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3-POLES MAGNETIC COUPLER FOR INDUCTIVE LINK OF TRANSCUTANEOUS IMPLANTABLE DEVICE IN MR IMAGING

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ABSTRACT

The number of patients who are implanted electronic medical devices has been rapidly increasing in recent years. However, for the patients of implanted electronic medical devices, scanning in the MRI bore has dangerous matter since the implantable electronic medical devices containing internal magnet would produce inevitable risk factors, such as, strong pulling force and torque generation, by strong base magnetic field.

In this paper, an improved fixation magnet method which is applicable implantable medical device for MRI scanning of patient is proposed. This method can reduce risk factors during MRI scanning process by canceling the generated magnetic force of each permanent magnet in transcutaneous signal and power transmission coil of the implantable device. To effectively cancel out the generated magnetic force between implanted magnet and base magnetic field of MRI, the 3-poles magnet method is introduced. Using the proposed 3-poles magnet, in-vitro tests were performed in the 1.5 T MRI. As the result, risk factors were markedly diminished. So, if patients using implantable electronic medical devices including 3-poles magnet undergo a MRI scan, the possibility of magnet protrusion from implanted device can be avoided.

KEY WORDS

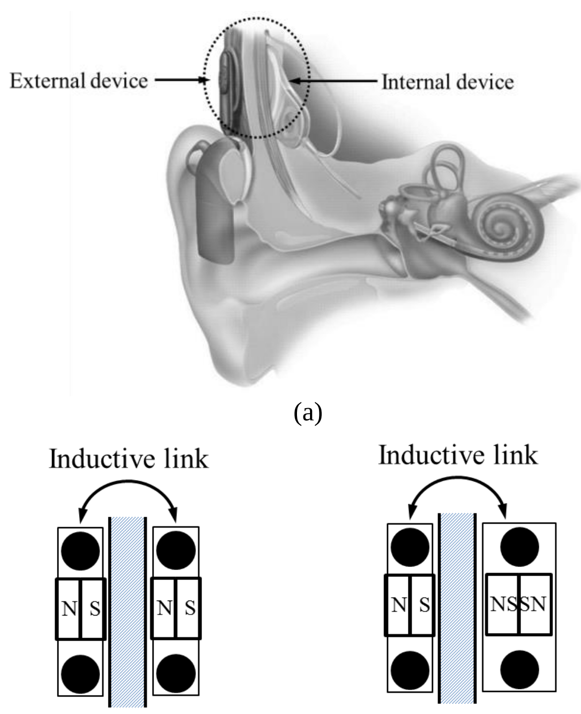
Magnetic coupler, Inductive link, Medical implant, Transcutaneous implantable device.

1. Introduction

Implantable medical devices, such as, cardioverter defibrillator(ICD), cochlear implant(CI), and brainstem implant(BSI), have being developed in accordance with advances of medicine and electronics [1]. Most of medical implants transcutaneously transmit energy and communicate data via inductive link [2]. For efficient coupling of the inductive link, alignment between a primary coil and a secondary coil is very important [3]. In previous studies, a permanent magnet is located at center of each coil and two coils were exactly and easily aligned by the pulling force of two magnets [4, 5].

However, serious problem could be happened by the implanted magnet of secondary coil in the human body. In case of MRI environment, patients might be experience unexpected pain because the magnet's movement due to high intensity magnetic field produced force and torque. To prevent this problem, in general, the implanted magnet should be removed before medical checkup using MRI [6]. Moreover, this method is very invasive and cumbersome during removal and reinsertion of the magnet.

To solve the problem, we propose a novel structure of magnetic coupler for aligning between the coils of transcutaneous inductive link. The implanted magnets of this structure, named 3-poles magnet, compose of a pair of magnets and those magnets same poles are forcibly



(b) (c)

Figure 1. An inductive link for transcutaneous implantable device; (a) example of cochlear implant, (b) conventional fixation method using dipole magnet, and (c) suggested method using 3-poles magnet

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attached. In this paper, to realize a MRI safe inductance coupling system, the principle of the 3-poles magnet in electromagnetic field is described. Then, an exact finite element analysis is performed to verify that this structure can guarantee tolerance to the torque in the magnetic field of 1.5 T, in case of 3-poles magnet. Finally, experiments measuring torque of the magnet in 1.5 T MRI were performed using a gravity of a mass. The measurements and simulated results were compared each other.

2. Issues of implantable medical devices in the MRI bore

Cochlear implant, widely implanted in the body, which consists of internal device implanted in the temporal bone behind ear and external device wore on the skin, is fixed by the force between permanent magnets of internal and external device (see Figure 1). And for stable attachment considering the skin tissue thickness about 6.1 mm of the temporal bone [7], the ferromagnet with high residual magnetic flux density is used.

Recently, MED-EL and Cochlear obtained cochlear implant's approval of FDA for compatibility of MRI scans at 1.5T without internal magnet and at 3.0T with internal magnet [8]. Therefore, research for decreasing the extrusion risk of internal magnet during scanning at 1.5T is needed.

2.1 Magnetic force

When a magnetic material is placed within the magnetic field of MRI, a magnetic force and torque is produced by magnetic field.

Mathematically, the force on a magnet having a magnetic dipole moment, p, due to a magnetic field, B, is:

$$F_m = (p \cdot \nabla)B. \tag{1}$$

Using the Cartesian coordinate system, this equation can be described to

$$\begin{aligned} F_m = & \left(p_x \frac{\partial B_x}{\partial x} + p_y \frac{\partial B_y}{\partial y} + p_z \frac{\partial B_z}{\partial z}\right)\hat{x} \\ & + \left(p_x \frac{\partial B_x}{\partial x} + p_y \frac{\partial B_y}{\partial y} + p_z \frac{\partial B_z}{\partial z}\right)\hat{y} \\ & + \left(p_x \frac{\partial B_x}{\partial x} + p_y \frac{\partial B_y}{\partial y} + p_z \frac{\partial B_z}{\partial z}\right)\hat{z}. \end{aligned} \tag{2}$$

In the MRI bore, static magnetic field goes along the z-axis of MRI, and x and y components are removed from this equation. Therefore, the force on a magnetic material can be described to

$$F_m = p_z \frac{\partial B_z}{\partial z}\hat{z}. \tag{3}$$

Here, this equation is written in

$$F_m = p_z \frac{\partial B_z}{\partial z} = \frac{M_s V}{\mu_0 \mu_s} \frac{\partial B_z}{\partial z}, \tag{4}$$

where V is the volume of magnetic material and M_s is the magnetic moment. Permeability is $\mu_0 = 4\pi \times 10^{-7}$ [H/m] in free air space and relative permeability is $\mu_s \approx 1$. The gravity for magnetic material can be described to

$$F_g = \rho_m g V, \tag{5}$$

where ρ_m is mass density and $g = 9.8\ [m/s^2]$ is the acceleration of gravity. Therefore, force ratio by the acceleration of gravity can be calculated as

$$\text{Force ratio} = \frac{F_m}{F_g} = \frac{M_s}{\mu_0 \mu_s \rho_m g} \frac{\partial B_z}{\partial z}. \tag{6}$$

In the environment of MRI bore, the method for testing implantable electronic medical device by measuring the amount of change of force induced by magnetic field, is proposed by American Society for Testing and Materials (ASTM) at F2052 [9]. According to this standard, the force for implantable electronic medical device caused by a static magnetic field density, B, of MRI can be measured as shown in Figure 2.

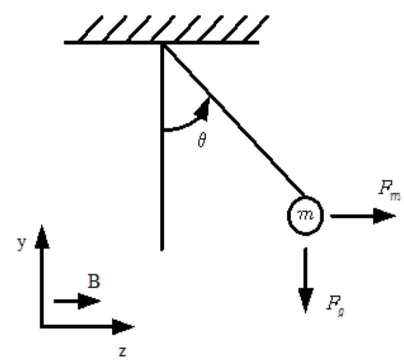


Figure 2. Analytical model of the deflection angle method for evaluation of translational force for an implantable electronic medical device in the MRI bore

Then, when magnetic material with mass, m, is under the gravity, g, and is affected by static magnetic field, B, along the z-axis of MRI, the deflection angle, θ, is measured and the force, F_m, is computed according to

$$F_m = mg\tan\theta. \tag{7}$$

2.2 Magnetic torque

Each magnetic field of permanent magnet and MRI is not placed in the same direction, the torque is generated. The torque is maximized in the condition of perpendicular each magnetic field. The patients using implantable hearing aid, are suffering according to increasing the torque [10]. Therefore, the torque is described to

$$T_m = mB\sin\theta, \tag{8}$$

where m is the magnetic moment. And the magnetic moment is described to

$$m = \frac{B_d V}{\mu_0 \mu_s}, \tag{9}$$

where B_d is magnetic flux density and V is the volume of the magnet. As shown in Figure 3, Christian et al. made experiments on magnetic torque [11].

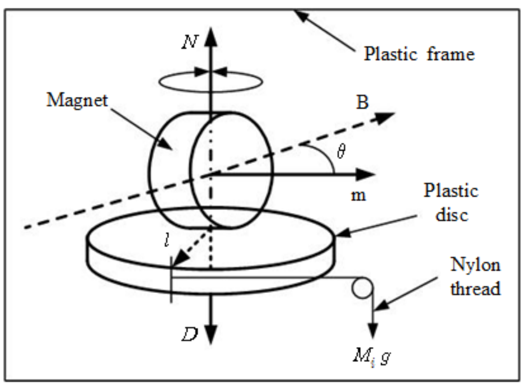


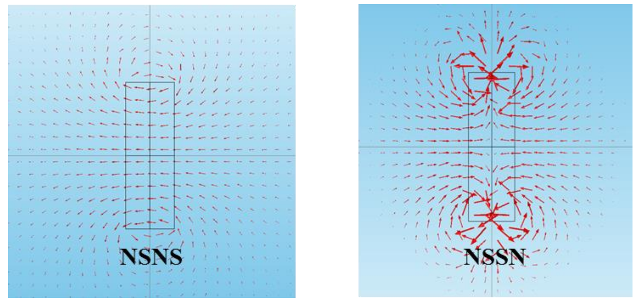
Figure 3. Schematic drawing of magnetic torque measurement [11]

The internal magnet having magnetic moment m with respect to the axis of rotation D, is fixed to the center of plastic disc. By hanging the weight with mass M_i at the point of distance l from the center of plastic disc, rotation of the disc is prevented. Thereafter, the magnet which is moved into MRI bore, is rotated at an angle of θ. At this time, the plastic disc is rotated with respect to the axis of rotation D, and the torque can be described to

$$N = M_i g \times l. \tag{10}$$

3. Magnetic coupler for medical implant

In this paper, we suggest a new coil align method, for transcutaneous inductive link in medical implant, which can reduce hazard to patient in MR image. The proposed 3-poles magnet has two cylindrical magnets which are coupled with same poles. The magnetic fields, generated from the 3-poles magnet, are symmetry with respect to facing surface as different to a normal dipole magnet. The magnetic field lines of 3-poles and dipole magnet are illustrated in Figure 4.



(a) (b)

Figure 4. Distribution of magnetic field lines of each magnet; (a) dipole (NSNS) magnet and (b) 3-poles (SNNS) magnet

A magnetic substance is forced on gravity, repulsion and torque, if there are in external magnetic fields such as MRI. Figure 5 shows induced force on each magnet structure in external magnetic fields. In the condition of external magnetic fields (B) existence (see Figure 5), induced forces of each magnet's pole-face are represented as F_1, F_2, F_3, and F_4. In the dipole magnet's center of gravity, the forces effect on M_1 and M_2 are same with counter clockwise. So, total induced force on dipole magnet (F_{dipole}) is represented as

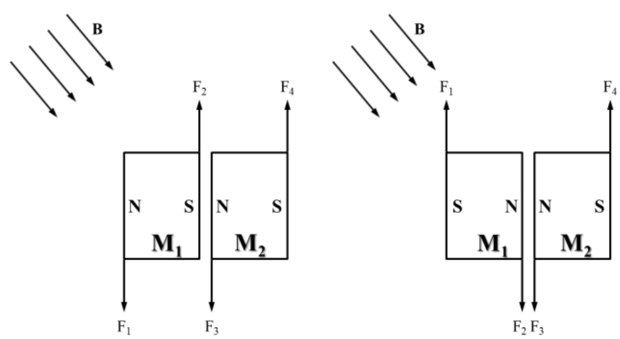


Figure 5. Directions of instantaneous force in the homogeneous magnetic field; (a) dipole (NSNS) magnet and (b) 3-poles (SNNS) magnet.

$$F_{M1} = F_1 + F_2 = F_{M2} = F_3 + F_4, \tag{11}$$

$$F_{dipole} = F_{M1} + F_{M2} = 2F_{M1}, \tag{12}$$

where F_{M1} and F_{M2} are induced force on magnet M_1 and M_2. But, in the 3-poles magnet's center of gravity, each force is canceled out because each magnet, component of 3-poles magnet, has opposite direction of force [12]. So, total induced force on 3-poles magnet ($F_{3\text{-poles}}$) are represented as

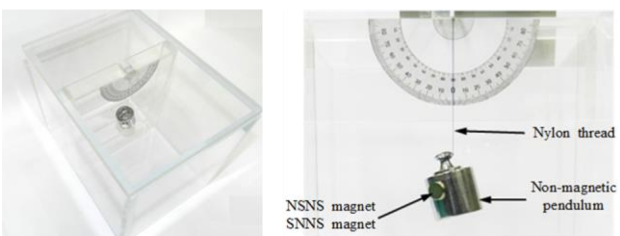
$$F_{M1} = F_1 + F_2 = -F_{M2} = F_3 + F_4, \quad (13)$$

$$F_{3\text{-poles}} = F_{M1} + F_{M2} = 0. \quad (14)$$

So, the suggested 3-poles magnet structure can reduce unnecessary force by external magnetic fields. But, magnetic fields from permanent magnet are not uniform, negligible induced force between external magnetic fields and 3-poles magnet.

4. Experiment and results

Induced force on magnet, by external magnetic fields, was investigated. The magnet was attached on nonmagnetic material and the material sets on protractor's center through lopped line. Experimental setup is in the acrylic case for protection. Lateral magnetic field was generated by using 1.5T MRI. The induced force was measured by angular variation refer to distance form isocenter of MRI bore to acrylic case. The experimental procedure refers to ASTM F2052 and the setup was shown in Figure 6.

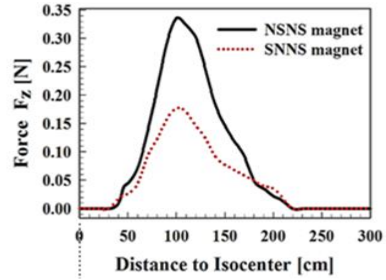


(a) (b)

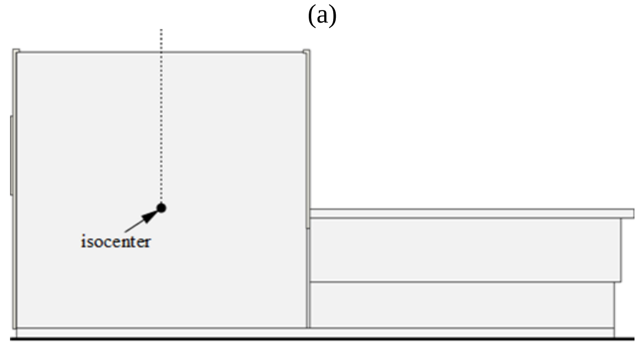
Figure 6. Experimental model for the pulling force measurement

Figure 7 shows gravity on dipole and 3-poles magnet, which are calculated from the measured angle and Eq. (7). The gravities are is almost zero around isocenter of MRI because there is absolutely high homogeneity of magnetic field. The gravity was observed from that acrylic case moves along the z-axis more than 40cm from the isocenter. In the case of dipole magnet, gravity was 0.336 N in 100 cm of distance. And, the gravity of 3-poles magnet was 0.177 N. More than 100 cm of distance, the gravity was decayed linearly.

Experimental setup for observing torque, which is induced on dipole and 3-poles magnet, referred to Christian et al. Rotation axis of magnets was aligned with rotating disc which has minimized fractional force (see Figure 8). The rotating disc was coupled with non-magnetic pendulum. The experimental setup was in the 1.5T MRI same as gravity experiment and torque of magnet can be calculated by measuring rotating angle and weight of pendulum. Measured weights of dipole and 3-pole magnet were 834 and 213 g, respectively. The torques of each magnet was calculated by Eq. (10) and the values were 0.0817 and 0.0208 N·m in the case of dipole and 3-poles magnet.

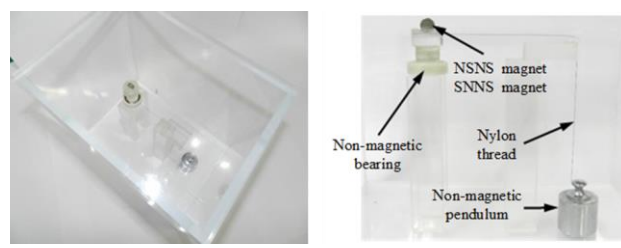


(a)



(b)

Figure 7. (a) Measurement result of pulling force for dipole magnet and 3-poles magnet in the MRI and (b) Schematic of MRI



(a) (b)

Figure 8. Experimental model for torque measurement

5. Conclusion

In this paper, a new magnetic coupler was proposed, which is different from general magnetic coupler aligning inductive link for medical implants. An implant part of the proposed magnetic coupler includes a pair of magnets and same polarity of each magnet was forcibly attached.

The proposed structure can theoretically cancel any force and torque by high electromagnetic field. Though patient implanted this magnetic coupler is exposed to MRI environment, surgical removal of magnetic coupler is unnecessary because the potential pain cannot be induced by movement of magnets.

To verify a function of the proposed structure, analysis and measurement of force and torque at 1.5T MRI were performed. Because the unwanted force and torque of the proposed 3 poles magnetic coupler are much smaller than the ordinary 2 poles magnet coupler, we predict that the previous magnetic coupler's defects will be effectively overcome.

Acknowledgements

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