cm×5cm faces. Their specific arrangement was shown in Figure1. The fourth magnet array, Spin-Halbach 5degree,was designed for curved region of interesting. A two-step procedure was used to obtain an estimate of the gradient of the field energy density about various magnetic arrays. In the first step, the magnetic field ***B*** was calculated using the finite-element scheme. Then the results of gradient could be yielded by magnetic flux density data. The gradient of energy density of the two types of Halbach magnets arrays shown in Figure 2 and Figure 3.

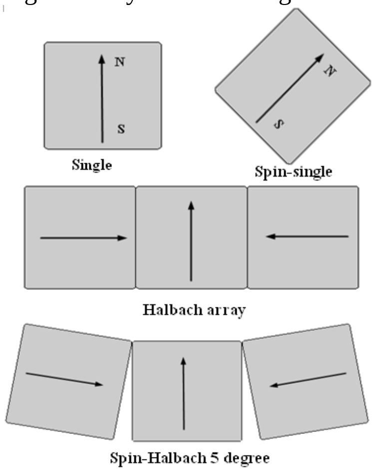

Fig. 1. Magnetization for four types of magnets

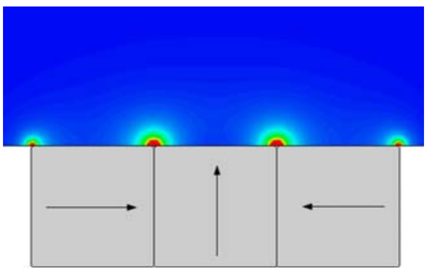

Fig. 2. Gradient of energy density of Halbach array

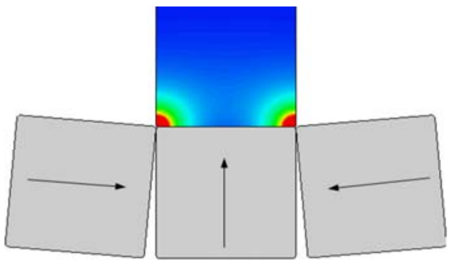

Fig. 3. Gradient of energy density of Spin-Halbach 5 degree

In order to evaluate the performance of each magnet arrays, an evaluation variable ξ

$$\xi = \frac{\boldsymbol{Weight}}{\boldsymbol{GradEn}^2}$$

is proposed to illustrate the difference of ability for arrays to exert magnetic force on individual magnetic nanoparticle(see in table I). Calculation of homogeneity for gradient of energy density employs the following expression:

$$2\left(\frac{\boldsymbol{GradEn}_{\max} - \boldsymbol{GradEn}_{\min}}{\boldsymbol{GradEn}_{\max} + \boldsymbol{GradEn}_{\min}}\right)$$

Above the ***Weight*** and ***GradEn*** stand for the weight of magnet arrays and gradient of energy density, respectively.

TABLE I
SUMMARY POINT PARAMETERS STATISTICS 3cm ABOVE THE SURFACE CENTER OF THE FOUR MAGNET ARRAY

Magnet array	|***B***| (T)	Gradient |***B***| (T/m)	Gradient Energydensity ($J/m^3/m*10^6$)	Homogeneity on transverse line(±0.5cm)	ξ
Single	0.12	4.5	0.436	0.0133	3.15
Spin-single	0.09	3.4	0.250	0.0280	9.37
Halbach array	0.28	9.1	1.97	0.0010	0.46
Spin-Halbach 5degree	0.28	9.1	1.98	0.0030	0.45

IV. Conclusion

Three main technical parameters, gradient energy density, homogeneity and evaluation variable ξ, are developed in this paper. This enables us rapid and cost-effective to design and evaluate one type of MDT magnets. Out of table I, the calculations clearly illustrate advantages of Halbach-like arrays of magnets relative to simple geometry arrays, both in terms of the energy gradient and the homogeneity on transverse line and ξ that can be achieved. These merits derived from the fact of the nearly one-sided flux of Halbach arrays.

Numerous and complex hydrodynamic and physiological factors influence the trapping of real magnetic microspheres. However, the calculation of the distribution of gradient of energy density provides useful insight into the relative effectiveness of magnet arrangements for drug-targeting applications.

V. Acknowledgment

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VI. References

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