Design and simulation of Helmholtz coil and Maxwell coil for low cost and low magnetic field MRI machine

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Abstract

Magnetic Resonance Imaging is a non-invasive technique which basically consists of a main magnet, gradients, radio-frequency transmitter and receiver and scanner. Commercially available MR scanners are quite heavy. However this bio-device can be made low cost, low weight and also low magnetic field. This work proposes the design and development of a low magnetic field MRI scanner of 0.2T magnetic field strength. This design is based on Helmholtz coil as the main magnet. The homogeneity observed within a radius of 15cm was about 2% in a coil of 30cm radius. While at the centre homogeneity was found much better. Strength of 75µT/m gradient magnetic field has been considered for the design. Maxwell coil has been used for longitudinal gradient and Saddle coil has been used for transverse gradient. The resonant frequency was obtained 8.516MHz for a main magnetic field of 0.2T for protons. Simulation results for magnetic flux density norm had been obtained for Helmholtz coil and Maxwell coil depicting the distribution of magnetic flux density. Also weight of the main magnet had been found to be quite less when compared with main magnet that are commercially used. Copyright © 2017 VBRI Press.

Keywords: Helmholtz coil, MRI, low-cost, low magnetic field, homogeneity, Maxwell coil.

Introduction

Magnetic Resonance Imaging, as the name suggests, is based on imaging for diagnosis purpose. Hence it is a non-invasive technique. The principle on which MRI (Magnetic Resonance Imaging) is based is known as Nuclear Magnetic Resonance. The foundation of this MRI technology began during the year 1946. Edward Purcell and Raymond Damadian are known as the founding fathers for their noted discoveries in this field. However first human being MRI was done in the year of 1977 [1]. Depending on the magnetic strength, MRI can be divided into Low-field MRI, Mid-field MRI or High-field MRI.

This paper presents a low field MRI machine. Usually for a low field MRI, the magnetic field intensity is below 0.5T. High field MRI gives good quality image because of good SNR. While images produced by low-field MRI may not be able to compete with high field MRI images, it is important to consider whether or not they can provide comparable diagnosis levels to justify their logistical benefits [2].

Tavernier and Cotton et al. stated that the primary limitation of low-field MRI is lower SNR, which has to be compensated for by increasing the slice thickness, reducing the in-plane resolution, increasing the number of acquisitions (and consecutively the acquisition time), and decreasing the bandwidth [3]. Tavernier and Cotton et al. concluded that implementation of low-field MRI systems may be useful, especially in orthopaedic centres, or if installation of an additional high-field scanner is not possible because of economic considerations [3]. Blanco et al showed that there is trade-off in image quality towards less resolution due to open structure of these systems [4]. The image quality of low-field scanners is, however, sufficient for interventional use. In a review article, Hayashi et al. noted that no reliable efficacy studies, however, exist comparing the diagnostic capabilities of low- versus high-field scanners [5]. In order to compensate for lower SNR, scanners with lowfield strength tend to have longer acquisition times, often resulting in greater image degradation due to patient movement. However, it is widely accepted that today's low-field scanners provide sufficient diagnostic information when spin-echo and gradient-echo techniques are used. Hayashi et al. conclude recent technological developments in the realm of low-field MR scanners will lead to higher image quality, shorter scan times, and refined imaging protocols [5]. Intervention and intraoperative use also supports the installation of low-field MR scanners. Utilization of low-field systems has the potential to enhance overall cost reductions with little or no loss of diagnostic performance.

Existing MRI machines are available that use permanent magnet as the main magnet. Permanent magnet with low magnetic field is quite heavy, weighing about 10,000 kgs [6]. In this design of MRI machine, Helmholtz coil is used in place of permanent magnet. Helmholtz coil gives good homogeneity that has been studied by Alvarez et. al. in the year 2010 and Zhan et. al. in the year 2015 [7,8]. Both these research group studied regarding the effect of geometry of the Helmholtz Coil on homogeneity and found the same results which indicated that square geometry gave better homogeneity than circular one. Copper is a better winding material for coils (as copper has better performance than any other metal like aluminium e.g. conductivity, low resistivity, good tensile strength, melting point etc.) as studied by Galvan et. al. in the year 2010 [9]. In spite of good homogeneity there may exist some inhomogeneities, especially when a particle or body is entered in to the field. That is why an additional gradient field is applied for getting good results. Research is still going on related to the design of gradient coil. Target Field method is the basis of gradient coil design for permanent magnet MRI machine that was studied by Guo-jun et.al. in 2006 [10]. The study indicated that Target field method can effectively be used to design gradient coils as well as shielded coils. S.S Hidalgo-Tobon in 2010 investigated on gradient coils on the basis of slew rate, current efficiency, linearity etc. and found that proper designing using recent techniques allowed decreased power consumption, heating, stored energy etc. and improves SNR and ROI [11]. Obtaining image from a MRI machine is the main aim of a MRI machine. Hence design of Radio-Frequency coil is one of the most important parts in designing a MRI machine. In 1997, Collins et. al. investigated on a 12-element birdcage coil at 125MHz and found that RF field strength and homogeneity is based on shield geometry [12]. Again in 2001 they studied RF fields as a function of frequency between 64 to 345 MHz on the basis of absorbed power and indicated that SNR slightly increases [13]. Michael Lang in 2011 constructed a 28.5mm birdcage resonator and compared with a 33mm resonator to observe 40% improved SNR [14].

This paper proposes a low magnetic field MRI machine using a pair of circular Helmholtz coil as the main magnet. Square coils will not be compact as compared to circular one and also can increase the weight to some extent. Due to that circular geometry was chosen. The magnetic field intensity is 0.2T at the centre of the pair of coils. The use of the Helmholtz Coil not only reduced the weight of the system but also reduced the cost of the system when compared to that of the permanent magnet MRI machine. For such a design, copper was chosen as the winding material. Since some inhomogeneities are purposefully introduced into the main magnetic field lines for getting better image, this linear variation of magnetic field is known as gradient field. The gradient field is varied linearly along the three axes. And the strength of the gradient field was considered as 75μT/m. For gradient field Maxwell Coil and Saddle Coil was used. The design of Radio-Frequency coil was considered with a low-pass Birdcage coil and for which the resonant frequency for the main magnetic field of 0.2T was obtained as 8.516MHz.

Material and methods

The design of the proposed MRI machine is based on Helmholtz Coil. Hence the design of Helmholtz Coil is an integral part. As well as the design of gradient coils and radi o-frequency coil is important. Gradient coil provide a linearly varying magnetic field which is essential for good quality image. Copper wires were chosen as winding materials for coils. The details on which the design of the coils is based are discussed here briefly.

Experimental Work

Helmholtz coil

According to Biot Savart's law**,**

$$B(x) = \frac{\mu_0 I n R^2}{2(R^2 + x^2)^{3/2}}$$

Here permeability constant $\mu_0 = 4\pi \times 10^{-7}$ Tm/A
I = current in coil (in Amperes)
R = radius of coil (in meters)
x = distance of a point from the coil on the axis (in meters)
n = number of turns of a coil

Based on Biot Savart's law, the magnetic field of Helmholtz coil at the centre is given by the expression below.

$$B(x) = \left(\frac{8}{5\sqrt{5}}\right)\frac{\mu_0 n I}{R}$$

This is the magnetic field strength generated at the center between the coils at a distance x=(R/2).

The design of the MRI machine has been done with an inner diameter of 40cm and outer diameter of 118cm. The inner diameter of the Helmholtz coil was taken 60cm. And the total number of turns obtained from Biot Savart's law is 6676 for a current of 10A. This much number of turns would be wound on a mould designed for Helmholtz coil. In order to make the system compact the length hole where the patient is to be put has been kept within 60cm. Hence the coil would have to be wound in multiple layers.

Homogeneity is calculated from the centre of the coil to any particular point. The homogeneity is measured in percentage change of magnetic field strength from the centre to any particular point. The formula [7] to calculate the homogeneity is given by equation 3,

$$H[\%] = \frac{B_i - B_0}{B_0} * 100$$

where B_0 = Magnetic field at the centre of the coils.
B_i = Magnetic field at another point within the volume.

Generally volumes of spheres or cylinders are considered to specify homogeneity. Here a sphere has been chosen to calculate homogeneity in the Helmholtz coil. From the homogeneity, the region of study can be predicted very well, thus defining the area where to place the patient.

Designing of Helmholtz coil

A Helmholtz coil is a parallel pair of identical circular coils separated at a distance equal to the radius of the coil and wound in such a manner that current flow in the same direction in both the coils. The Helmholtz coils produce a uniform magnetic field between the coils. The coil was designed and built in COMSOL Multiphysics. A solid 3D model (finite element model) of Helmholtz coil was generated having a radius of 30cm. The material of Helmholtz coil was considered as copper. A spherical domain of radius 70cm was created to study the effect of magnetic flux density. Surrounding domain was considered as air. Meshing was done using tetrahedral element. Then multi-turn coil domain was chosen as the boundary condition where current (10A) and number of turns (6676) were given as input. Stationary study was performed to obtain magnetic flux density norm. **Fig. 1** shows the 3-dimensional model of the proposed design. **Fig. 2** shows the solid model of Helmholtz coil generated in COMSOL multiphysics.

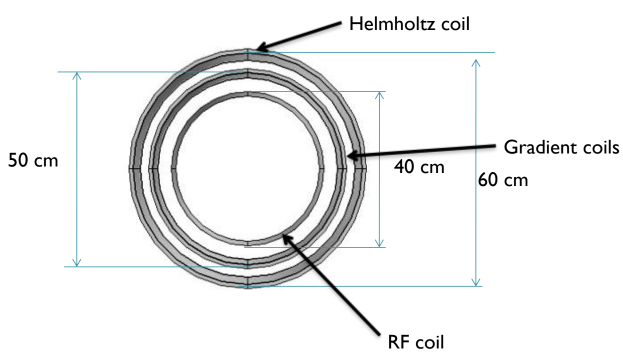

Fig. 1. 3-dimensional model of the proposed design.

This model of Helmholtz coil for low cost and low magnetic field MRI system was simulated for the analysis of magnetic field generated by the coils, magnetic flux density and homogeneity. The results are displayed in the results and discussion section.

Designing of gradient coils

Gradient coils provide spatial information in a MR system. This linearly varying gradient field is provided by gradient coils. The basic equation [11] for gradient magnetic field is given by,

$$B_z(x,y,z) = B_0 + \frac{\partial B_z}{\partial x}x + \frac{\partial B_z}{\partial y}y + \frac{\partial B_z}{\partial z}z$$
$$= B_0 + G_x x + G_y y + G_z z$$

where G_x and G_y is the transverse gradient and G_z is the longitudinal gradient.

Maxwell coil was used for the designing of longitudinal gradient and Saddle coil was used for transverse gradient. The basic equation for Maxwell coil is,

$$B = \frac{\mu_0 I a^2}{2} \frac{1}{\left(\left(\frac{d}{2} - z\right)^2 + a^2\right)^{\frac{3}{2}}} - \frac{1}{\left(\left(\frac{d}{2} - z\right)^2 + a^2\right)^{\frac{3}{2}}}$$

Here permeability constant $\mu_0 = 4\pi \times 10^{-7}$ Tm/A
I = current in coil (in Amperes)
a = radius of coil (in meters)
z = distance of a point from the coil on the axis (in meters)
d = distance between the coils

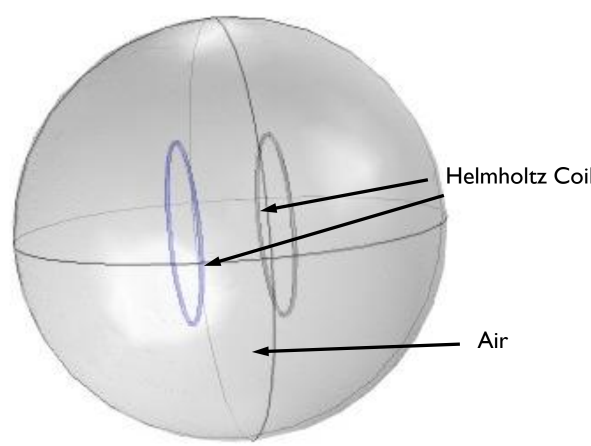

Fig. 2. Solid model of Helmholtz coil.

This equation has been plotted in MATLAB environment from where the slope of the gradient was obtained keeping current and radius as the independent variable. With a current of 5A and radius of coil as 25cm, the gradient strength obtained as 75µT/m. The Maxwell coil has been designed and built in the same way as the Helmholtz coil in COMSOL Multiphysics to obtain the magnetic flux density distribution. Lastly, a low-pass Birdcage coil has been considered for the radio-frequency trans-receiver unit with a radius of 20cm.

Results and discussion

The Helmholtz coil design was simulated in COMSOL Multiphysics for analysis of magnetic flux density norm distribution. The results are given here. **Fig. 3** shows the magnetic flux density distribution having unit Tesla. From the distribution graph it is clear that at the centre the magnetic flux was near about 0.2T (0.178T to be exact). When going outwards the coil the magnitude of flux is found to decrease. From the simulation homogeneity was also determined in terms of percentage. The colour code from the flux distribution graph also makes it clear that within the coil the magnetic field is uniform and hence homogeneous. A graph of homogeneity is shown here which depicts the homogeneity of the magnetic field in the domain of study. The variation of homogeneity in the domain of study is more clearly seen from **Fig. 4**. Also when compared to the commercially available MRI that use permanent magnet as the main magnet, the weight has been found to reduce to a great extent. While the commercially available permanent magnets weigh near about 10,000 to 12,000 kgs, the proposed design using Helmholtz coil as the main magnet it weighs 1390 kgs.

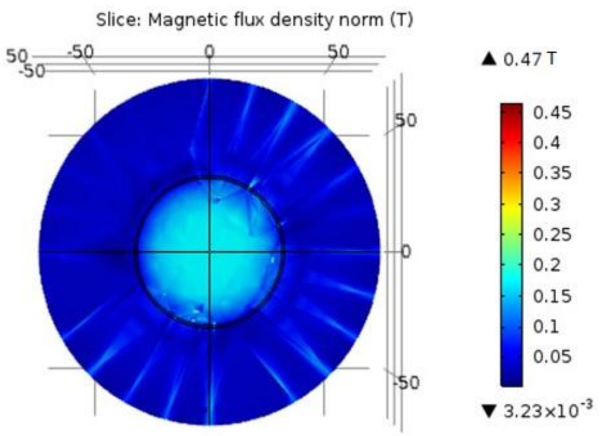

Fig. 3. Distribution of magnetic flux density for Helmholtz coil.

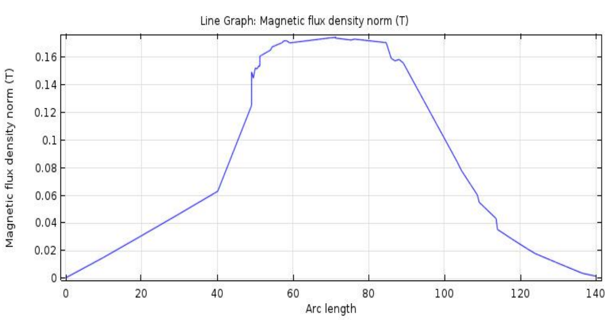

Fig. 4. Homogeneity of Helmholtz coil in the region of study.

Table 1. Homogeneity obtained from different points within the coil.

Radius(cm)	Homogeneity(%)
4.29	0.33
11.5	0.48
11.85	0.47
12.9	1.8
14.53	2.63
25.85	39

Regarding the simulation of Maxwell coil for obtaining magnetic flux density norm, it has been done in the same way as the Helmholtz coil but here the current in both the coils is in opposite direction having the same magnitude. The simulation result is shown in **Fig. 5**. From the simulation result it can be clearly observed that the magnetic field intensity varies from the centre of the coil to outwards. The colour bar represents the same. And the gradient field strength obtained from the MATLAB plot has been shown in **Fig. 6**.

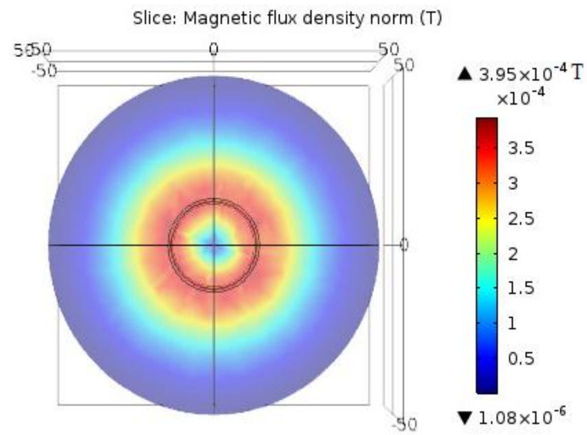

Fig. 5. Magnetic flux density distribution of the Maxwell coil.

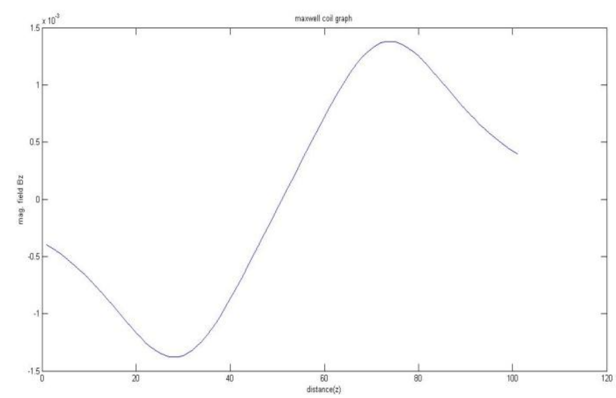

Fig. 6. MATLAB plot for obtaining gradient strength.

Conclusion

A MRI machine can be implemented using Helmholtz coil as the main magnet. Homogeneity is the main concern for the main magnetic field, but as because Helmholtz coil gives good homogeneity within the coil; it can be used in place of permanent magnet. For low magnetic field of 0.2T, a gradient strength of 75µT/m would be used to observe the quality of image obtained from it. The Maxwell coil is simulated for magnetic flux density to observe the variation of the gradient magnetic field and hence the slope is verified. In order to provide diagnostic support at the point of care, the MRI is proposed to be of sufficient small weight, because of which Helmholtz coil instead of permanent magnet is proposed to be used to generate the main magnetic field.

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