

# Electromagnetic Field Simulation of Helmholtz Coils for Biological Applications

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## Abstract

This study performs an electromagnetic simulation of Helmholtz coil configurations designed to generate low-frequency magnetic fields for pulsed electromagnetic field therapy. Using COMSOL Multiphysics®, a coil design is developed to produce magnetic flux densities of  $\sim 2$  mT, like those in therapeutic magnetic stimulators. The simulation environment is modeled with air alone, allowing for the examination of the magnetic field's distribution, uniformity, and decay over distance in free space. The results offer a conceptual insight into how coil shape, the number of turns, and the distance from the coil's center influence magnetic flux density and uniformity, supporting the design and optimization of low-frequency magnetic stimulation coils.

**Keywords:** Magnetic field modeling, COMSOL Multiphysics®, PEMF, low-frequency coils, biomedical simulation.

## Introduction

Most people will have at least one bone fracture in their lives, making it one of the most common medical conditions. The complicated process of bone healing is made more difficult in elderly individuals by various factors, including general health, the type of fracture, and the presence of infection. Due to decreased cellular activity, poor blood flow, and age-related health problems, healing is frequently slower in the elderly. Due to discomfort, restricted mobility, and increased dependence, this prolonged recovery period can seriously lower the quality of life [1].

As people age, their risk of developing bone and joint issues increases significantly. Osteoporosis is a common degenerative disease that weakens bones by increasing their brittleness and thereby increasing the risk of fractures. It is characterized by structural deterioration and a decrease in bone mineral density. In addition to damaging bones and joints, metabolic illnesses like gout can cause inflammation that limits movement. Older adults are more vulnerable to serious side effects from invasive or surgical procedures because of their frail bones and slow wound healing. Therefore, it is essential to find safe, non-invasive treatments that promote bone healing [1].

About 60% inorganic minerals, mostly hydroxyapatite, 30% organic matrix, mostly type I collagen, and 10% water make up bone tissue. The organic matrix is crucial for maintaining the strength and flexibility of the bone, providing a framework for the deposition of minerals. Osteoblasts, which generate collagen and enzymes such as osteocalcin (OCN) and alkaline phosphatase (ALP), are primarily responsible for the regeneration process. These materials are necessary for bone remodeling and mineralization. According to several studies,

electromagnetic stimulation may promote osteoblast activity, thereby enhancing bone development and increasing levels of osteogenic markers [1].

Low-frequency electromagnetic fields have been studied as a non-invasive method to influence osteoblast activity. Many effects of these fields on proliferation and differentiation are mediated through intracellular calcium signaling. Although low-intensity fields appear promising for enhancing bone formation, the roles of coil design, field strength, and spatial distribution remain unclear [2]. Lennart et al. [1] demonstrated osteoblastogenesis and enhanced mineralization production for the first time, offering potential clinical applications in fracture healing through Extracorporeal Magnetotransduction Therapy (EMTT). Although the support of electromagnetic fields for bone healing remains poorly understood to date. Nismayanti et al. [2] demonstrated PEMF simulations using a Helmholtz coil and generated a magnetic field of 1.5 mT with 150 turns. Authors have also demonstrated the effect of current on the magnetic field, as well as the influence of different coil diameters and the distance between the coils. This study focuses on modeling low-frequency electromagnetic fields generated by circular air-core coils at 10 Hz. COMSOL simulations and Biot-Savart calculations are employed to assess magnetic flux density and uniformity for various coil geometries in Pulsed Electromagnetic Field (PEMF) therapy. A portable, easy-to-use, and low-power therapy device is desirable for home application.

## Theory and Numerical Model

The analysis was carried out in COMSOL Multiphysics® using the Magnetic Fields interface. The excitation frequency (10 Hz) is far below the electromagnetic wave regime; thus, the system can be treated as a magneto quasi-static system

(below 1 kHz). This enables accurate evaluation of the magnetic field distribution without considering wave propagation or radiation effects.

A pair of identical circular coils was modeled in the Helmholtz configuration, as shown in Figure 1. Each coil had a radius of 0.05 m, and the separation between the coils was also set to 0.1 m.

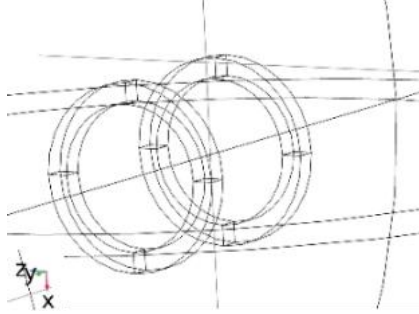


Figure 1: COMSOL model of a Helmholtz coil with a radius of 0.05 m, a distance between the two coils of 0.1 m, and 200 turns.

The coil cross-section was approximated as a square region of  $0.0125 \text{ m} \times 0.0125 \text{ m}$  ( $1.25 \text{ cm}^2$ ), representing bundled copper windings. The number of turns  $N$  varied between 50 and 200 in different simulations. The coils were excited with a sinusoidal current of 20 A at 10 Hz. Copper material was applied to the coil domain ( $\sigma = 6e7 \text{ S/m}$ ) and  $\mu_r = 1$ . The surrounding air domain was modeled as a sphere with a radius of 0.325 m to avoid boundary interference. The mesh was refined near the coil and tissue region, and the study was solved in the frequency domain.

## Results and Discussion

Magnetic flux density was evaluated at the center of the XZ-plane between the coils and at several

distances from the center of both coils and in the Y direction, as shown in Figure 2 and 3. Magnetic flux densities of 35.60 mT, 54.77 mT, and 19.43 mT were simulated at the center of the coils, at distances of 0.05 m and 0.1 m from the center of both coils, respectively, illustrated in Figure 2.

The computed magnetic flux density (B-field) exhibits strong localization at the coil, which is placed at 0.05 m (represented by the orange dotted line in the plot), with a maximum amplitude of approximately 13.62 mT (50 turns), as illustrated in Figure 3(A). The field at 0.125 m (from the center of the Helmholtz coil (HC) configuration) is  $\sim 2.2 \text{ mT}$ , which is comparable to a pulsed electromagnetic field (PEMF), i.e., the field required for therapy. Whereas, with an increasing number of turns, the magnetic field increases to  $\sim 8.4 \text{ mT}$  for the same distance, i.e., 0.125 m, and with 200 turns. The magnetic field strength increases proportionally with turn count. With a higher number of turns, i.e., 200, the magnetic field of  $\sim 2 \text{ mT}$  is also evaluated by varying the position from the center of the coils, such as at  $\sim 0.2 \text{ m}$  from the center of the HC configuration. These results are consistent with analytical estimates from the Biot-Savart law and provide a realistic prediction for experimental prototypes. The observed mT-level fields are comparable to those reported in recent PEMF studies, sufficient to affect superficial tissue zones without significant heating.

The spatial distribution of the magnetic field was also estimated along the XZ plane, at the center of the Helmholtz coil configuration, as illustrated in Figure 3(B). The intensity is higher at the center and then decreases at the edges of the coil, representing the uniformity of the field distribution.

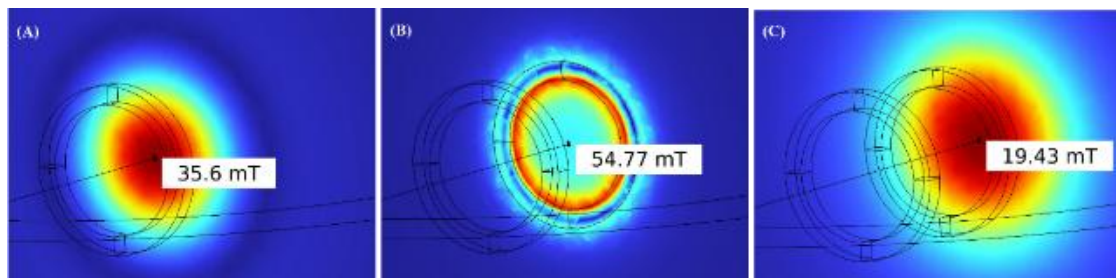


Figure 2: (A-C) Magnetic field intensity (mT) in XZ plane with 200 turns at different distances from center: (B) at center; (C) at 0.05 m; (D) at 0.1 m.

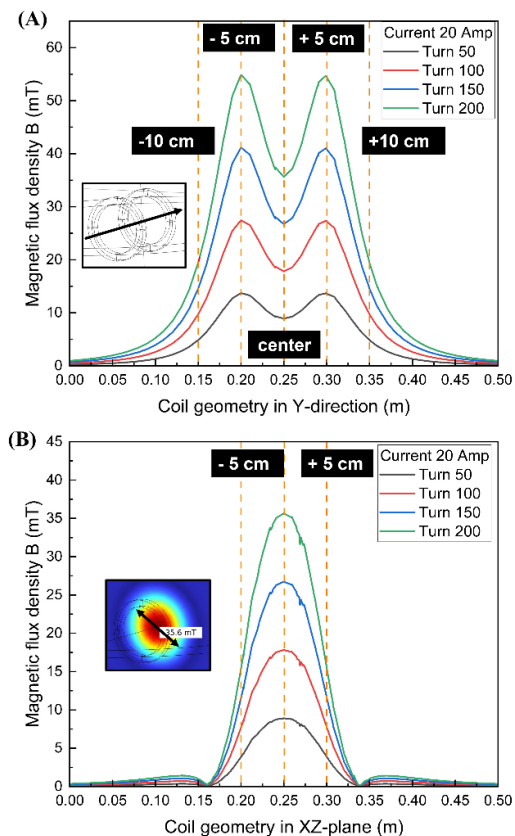


Figure 3: Magnetic Field along: (A) Y direction; (B) XZ plane. The dotted line represents the position of the coil.

## Conclusions

This work examined how coil geometry, turn count, and drive current influence low-frequency magnetic fields using a simple Helmholtz setup. The simulations yielded predictable and consistent results, providing a practical starting point for developing portable PEMF devices intended for biological use. Further work will include refining the coil design, adding tissue models, and experimentally confirming the fields.

## References

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