Cumhuriyet Sci. J., 45(3) (2024) 578-584
DOI: https://doi.org/10.17776/csj.1453508

Cumhuriyet Science Journal

| csj.cumhuriyet.edu.tr | Founded: 2002 ISSN: 2587-2680 e-ISSN: 2587-246X Publisher: Sivas Cumhuriyet University

Static Magnetic Field Focusing with Neodymium Magnets for Wound Healing: A Numerical Study

Elif Feyza Aydın [1,a], Reyhan Zengin [1,b,*]

[1] *Department of Biomedical Engineering, Faculty of Engineering, İnönü University, Malatya, Türkiye.*
**Corresponding author*

Research Article

History
Received: 15/03/2024
Accepted: 16/09/2024

ABSTRACT

Static magnetic fields (SMFs) find widespread applications in diverse scientific, technological, and medical domains. This study explores the potential of neodymium permanent magnets in focusing and controlling SMFs, specifically emphasizing wound healing applications. Numerical simulations using COMSOL Multiphysics create a uniform static magnetic field for wound healing. The study systematically increases the number of neodymium magnets, demonstrating enhanced magnetic flux density and a focused magnetic field. The results affirm the efficacy of neodymium magnets in generating a uniform static magnetic field between 190-620 m Tesla. This research proposes neodymium permanent magnets as a promising tool for wound healing applications, offering a non-invasive and focused therapeutic approach. While the study provides valuable insights, further experimental and clinical validations are necessary to establish the real-world efficacy of this method. The work contributes to the evolving understanding of static magnetic fields as a viable therapeutic modality for various medical conditions, particularly in the context of wound healing.

Keywords: Static magnetic fields, Wound healing, Neodymium permanent magnets.

[a] *elifeyza97@hotmail.com* *https://orcid.org/0009-0008-3743-6672*
[b] *reyhan.zengin@inonu.edu.tr* *https://orcid.org/0000-0001-8631-3339*

Introduction

Static magnetic fields (SMFs) have extensive applications in contemporary science and technology, as well as in industrial, agricultural, medical, and healthcare sectors, among other fields [1]. Static magnetic fields are essential in numerous fields, including but not limited to applications like magnetic resonance imaging (MRI) [2], transcranial magnetic stimulation [3], control of magnetic nanoparticles for gene and drug delivery [4,5], and the development of magnetic sensors [6]. Higher static magnetic fields facilitate the advancement of these applications. There are two distinct approaches to enhancing static magnetic fields: one aims to amplify them over a wide free space, potentially enhancing spatial resolution in MRI applications. The other concentrates on intensifying static magnetic fields within a confined space, enhancing sensitivity in magnetic sensors, and advancing the application of magnetic nanoparticles in gene and drug delivery [1]. Magnetic fields are increasingly utilized in diverse bioengineering and biomedical applications, offering significant advantages in lower patient invasiveness, especially regarding non-ionizing radiations. The non-magnetic nature of human tissues allows magnetic fields to penetrate without attenuation, distinguishing them from electric fields. This property is harnessed in various diagnostic and therapeutic methods, including Magnetic Resonance Imaging (MRI), Magnetic Fluid Hyperthermia (MFH) for hyperthermia and thermoablation with magnetic nanoparticles, and Transcranial Magnetic Stimulation (TMS). In MRI, a homogeneous magnetic field is crucial for imaging various pathologies across different anatomical regions, requiring a larger field of view (FOV). Conversely, in Magnetic Fluid Hyperthermia (MFH), the focused magnetic field induces localized heating for cancer therapy, aiming to preserve surrounding tissue. Similarly, in Transcranial Magnetic Stimulation (TMS), focusing the induced electric field within the brain enhances procedure effectiveness and accuracy and reduces patient invasiveness. The challenge lies in generating the desired magnetic distribution due to diffraction and attenuation phenomena, especially at lower frequencies, prompting research into technologies for optimizing and controlling this aspect [7]. The literature has documented various radiation configurations capable of manipulating diverse magnetic fields, representing significant advancements in this field. Volume, Helmholtz, and Birdcage Coils generate and focus magnetic fields for various applications. Volume Coils offer advantages such as medium homogeneity, scalability in terms of geometry, and high efficiency. However, a notable drawback is that their length must be greater than the solenoid section [8, 12-15, 16, 17]. On the other hand, Helmholtz coils provide a very homogeneous field but come with the disadvantage of poor efficiency [9,10,11]. Birdcage coils are characterized by their ability to generate circular or linear homogeneous fields, but their design complexity is a notable drawback [18,19].

In contemporary research, there is significant interest in utilizing neodymium permanent magnets to focus and control static magnetic fields. Their capacity to concentrate magnetic fields presents potential advantages across diverse fields, from medical imaging systems to industrial applications. General Motors and

Hitachi collaborated in the 1980s to create neodymium-iron-boron magnets. Due to their ability to generate substantial magnetic force with minimal material, these magnets have gained significance in producing robust permanent magnets composed of rare earth elements. In information technology, neodymium magnets find specific applications in hard disc drives, mobile phones, and television audio and video systems [20]. Neodymium magnets find application in the health sector, integrated into medical devices like magnetic resonance imaging (MRI) machines used for diagnosing and treating various conditions such as chronic pain syndrome, arthritis, wound healing, insomnia, headaches, and other diseases, owing to their capacity to generate a static magnetic field. Over the past decade, there has been a notable rise in their utilization [21].

The static magnetic field (SMF) emerges as a viable and non-invasive therapeutic approach with potential advantages [22-24]. Despite having less robust support in scientific literature, magnets have been utilized in alternative medicine to expedite the healing process and alleviate pain. Limited data indicates three potential mechanisms underlying the effectiveness of static magnetic fields (SMF): 1) an anti-inflammatory impact; 2) assistance in endothelial cell proliferation; 3) stimulation of collagen formation [25]. SMFs are recognized as powerful promoters of cell proliferation, migration, and differentiation, hastening the differentiation of osteoblast-like cells in laboratory settings [23].

Recent studies suggest that exposure to static magnetic fields (SMF) can affect the release of inflammatory cytokines by macrophages and lymphocytes [26]. The US FDA has approved SMF for the treatment of pain and edema, confirming its impact on cell metabolism and proliferation [27]. Prolonged exposure to SMF has shown potential in controlling hypertension [28] and has produced positive results in the treatment of osteoarthritis and nonunion fractures [27, 29, 30].

Research findings indicate that a static magnetic field of 220 mT enhanced the recovery rate in normal rats [25]. More recent investigations have delved into the effects of a 230 mT static magnetic field generated by a permanent NeFeB magnet on cutaneous wound healing in diabetic rats [24]. Additionally, a study conducted in 2016 demonstrated accelerated wound healing in rats by applying a pulsed electromagnetic field (PEMF) signal using a Helmholtz coil at a frequency of 75 Hz and a magnetic field intensity of 1 mT. This effect was observed when combined with pulsed radiofrequency energy (PRFE) at a carrier frequency of 27.12 MHz [31].

Furthermore, current studies have noted that a moderate-intensity static magnetic field (0.6 T) notably enhances the healing of wounds in a mouse model of type 2 diabetes. Even field strengths below 180-230 mT have demonstrated positive effects on healing streptozotocin-induced diabetic wounds in mice [32].

In this research, we examined the focusing of static magnetic fields using permanent neodymium magnets for applications in wound healing. Numerical simulations were employed to generate a uniform static magnetic field, specifically between neodymium magnets positioned at defined distances, to achieve optimal focus.

Materials and Methods

Static magnetic field theory

Static magnetic fields occur from either permanent magnets or direct current (DC) flow in conductive materials. The Biot-Savart law defines the contribution of a magnetic field (d**B**) created by a small wire segment of length **(dL)** carrying a current (**I**) as follows [33]:

$$d\boldsymbol{B} = \frac{\mu I\, d\boldsymbol{L}\times \boldsymbol{r}}{4\mu r^2} \qquad (1)$$

Here, **r** is the vector from the current element to the point where the field is being calculated, and μ represents the permeability of the medium. Equation (1) illustrates that the magnetic field is a vector circulating around the current element and decreases with the square of the distance from it. Integrating this law (Equation 1) enables the assessment of magnetic fields around structures carrying current, such as coils or electrical distribution networks.

Magnetic fields are identified by the force they exert on moving charges, such as those composing electric currents. The force (**F**) in newtons is proportional to the charge (q) in coulombs and velocity (**v**) in meters per second, and it is perpendicular to both the motion and the field direction. Mathematically, this relationship is expressed as:

$$\boldsymbol{F} = q(\boldsymbol{v} \times \boldsymbol{B}) \qquad (2)$$

The magnetic flux densities (**B**) are measured in tesla (T). The actual magnetic field strength (**H**) is quantified in amperes per meter (A m^{-1}) and is linked to magnetic flux density through

$$\boldsymbol{B} = \mu \boldsymbol{H} \qquad (3)$$

In materials without magnetic properties, such as air, permeability is equivalent to the permeability of free space (μ_0), defined as $4\pi\times10^{-7}$H m^{-1}**.**

Numerical Studies

Numerical analysis is often used to solve problems that may have complex or impossible analytical solutions. This study utilizes the numerical analysis program COMSOL Multiphysics based on the finite element method. This study aims to develop a uniform static magnetic field environment for wound healing techniques. Static magnetic fields have been produced in various ways in the past, but this study aims to concentrate a homogeneous static magnetic field on a specific region and create a setting that can be used in animal experiments with permanent magnets. Four neodymium magnets were positioned in Figure 1 to generate a uniform magnetic field. The dimensions of the magnets were chosen as 10 cm x 10 cm x 5 cm. The distance between the two magnets is 16 cm. In COMSOL, Magnetic Fields, No Currents module was selected as the Physics Module. The air environment that would contain the magnets was also modeled. Figure 2 (a) shows two selected domains subjected to magnetization in the y direction, and Figure 2 (b) shows two selected domains subjected to magnetization in the x direction. The mesh image for four magnets is shown in Figure 3.

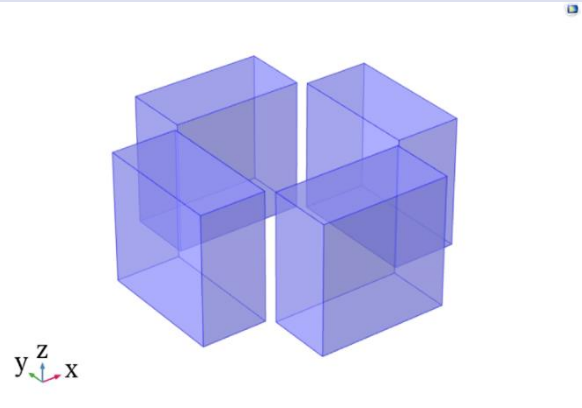
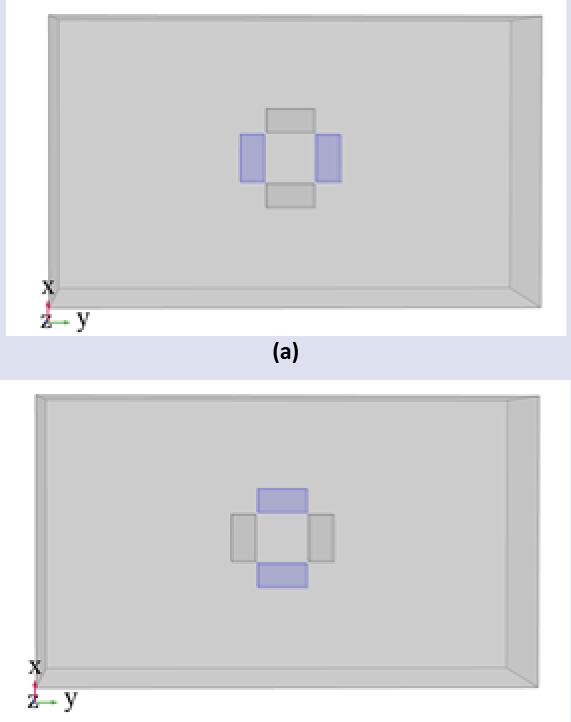


Figure 1. 3D geometry of neodymium magnets is arranged in a mutually facing configuration with four magnets focused. The dimensions of the magnets are 5 cm x 10 cm x 10 cm along the x, y, and z axes, respectively.



(a)

(b)

Figure 2. Selected areas for magnetization applied in the (a) y direction and (b) x direction.

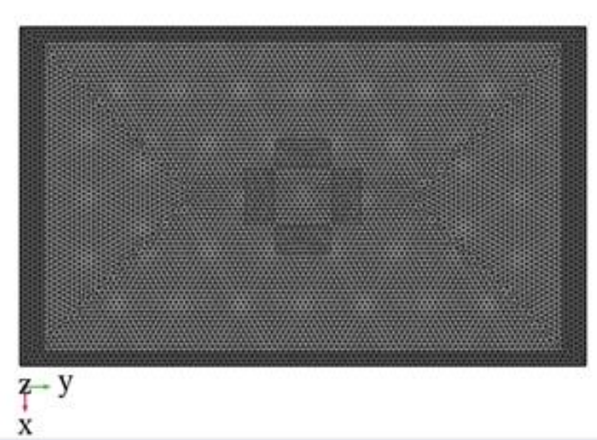


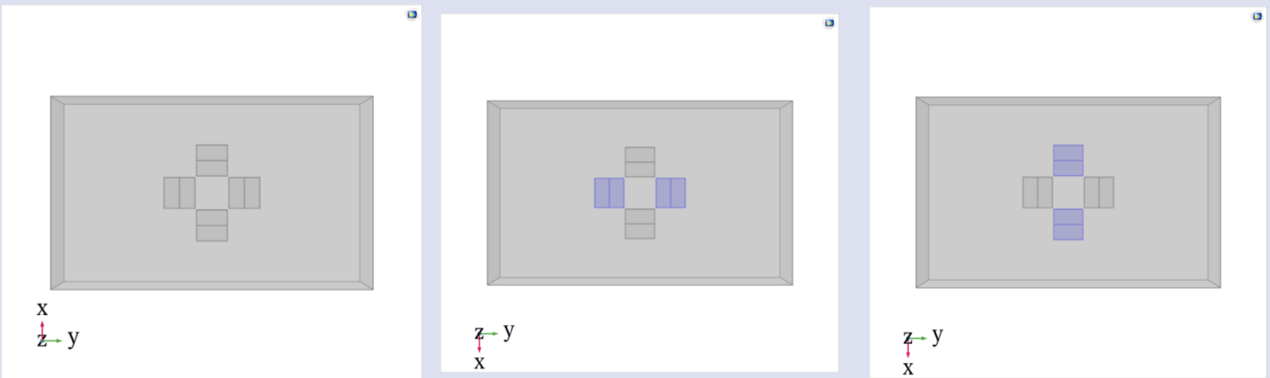
Figure 3. Mesh image of four magnets placed opposite each other.

The mesh consists of 6289137 domain elements, 77580 boundary elements, and 1326 edge elements. Each model takes approximately 148 seconds to run. We used a Free Tetrahedral element size with an extremely fine mesh structure. The mesh was highly detailed to achieve results as close to the actual outcome.

First, the edges of the rectangular structure surrounding the magnet, defined as air in Figure 2 and other figures, were set as boundary conditions. These boundary conditions were defined as Magnetic Insulation.

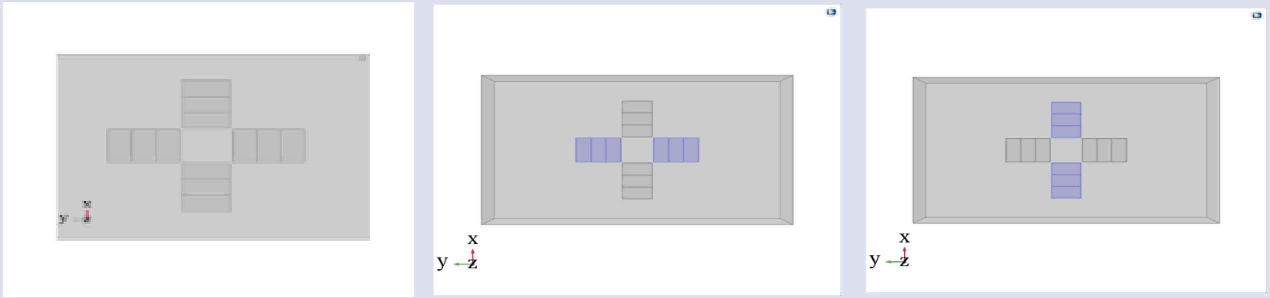
In Figure 4 (a), eight electrodes are modeled by adding one magnet behind each of the four magnets. The number of magnets was increased to increase the magnetic flux density value in the area between the magnets. Figure 4 (b) shows four selected domains that were subjected to magnetization in the y direction. Figure 4 (c) shows four selected domains that were subjected to magnetization in the x direction.

In Figure 5 (a), twelve electrodes are modeled by adding two magnets behind each of the four magnets. The number of magnets was increased to increase the magnetic flux density value in the area between the magnets. Figure 5 (b) shows six selected domains that were subjected to magnetization in the y direction. Figure 5 (c) shows six selected domains that were subjected to magnetization in the x direction.



(a) (b) (c)

Figure 4. (a) Two pairs of Neodymium magnets arranged in a mutually facing configuration with eight magnets focused, (b) Selected areas for magnetization applied in the y direction, (c) Selected areas for magnetization applied in the x direction.

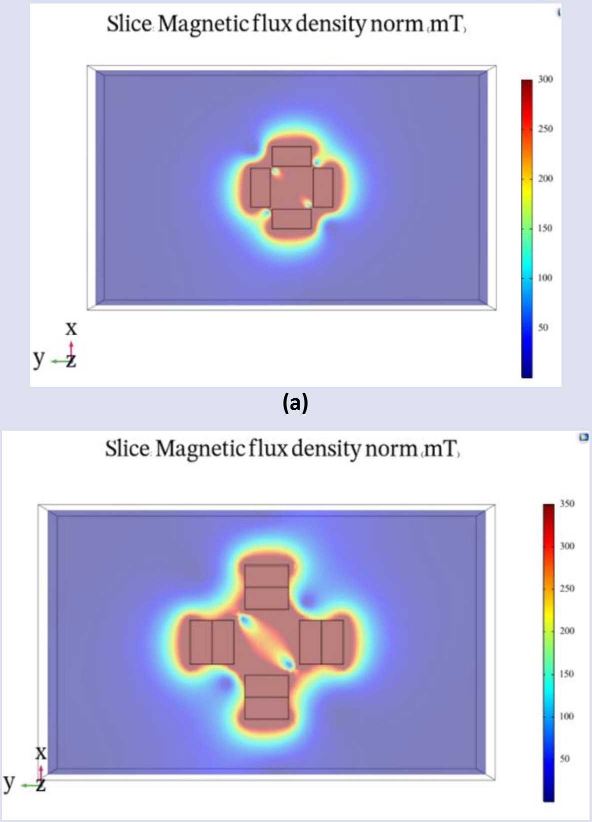


(a) b) (c)

Figure 5. (a) Triple pairs of Neodymium magnets are arranged with twelve magnets focused in a mutually facing configuration, (b) Selected areas for magnetization applied in the y direction, (c) Selected areas for magnetization applied in the x direction.

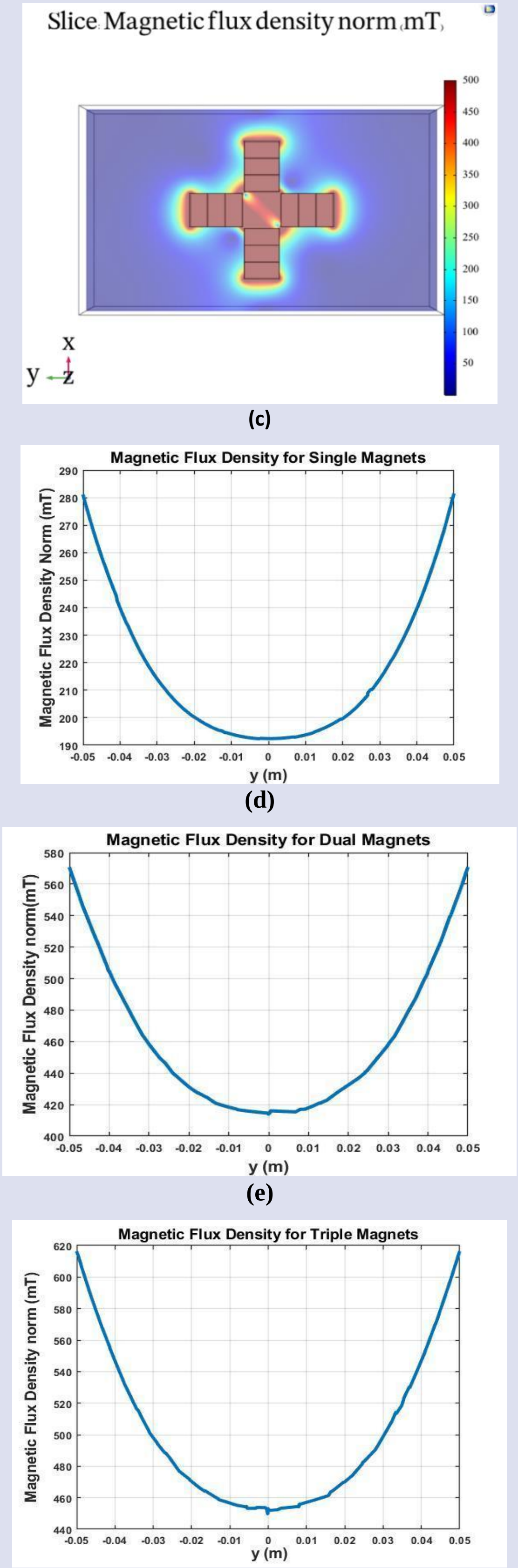
Results

Single, double, and triple permanent magnet groups were utilized to obtain static magnetic flux distributions focused on a wide area within the region between the magnets. These distributions are given in Figures 6 (a-c) for single, dual, and triple magnet configurations, respectively. Magnetic field changes were graphed as a 1D plot on a line passing through the center of opposing magnets. To compare these three configurations, a line graph showing the change in magnetic flux density value depending on distance is shown in Figure 6 (d-f). Figure 7 shows a line graph showing the change of magnetic flux density value depending on distance for comparison of all magnets.



(a)

(b)



(c)

(d)

(e)

(f)

Figure 6. Magnetic flux density distribution of (a) single magnets, (b) dual magnets, and (c) triple magnets. Line graph showing the change of magnetic flux density value depending on distance for single (d), dual (e), and triple (f) magnets.

.

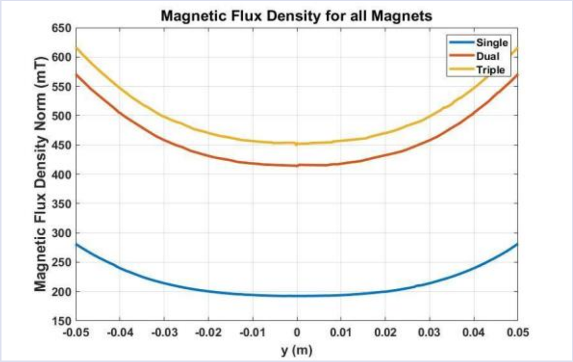


Figure 7. Line graph showing the change of magnetic flux density value depending on distance for comparison of all magnets.

Figure 6 and Figure 7 demonstrate that the SMF distribution ranges from 190-290 mTesla with a single magnet group in an area of approximately 10 cm^2 between the magnets. The SMF distribution with the dual magnet group is within the 400-580 mT range. With the triple magnet group, the SMF distribution is within the 440-620 mT range in a higher and wider area. As a result, increasing the number of magnets increased the magnetic flux density values.

Conclusions and Discussion

Static magnetic fields (SMFs) play a pivotal role in various scientific, technological, and medical applications, including magnetic resonance imaging (MRI), transcranial magnetic stimulation, and magnetic nanoparticle-based therapies. The ability to enhance and control static magnetic fields is crucial for advancing these applications. This study explored the utilization of neodymium permanent magnets to focus and control static magnetic fields, with a specific focus on wound healing applications.

The literature review highlighted the diverse applications of SMFs in bioengineering and biomedical fields, emphasizing their non-invasive nature and penetrative capability through human tissues. The study delved into the potential therapeutic benefits of SMFs, including anti-inflammatory effects, cell proliferation assistance, and collagen formation stimulation.

Numerical simulations using COMSOL Multiphysics were conducted to generate a uniform static magnetic field for wound healing. The study systematically increased the number of neodymium magnets to enhance magnetic flux density, resulting in a focused and homogeneous magnetic field. The numerical results demonstrated that increasing the number of magnets led to higher magnetic flux density values, emphasizing the effectiveness of the neodymium magnets in creating a uniform static magnetic field.

Overall, the findings suggest that neodymium permanent magnets hold promise for applications in wound healing, offering a non-invasive and focused approach to harnessing the therapeutic benefits of static magnetic fields. Further experimental validations and clinical studies are warranted to validate the efficacy of this approach in real-world medical scenarios. The study contributes to the ongoing exploration of static magnetic fields as a viable therapeutic modality with potential benefits for various medical conditions, including wound healing.

Conflict of interest

There are no conflicts of interest in this work.

Acknowledgement

The Scientific and Technological Research Council of Turkey (TÜBİTAK), project number 122E150, supports this study.

References

[1] Wang S., Zheng M., Lou C., Chen S., Guo H., Gao Y., Lv H., Yuan X., Zhang X., Shang P. , Evaluating the biological safety on mice at 16 T static magnetic field with 700 MHz radio-frequency electromagnetic field, *Ecotoxicology and Environmental Safety*, 230 113125 (2021).

[2] Brown M. A., Semelka R. C. , MRI: Basic Principles and Applications, *Wiley-Blackwell*, (2010).

[3] Kobayashi M., Pascual-Leone A., Transcranial magnetic stimulation in neurology, *Lancet Neurology*, 2(3) (2003) 145–156.

[4] Veiseh O., Gunn J. W., Zhang M., Design and fabrication of magnetic nanoparticles for targeted drug delivery and imaging, *Advanced Drug Delivery Reviews*, 62(3) (2010) 284–304.

[5] Dobson J., Magnetic micro- and nano-particle-based targeting for drug and gene delivery, *Nanomedicine*, 1(1) (2006) 31–37.

[6] Ripka P., Janosek M. , Advances in magnetic field sensors, *IEEE Sensors Journal*, 10(6) (2010) 1108–1116.

[7] Rotundo S., Brizi D., Flori A., Giovannetti G., Menichetti L., Monorchio A., Shaping and Focusing Magnetic Field in the Human Body: State-of-the-Art and Promising Technologies, *Sensors*, 22(14) (2022) 5132.

[8] Stauffer P. R., Sneed P. K., Hashemi H., Phillips T. L. , Practical induction heating coil designs for clinical hyperthermia with ferromagnetic implants, *IEEE Transactions on Biomedical Engineering*, 41 (1994) 17–28.

[9] Nemkov V., Ruffini R., Goldstein R., Jackowski J., DeWeese T. L., Ivkov R. , Magnetic field generating inductor for cancer hyperthermia research, *COMPEL - The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, 30(5) (2011).

[10] Nieskoski M. D., Trembly B. S., Comparison of a single optimized coil and a Helmholtz pair for magnetic nanoparticle hyperthermia, *IEEE Transactions on Biomedical Engineering*, 61 (2014) 1642–1650.

[11] Hadadian Y., Azimbagirad M., Navas E. A., Pavan T. Z., A versatile induction heating system for magnetic hyperthermia studies under different experimental conditions, *Review of Scientific Instruments*, 90 (2019) 074701.

[12] Cano M. E., Barrera A., Estrada J. C., Hernandez A., Cordova T., An induction heater device for studies of magnetic hyperthermia and specific absorption ratio measurements, *Review of Scientific Instruments*, 82 (2011) 114904.

[13] Mazon E. E., Sámano A. H., Calleja H., Quintero L. H., Paz J. A., Cano M. E., A frequency tuner for resonant inverters suitable for magnetic hyperthermia applications, *Measurement Science and Technology*, 28 (2017) 095901.

[14] Brizi D., Fontana N., Giovannetti G., Flori A., Menichetti L., Doumett S., Baldi G., Monorchio A., A novel approach for determining the electromagnetic properties of a colloidal fluid with magnetic nanoparticles for hyperthermia applications, *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, 2 (2018) 70–77.

[15] Di Barba P., Dughiero F., Sieni E. , Magnetic field synthesis in the design of inductors for magnetic fluid hyperthermia, *IEEE Transactions on Magnetics*, 46, (2010) 2931–2934.

[16] Frijia F., Flori A., Giovannetti G., Design, simulation, and test of surface and volume radio frequency coils for 13C magnetic resonance imaging and spectroscopy, *Review of Scientific Instruments*, 92 (2021) 081402.

[17] Bordelon D. E., Goldstein R. C., Nemkov V. S., Kumar A., Jackowski J. K., DeWeese T. L., Ivkov R., Modified solenoid coil that efficiently produces high amplitude AC magnetic fields with enhanced uniformity for biomedical applications, *IEEE Transactions on Magnetics*, 48 (2011) 47–52.

[18] Gresits I., Thuróczy G., Sági O., Gyüre-Garami B., Márkus B. G., Simon F., Non-calorimetric determination of absorbed power during magnetic nanoparticle based hyperthermia, *Scientific Reports*, 8, (2018) 1–9.

[19] Giovannetti G., Landini L., Santarelli M. F., Positano V., A fast and accurate simulator for the design of birdcage coils in MRI, *Magnetic Resonance Materials in Physics, Biology and Medicine*, 15 (2002) 36–44.

[20] Du X., Graedel T. E., Global rare earth in-use stocks in NdFeB permanent magnets, *Journal of Industrial Ecology*, 15 (2011) 836–843.

[21] Colbert A. P., Wahbeh H., Harling N., Connelly E., Schiffke H. C., Forsten C., William L. G., Marko S. M., James J. S., Patricia E., Valerie K., Static magnetic field therapy: a critical review of treatment parameters, *Evidence-Based Complementary and Alternative Medicine*, 6 (2009) 133–139.

[22] Lim K. T., Cho C. S., Choung Y. H., Influence of static magnetic field stimulation on cells for tissue engineering, *Tissue Engineering and Regenerative Medicine*, 6(1–3) (2009) 250–258.

[23] Yun H. M., Ahn S. J., Park K. R., Magnetic nanocomposite scaffolds combined with static magnetic field in the stimulation of osteoblastic differentiation and bone formation, *Biomaterials*, 85 (2016) 88–98.

[24] Zhao J., Li Y., Deng K., Yun P., Gong Y., Therapeutic Effects of Static Magnetic Field on Wound Healing in Diabetic Rats, *Journal of Diabetes Research*, (1-3) (2017) 1–5.

[25] Henry S. L., Concannon M. J., Yee G. J., The Effect of Magnetic Fields on Wound Healing Experimental Study and Review of the Literature, *Eplasty*, 8, (2008) e40.

[26] Vergallo C., Dini L., Szamosvölgyi Z., Tenuzzo B. A., Carata E., Panzarini E., László J., In Vitro Analysis of the Anti-Inflammatory Effect of Inhomogeneous Static Magnetic Field-Exposure on Human Macrophages and Lymphocytes, *PLoS One*, 8(8) (2013).

[27] Zhang L., Wang J., Wang H., Wang W., Li Z., Liu J., Zhang X., Moderate and strong static magnetic fields directly affect EGFR kinase domain orientation to inhibit cancer cell proliferation, *Oncotarget*, 7(27) (2016) 41527–41539.

[28] Tasić T., Djordjević D., De Luka S., Trbovich A., Japundžić-Žigon N., Static magnetic field reduces blood pressure short-term variability and enhances baroreceptor reflex sensitivity in spontaneously hypertensive rats, *International Journal of Radiation Biology*, 93(5) (2017) 527–534.

[29] Brown C. S., Ling F. W., Wan J. Y., Pilla A. A., Efficacy of static magnetic field therapy in chronic pelvic pain: a double-blind pilot study, *American Journal of Obstetrics and Gynecology*, 187(6) (2002) 1581–1587.

[30] Darendeliler M. A., Darendeliler A., Sinclair P. M., Effects of static magnetic and pulsed electromagnetic fields on bone healing, *The International Journal of Adult Orthodontics and Orthognathic Surgery*, 12(1) (1997) 43–53.

[31] Gümüşay M., Gülbağça F., Aydemir I., Sayğılı S., Kaya A., Tuğlu M. İ., Sıçan Derisinde Oluşturulan Yara Modeli Üzerinde İyileşme Sağlanması için Elektromanyetik Alan Sistemi Geliştirilmesi ve Sensör Uygulaması, *EMO Dergisi*, (2016) 678-681.

[32] Shang W., Chen G., Li Y., Zhuo Y., Wang Y., Fang Z., Ren H., Static Magnetic Field Accelerates Diabetic Wound Healing by Facilitating Resolution of Inflammation, *J Diabetes Res*. (2019).

[33] Health Protection Agency., *Static Magnetic Fields*, (2008).