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Therapeutic Potential of Alternating Magnetic Fields for Normalizing Blood Parameters and Restoring Renal, and Cardiac Function in Diabetic Mice

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Abstract

Background: In recent years, the number of adults aged 20-79 years living with diabetes has increased more than threefold. Currently, the treatment of diabetes typically involves the long-term use of chemical and herbal drugs. However, prolonged use of chemical drugs may lead to side effects that can be detrimental to health. Therefore, this study aims to normalize blood glucose levels and restore kidney and heart cells.

Methods: The research was conducted using diabetic mice as experimental subjects. The treatment involved exposure to an alternating Magnetic Field with Magnetic Flux Densities of 0.3 and 0.6 *mT* for 20 *min/day* over five consecutive days. The frequencies of the applied Magnetic Fields were 50, 100, 150, and 200 *Hz*.

Results: The results showed that the greatest reduction in blood glucose levels (92.11%) was observed at a frequency of 100 *Hz* and an Magnetic Flux Density of 0.6 *mT*. Meanwhile, the highest increase in hemoglobin levels (81.11%) occurred at a frequency of 150 *Hz* and a Magnetic Flux Density of 0.3 *mT*. Other parameters that experienced non-linear changes included cholesterol levels, blood viscosity, and erythrocytes count, glomerulus and kidney cell density, and heart cell density.

Conclusion: The optimal effects of magnetic field exposure do not always occur at the same frequency or Magnetic Flux Density.

Keywords: Blood, Diabetes mellitus, Blood glucose, Heart, Kidney
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Introduction

Attention to the health conditions of the elderly population is increasing due to their heightened vulnerability to diseases. Age is an important factor in understanding health, as the body's immune resistance tends to decline with advancing age [1]. The aging process is typically associated with a decline in organ function, resulting in decreased productivity and greater vulnerability to disease [2]. Diabetes Mellitus (DM) is commonly found in elderly individuals. Globally, the estimated prevalence of diabetes in adults aged 20-79 years has more than tripled since 2000, rising from approximately 151 million (4.6%) to 537 million (10.5%) in 2021 [3]. Diabetes is characterized by chronic hyperglycemia and abnormalities in carbohydrate metabolism [4]. DM can make sufferers prone to complications, which may ultimately result in impaired kidney function [5]. DM causes blood glucose levels to increase, leading to increased blood viscosity and a higher risk of hyperlipidemia, hypertriglyceri-demia, and abnormal platelet formation. Further risks include increased cholesterol levels, triglycerides, and atherosclerosis, which can ultimately lead to coronary heart disease [6].

Currently, the treatment of diabetes typically involves the long-term use of chemical and herbal medications. However, prolonged use of chemical drugs may cause side effects that can be harmful to health, particularly in individuals with diabetes [7]. The current principle of diabetes treatment is to maintain blood glucose levels within normal limits, as there is no medication that can completely cure the disease. The use of herbal medicines still requires careful consideration of their toxicity, efficacy, and standardization [8]. Another common way to maintain glucose

levels is to avoid foods that contain a lot of glucose. Meanwhile, foods that contain a lot of glucose contain other nutrients needed by the body, so they have the potential to disrupt the health of other organs. Therefore, other efforts to treat diabetes by minimizing side effects need to be undertaken.

In recent years, extensive research has explored the application of magnetic fields to address various health problems. Bahaoddini *et al* [9] reported that exposing mice to a magnetic field with a frequency of 50 *Hz*, and a magnetic flux density of 500 μT for 10 *hr* per day over 2 months significantly reduced blood cholesterol levels. Similarly, another study reported that mice exposed to the same magnetic field parameters had lower cholesterol levels compared to controls[10]. Takeuchi and Iwasaka [11] demonstrated that applying a magnetic field to Monosodium Urate (MSU) crystals can increase the rate of crystal dissolution. Pulsed magnetic field treatment of 1.3 T for 1 *min* has been shown to reduce blood viscosity by 20-30%, while Lotfi *et al* [12] reported that static or 50 *Hz* pulse magnetic fields decreased blood glucose concentrations in BALB/C mice. Tao and Huang [13] also confirmed that a 1.3 T magnetic field in blood flow can lower blood viscosity by 20-30% within one *min*.

Several previous studies have shown that magnetic fields may positively affect the circulatory system and blood composition. These studies generally use magnetic fields with a high flux density of around 1.3 T or involve prolonged exposure times of up to 10 *hr/day*. Theoretically, the strength of the interaction force generated by a magnetic field depends on the field gradient [14]. Therefore, this study uses an alternating magnetic field so that the required magnetic flux density is lower and the treatment time is shorter. This study aims to find the optimum effect of magnetic field exposure on glucose levels, hemoglobin, erythrocytes, cholesterol, and blood viscosity of mice, and its effects on kidney, blood and heart histology.

Materials and Methods

Sample preparation

In this study, 45 male mice (*Mus musculus*), aged 8 weeks and weighing an average of 25-30 *g*, were used as samples. The mice were acclimatized in the laboratory for 1 week before being made diabetic. During the acclimation process, the mice were caged and fed BR-1 *ad libitum*. After acclimation, the mice were made diabetic by inducing Alloxan monohydrate intraperitoneally with a single dose of 210 *mg/kg* BB. After 96 *hr*, the mice's blood glucose levels were checked to ensure that they had diabetes. Blood glucose levels were measured by taking blood through the tail. Mice with fasting blood glucose levels reaching 200 *mg/dL* or more were declared diabetic. Mice suffering from diabetes were then divided into 9 groups, with each group containing 5 mice.

Preparation of alloxan monohydrate solution

The Alloxan monohydrate solution was prepared immediately before injection by dissolving 226.8 *mg* of Alloxan in 27 *ml* of 0.9% NaCl until fully homogeneous, resulting in a solution containing 8.4 *mg* of Alloxan *per/ml*. Each mouse was then injected intraperitoneally with 1.0 *ml* of this solution.

Magnetic field generation

An alternating magnetic field was generated using a solenoid connected to an electronic circuit that produced a sinusoidal current [15]. The solenoid was 10 *cm* in length and 6.3 *cm* in diameter and was wound with 1.0-*mm* copper wire. Two coil configurations were constructed: 250 turns to generate a magnetic flux density of 0.3 *mT*, and 500 turns to produce 0.6 *mT*. The alternating-current generator circuit used in this setup is shown in figure 1.

The peak current required to drive the solenoid was 120 *mA*, with an RMS current of 84.85 *mA*. Although the magnetic field inside the solenoid was not perfectly uniform, the distribution was sufficiently homogeneous in the central region. The center of the solenoid reached a maximum magnetic flux density of 0.3 *mT* for the 250-turn coil and 0.6 *mT* for the 500-turn coil. Magnetic Flux Density measurements were performed using a Kanetec TM-801 field meter.

In the central zone, the magnetic field was relatively uniform along the axial direction but decreased to 0.18 *mT* near the ends. Radially, the magnetic field showed a slight reduction, with the largest drop occurring near the coil windings. The magnetic field distribution in this long solenoid follows the mathematical expression commonly used for finite-length solenoids [16,17].

(1) $B = \frac{\mu_o nIL}{\sqrt{L^2+4R^2}}$

where $\mu_0 = 4\pi \times 10^{-7}$ *H/m*, *L* is the solenoid length, *R* is the solenoid radius, and n is the turn density *(N/L)*.

Magnetic field treatment

This study used nine groups of mice, with each group consisting of five animals. Each mouse was housed in an individual cage with equal access to food

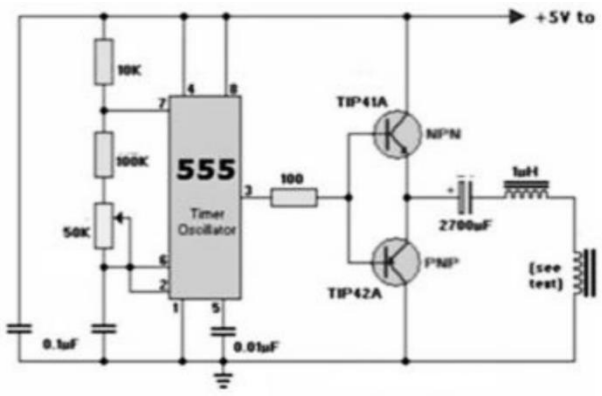

Figure 1. Alternating current generating circuit.

and water, following standard laboratory animal care guidelines [18]. The experimental design consisted of a control group with no magnetic field exposure, four groups exposed to a magnetic flux density of 0.3 *mT*, and four groups exposed to 0.6 *mT*.

The treatment groups received magnetic field exposure at different frequencies: 50 *Hz*, 100 *Hz*, 150 *Hz*, and 200 *Hz*. The exposure protocol was carried out for 20 *min* per session, once per day, for five consecutive days, following procedures commonly used in extremely low-frequency magnetic field studies [19-20]. During each session, the mice were placed at the center of the solenoid, which had a calibrated magnetic flux density of either 0.3 *mT* or 0.6 *mT*. During exposure, the movement of the animals was restricted to the solenoid area to ensure consistent field application. The mice were positioned longitudinally so that their bodies, from head to tail, aligned with the solenoid axis, ensuring uniform axial exposure [21].

Dosimetry

The external magnetic field (B) induces an electric field inside the body based on Faraday's Law of Induction [16]. This induced electric field is responsible for the stimulation of nerves and muscles. The peak induced electric field at a given point in the human body—modeled as a cylindrical conductor—can be expressed as:

(2) $E_{\max} = \pi f B_{\max} r$

where $E_{\max}$is the peak induced electric field (V/m); f is the frequency of the alternating magnetic field (*Hz*); $B_{\max}$is the peak external magnetic flux density (T); and r is the radial distance from the center of the induced current loop to the point of interest (m).

The current density generated by the induced electric field follows Ohm's law for biological tissues [22,23]:

(3) $J = \sigma E$

where J is the induced current density (A/m^2), and σ is the electrical conductivity of biological tissue.

An exposure duration of 20 *min* was used to characterize the total dose. Thermal dosimetry was evaluated using the Specific Absorption Rate (SAR), which quantifies the power absorbed per unit mass [24]:

(4) $SAR = \frac{\sigma E_{\mathrm{RMS}}^2}{\rho}$

where ρ is the tissue mass density (kg/m^3). Based on the study parameters—tissue density ≈300 kg/m^3, conductivity $\sigma \approx 0.2$ S/m, frequencies of 50-200 *Hz*, and magnetic flux densities of 0.3 and 0.6 *mT*—the resulting SAR value was less than 0.000005024 *W/kg*. This value is far below the ICNIRP whole-body thermal limit of 0.08 *W/kg*, indicating that thermal mechanisms are not relevant as a primary dosimetric parameter in this study [24].

Measurement of cholesterol, hemoglobin and glucose levels

Measurement of cholesterol, hemoglobin and blood glucose levels was carried out using the strip method [25]. Blood from the mice was collected from the tail. Before blood collection, the mouse's tail was sterilized with alcohol and then slightly incised by cutting the tip. The blood that emerged was dropped onto the appropriate test strip according to parameter being measured.

Viscosity measurement

Blood viscosity was measured by collecting blood from mice through the retro-orbital sinus using a hematocrit micropipette [26]. The blood was placed into an appendorf or microcentrifugetube without anticoagulant. The tube was then inserted into a centrifuge with the opposite position as a counterweight and spun at 3000 *rpm* for 15 *min*. Measurement was carried out by determining the hematocrit value, obtained by dividing the height of the erythrocyte sediment by the total height of the blood and multiplying by 100%.

(5) $\%\eta_{hematokrit} = \frac{h_{eritrosit}}{h_{darah}} 100\%$

The hematocrit value obtained was then used to calculate blood viscovity using Formula 5, which was derived from data on the effect of hematocrit on blood viscosity.

(6) $y = 1.5 + 0.0708x - 0.0019x^2 + (4 \times 10^{-5})\, x^3$

Erythrocyte count calculation

The calculation of the number of erythrocytes was performed using the hemocytometer method. Blood from the tail was drawn using a Thoma pipette up to the 0.5 or 1.0 mark. Hayem's diluting solution was then drawn into the Thoma pipette up to the 101 mark, resulting in a dilution of 1/200 or 1/100 occurs. Both ends of the pipette were closed and shaken back and forth. 1-2 drops of liquid in the Thoma pipette were discarded, and for the next drop, the tip of the micro pipette was placed on one side of the counting chamber, which had been fitted with a cover glass with tissue paper applied on the other side. The liquid in the Thoma pipette flowed to fill the counting chamber, which was then placed under a microscope at a 40× magnification. The erythrocytes in the 5 counting chambers (R) were counted. Counting began from the left in a zigzag manner. To avoid inaccurate results, erythrocytes on the left and upper borders of a small chamber were counted as part of that chamber. The actual number of erythrocytes can be determined using the following calculation [27]: Length of one side of chamber R=0.2 *mm*, depth of the counting chamber= 0.1 *mm*, blood dilution (p)=100 or 200. number of erythrocytes from 5 counting chambers=N, volume of 5 counting chambers=V mm^3, number of erythrocytes per mm^3 = N p/V (S)

Histology staining of heart and kidney

Histological examination of the heart and kidneys was performed using Hematocrityl-Eosin stain [28]. The selected tissue sections were arranged on a preparation rack. The next stage was deparaffinization using xylol I, xylol II and xylol III solutions with a soaking time of each solution for 5 *min*. Following this, rehydration

was carried out using absolute alcohol solutions I, absolute II and absolute III for 3 *min*, followed by 70% alcohol for 3 *min*, 80% alcohol for 3 *min*, and 90% alcohol for 3 *min*. The samples were then washed with tap water for 5-10 *min* twice. The next stage is Hemaktocillin staining for 5 *min*. The slides were then soaked again in tap water, placed into Eosin solution for 5 *min*, and washed again. Next, dehydration was carried out by removing water from the tissue using 70% alcohol, 80% alcohol, 90% alcohol for a few seconds, absolute alcohol I for a few seconds, absolute alcohol II for 1 *min*, absolute alcohol III for 3 *min*, and Xylol I, Xylol II and Xylol III for 3 *min* each. Finally, the preparation was mounted and observed using a CX23 microscope equipped with an Optilab Advance camera at 400x magnification.

Erythrocyte staining

The samples used in this study were blood samples treated with Ethylen Diamine Tetra Acetic Acid (EDTA) [29]. In this procedure, 1-3 *ml* of blood was collected and placed into an EDTA-containing vacuta-iner tube, which was then labeled. A total of 45 blood preparations were made and fixed using a 96% fixative solution with varying fixation times: 3 *min* (standard time), 5, 10, and 15 *min*. After the preparation dried, Giemsa staining was performed using a 1: 9 (1 *ml* Giemsa diluted with 9 *ml* distilled water). With this dilution, staining was carried out for 25 *min*, followed by rising with running water and air-drying in a vertical position. Once the slides were dry, microscopic observation was performed at 400× magnification using immersion oil. Images were captured with an Optilab Advance camera mounted on the microscope.

Statistical analysis

The data obtained were analyzed using the analysis of variance (ANOVA) test statistic. Before being tested using ANOVA, a homogeneity test was first performed. Determination of differences between groups was carried out using the Tukey test.

Results

Cholesterol levels

Exposure to alternating magnetic fields in mice can reduce blood cholesterol levels. The magnitude of the decrease in cholesterol levels is influenced by the magnetic flux density and its frequency. Cholesterol levels without exposure were 111.67±2.08 *mg/dL*, while when exposed to a magnetic field with a magnetic flux density of 0.3 *mT* and a frequency of 200 *Hz* for 20 *min* a day, after 5 days it became 100.67±1.16 *mg/dL*. Meanwhile, when mice were exposed to a magnetic flux density of 0.6 *mT* and a frequency of 200 *Hz*, their cholesterol levels dropped to 101.67±1.53 *mg/dL*, as seen in figure 2. The results of the test using statistics showed that changes in frequency and magnetic flux density had a significant effect (p=0.002, ≤0.05) on cholesterol levels. The lowest cholesterol levels were obtained from exposure using a magnetic flux density of 0.3 *mT* with a frequency of 200 *Hz*.

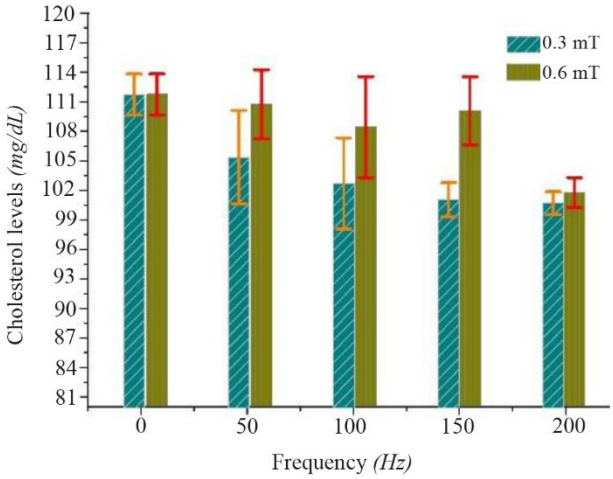

Figure 2. Blood cholesterol levels of mice exposed to magnetic fields at frequencies of 50-200 *Hz*.

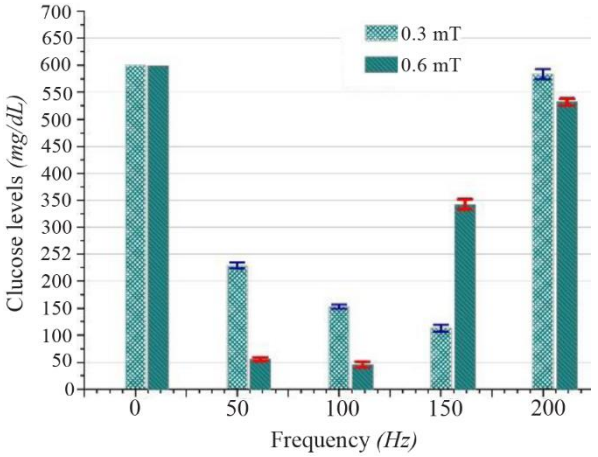

Figure 3. Blood glucose levels of mice exposed to magnetic fields at frequencies of 50-200 *Hz*.

Glucose levels

Glucose is one of the most important carbon sources used as an energy source. Normal fasting blood glucose levels in adults are 70-100 *mg/dL*. Blood glucose levels were measured after the mice were fasted for 8 *hr*. Exposure to magnetic fields affected blood glucose levels in mice. Changes in frequency and magnetic flux density of the magnetic field used had a significant effect (p=0.000, ≤0.05) on glucose levels, as shown in figure 3. Without exposure to magnetic fields, blood glucose levels were 600.00±0.00 *mg/dL*. Exposure to magnetic fields with a magnetic flux density of 0.3 *mT* and frequencies of 50, 100, 150, and 200 *Hz* caused blood glucose levels to be 229.00±5.29; 153.00±4.00; 113.33±6.43; and 583.33±9.23 *mg/dL*, respectively. Meanwhile, exposure with a magnetic flux density of

0.6 *mT* resulted in 57.67±3.51; 47.33±5.69; 344.33± 9.61; and 533.67±6.66 *mg/dL*, respectively.

Blood viscosity

Viscosity (η) is the internal friction force between molecules and particles that make up a fluid in cylindrical blood vessels. The main determinants of blood viscosity are hematocrit, red blood cell aggregation, and plasma viscosity. Exposure to magnetic fields affects blood viscosity (Figure 4). Blood viscosity without exposure to magnetic fields was 17.86± 0.50 *mPas*. Exposure to magnetic fields with a magnetic flux density of 0.3 *mT* at frequencies of 50, 100, 150, and 200 *Hz* for 20 *min* per day changed blood viscosity to 11.87±0.49; 10.25 0.63; 9.02±0.58 and 17.29±1.09 *mPas*, respectively. When exposed to a magnetic field with a magnetic flux density of 0.6 *mT*, viscosity changed successively to 7.47±0.44; 5.15± 0.78; 14.30±0.63; and 16.54±0.96 *mPas*. Statistical tests showed that changes in magnetic field frequency and flux density (p=0.001, ≤0.05) significantly affected blood viscosity.

Hemoglobin levels

Hemoglobin is a protein in red blood cells that plays an important role in transporting oxygen throughout the body. Exposure to magnetic fields with magnetic flux densities of 0.3 *mT* and 0.6 *mT* and magnetic field frequencies of 50-200 *Hz* has a significant effect (p=0.046, ≤0.05) on hemoglobin levels, as shown in Figure 5. Exposure to frequencies of 50, 100, 150, and 200 *Hz* at a magnetic flux density of 0.3 *mT* changed hemoglobin levels from 13.37±0.21 *g/dL* to 15.63±.32; 19.63±0.87; 17.73±0.64; and 15.90±0.78 *g/dL*, respectively. Meanwhile, exposure at a magnetic flux density of 0.6 *mT*changed hemoglobin levels to 14.27±0.45; 17.10±0.61; 18.50±0.72; 16.60±0.92 *g/dL*, respectively. The highest hemoglobin level was observed in the blood of mice exposed to a magnetic flux density of 0.3 *mT* at a frequency of 100 *Hz*, namely 19.63±0.87 *g/dL*.

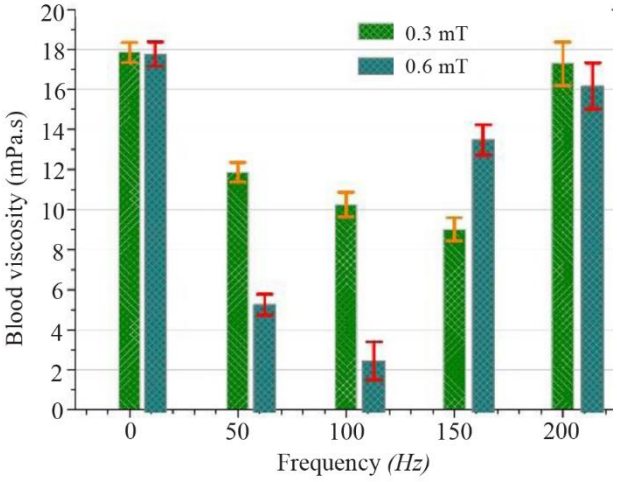

Figure 4. Blood viscosity of mice exposed to magnetic fields at frequencies of 50-200 *Hz*.

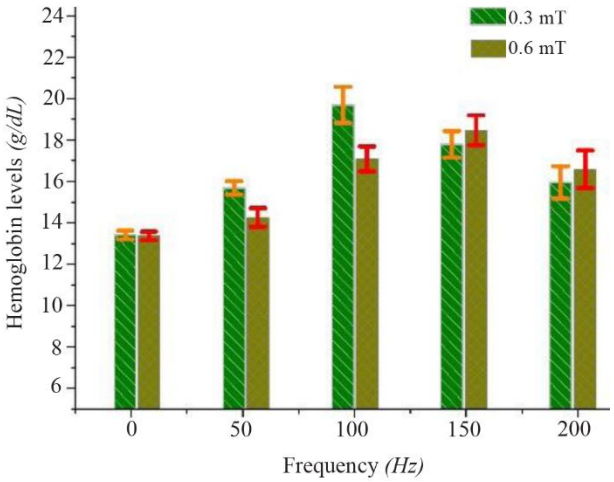

Figure 5. Hemoglobin levels in the blood of mice exposed to magnetic fields at frequencies of 50-200 *Hz*.

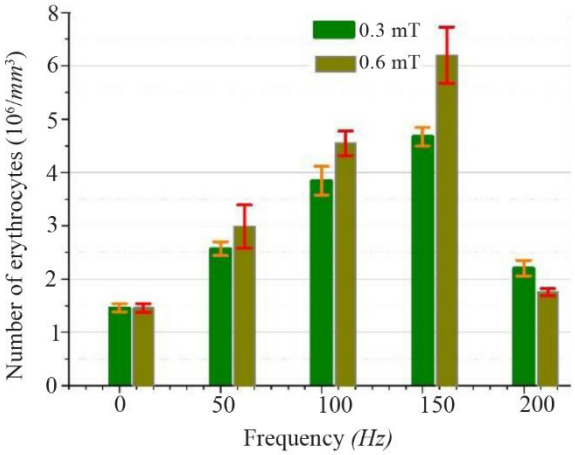

Figure 6. Blood erythrocyte levels of mice exposed to magnetic fields at frequencies of 50-200 *Hz*.

Number of erythrocytes

Erythrocytes are blood cells that do not have a nucleus, round or slightly oval looking like biconcave discs with a size of 7-8 *μm*. The normal value of the number of erythrocytes depends on age and gender. Males have 4.4-5.6 million cells/mm^3, women 3.8-5.0 million cells/mm^3 and children 3.5-5.5 million cells/mm^3. The number of erythrocytes in the blood of mice that were not exposed to a magnetic field was 1.46± 0.08 million cells/mm^3. In mice exposed to a 0.3 *mT* magnetic field for 20 *min* a day with a magnetic field frequency of 50, 100,150, and 200 *Hz*, it changed to 2.57±0.13; 3.85±0.27; 4.67±0.17; 2.20±0.15 million cells/mm^3 (Figure 6). Meanwhile, mice exposed to a magnetic flux density of 0.6 *mT* changed to 2.97±0.40; 4.51±0.23; 6.14±0.52; 1.75±0.07 million cells/mm^3. The results of statistical tests showed that changes in frequency and magnetic flux density were significant (p=0.000, ≤0.05) in changing the number of blood erythrocytes. The number of normal erythrocyte cells

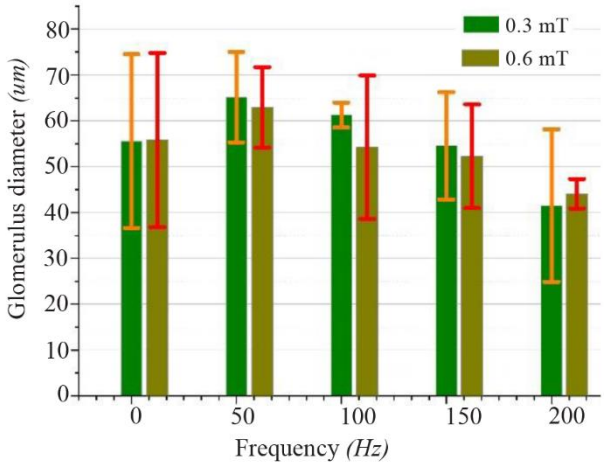

Figure 7. Diameter of mice kidney glomeruli exposed to magnetic fields at frequencies of 50-200 *Hz*.

was obtained from exposure to a magnetic flux density of 150 *Hz* at a magnetic flux density of 0.3 *mT* and 100 *Hz* at a magnetic flux density of 0.6 *mT*.

Renal glamorous diameter

The glomerulus is a kidney structure that functions to filter waste and toxins from the blood, as well as remove excess fluid from the body. The diameter of the glomerulus changes due to exposure to magnetic fields (Figure 7). Exposure to magnetic fields with a magnetic flux density of 0.3 *mT* at frequencies of 50 *Hz* and 100 *Hz*, and a magnetic flux density of 0.6 *mT* at a frequency of 50 *Hz*, enlarged the glomerular diameter from 55.53±18.95 *μm* to 65.13±9.89, 61.27± 2.73 *μm*, and 62.67±8.74 *μm*, respectively. Meanwhile, the lowest diameter was obtained from exposure to a magnetic field with a magnetic flux density of 0.3 *mT* at a frequency of 50 *Hz*, namely 41.47±16.64 *μm*. However, the results of the statistical test showed that the differences were not significant. The largest change in glomerular diameter occurred at exposure to a magnetic flux density of 0.3 *mT* and a frequency of 50 *Hz* (Figure 8).

Histology of erythrocytes

The condition of erythrocytes varied with each exposure, particularly regarding coagulation and the presence of other elements, as shown in figure 9. The most optimal condition, characterized by the lowest cell coagulation and minimal presence of other elements, was observed at exposure to a frequency of 200 *Hz* and a magnetic flux density of 0.3 *mT*. In contrast, the highest cell coagulation and greatest presence of other elements occurred at exposure to a frequency of 50 *Hz* and a magnetic density of 0.6 *mT*.

Discussion

Exposure of blood to alternating magnetic fields causes eddy currents and induction of electromotive force [30]. The presence of eddy currents can produce a thermal effect. However, in this study the thermal

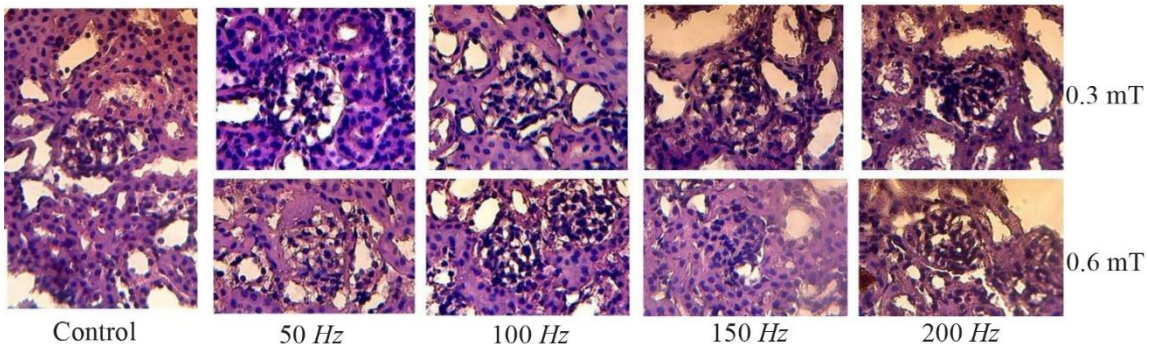

Figure 8. Histology of mice kidneys exposed to magnetic fields at frequencies of 50-200 *Hz*.

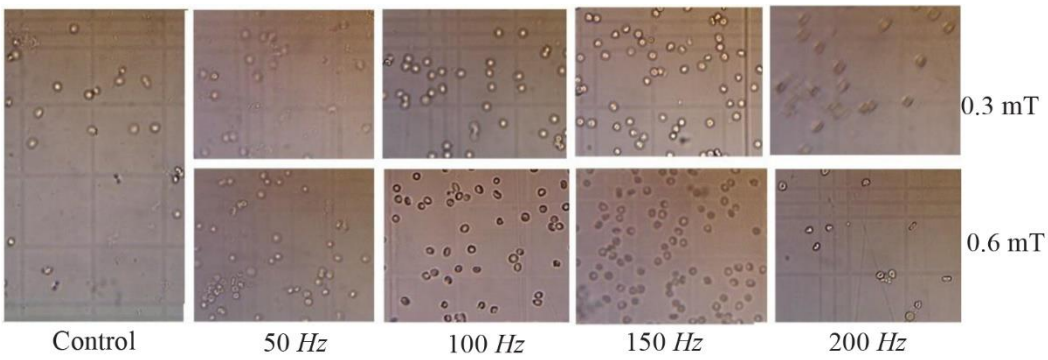

Figure 9. Histology of mice erythrocytes exposed to magnetic fields at frequencies of 50-200 *Hz*.

effect did not significantly affect the blood, as temperature measurements of mice after exposure showed no significant increase. Similarly, the induced voltage did not affect the blood. This is evidenced by the observation that exposure at a magnetic flux density of 0.6 *mT* resulted in a smaller decrease in cholesterol levels compared to exposure at 0.3 *mT*.

Another possible effect is that cells exposed to a very weak magnetic field experience ion movement across the membrane, particularly calcium ions [31]. This effect has also been observed in the development of chicken embryos [32]. Whole-body exposure of mice in this study highlighted the role of magnetic flux density and frequency in influencing cholesterol, hemoglobin, glucose, blood viscosity, erythrocyte count, and the histology of kidney and erythrocytes.

The liver, as the primary source of lipoproteins and cholesterol in the bloodstream, is a central target in studies such as those conducted by Wang *et al* [33]. Exposure to alternating magnetic fields with flux densities of 0.3-0.6 *mT* has been shown to modulate hepatic cholesterol synthesis, thereby influencing circulating cholesterol levels. Interestingly, these metabolic effects occur only at specific frequencies and flux densities [34], suggesting the possibility of resonance-like interactions between magnetic fields and biological systems—a phenomenon that warrants further investigation [21].

One proposed mechanism is Ion Cyclotron Resonance (ICR), described by the equation $f = qB/2\pi m$. At a magnetic flux density of 0.3 *mT* and frequencies between 50 and 100 *Hz*, calcium ions (Ca^{2+}) may reach resonance due to their effective mass in biological environments [21]. Such resonance may facilitate efficient energy transfer, increasing the kinetic energy of ions and enabling them to overcome cellular energy barriers. The resulting elevation in intracellular calcium can function as a secondary messenger that initiates extensive signaling cascades. This pathway may explain observed alterations in glucose metabolism through enhanced insulin sensitivity and modulation of hepatic enzymes, as well as changes in cholesterol synthesis via regulation of HMG-CoA reductase [35].

A complementary explanation involves the Radical Pair Mechanism (RPM). Alternating magnetic fields in the 50-100 *Hz* range can influence electron spin precession within radical pairs, shifting the balance of singlet–triplet interconversion [36]. These spin-dependent changes can elevate the production of Reactive Oxygen Species (ROS), which act as redox signals that activate transcription factors such as Nrf2 and NF-κB. These pathways subsequently modify gene expression and enzymatic activity, including that of HMG-CoA reductase, ultimately altering hepatic cholesterol production and its plasma concentration [37].

Living systems constantly produce free radicals as a result of biochemical reactions in oxidative metabolic processes [38]. Exposure to magnetic fields can eliminate the degeneracy of the triplet radical pair energy levels and affect the rate of the these reactions [39]. The relatively small energy exchange between the external magnetic field and free radical-driven reactions can induce physiological changes. The decrease in cholesterol levels in the blood of mice indicates that the magnetic field affects the hormonal system, which can reduce metabolism. When the frequency of the magnetic field applied to diabetic mice is right, it will slow down the metabolism. This causes homeostatic changes and increases insulin release, which can lower blood glucose levels. The liver plays an important role in overall metabolism, particularly in patients with diabetes mellitus [40]. Therefore, the decrease in blood glucose levels in this study was not linear with changes in the frequency of the magnetic field applied.

The aggregate chains parallel to the direction of blood flow help maintain stable blood viscosity, which then slowly increases again to restore its original value [41]. Exposure to magnetic fields causes these chains to align and reduces blood viscosity [41]. When the applied magnetic field reaches zero, the effective viscosity equals the kinematic viscosity, and the magnetic torque exerted on the blood cells increases friction between the plasma and the red blood cells. Exposure to alternating magnetic fields with low magnetic flux density and aggregate alignment with the direction of blood flow is not the only cause of decreased blood viscosity. In this study, a linear relationship was found between viscosity and blood glucose levels. Therefore, the decrease in viscosity observed is more dominantly caused by a decrease in blood glucose levels.

The alternating magnetic field has a direct effect on the conformation of Hb through its interaction with water molecules bound to Hb [37]. Water plays an important role in maintaining protein macromolecules in their natural state [42]. Exposure to an alternating magnetic field altersthe length of the hydrogen bonds in water, which leads to a more stable structure and results in reduced absorption of the hemoglobin band. This may reflect changes in aggregation state and the local environment, causing conformational changes in the Hb protein. The results of this study indicate that hemoglobin changes are influenced more by frequency than by magnetic flux density.

Mice exposed to alternating magnetic fields experienced changes in the number of erythrocytes. Figure 6 shows an increasing trend at a frequency of 150 *Hz* and a decreasing trend at 200 *Hz*. These findings indicate that exposure to magnetic fields can induce oxidative stress in red blood cells. Changes in hemoglobin conformation caused by magnetic fields may lead to a hypoxia-like state, which can stimulate erythrocyte production in the bone marrow [43].

Free radicals, especially ROS, are products of biochemical reactions in metabolically active cells. Exposure to a sinusoidal alternating magnetic field in the heart induces a window effect on cardiac cells [44], as indicated by changes in cell density. Exposure to mag-

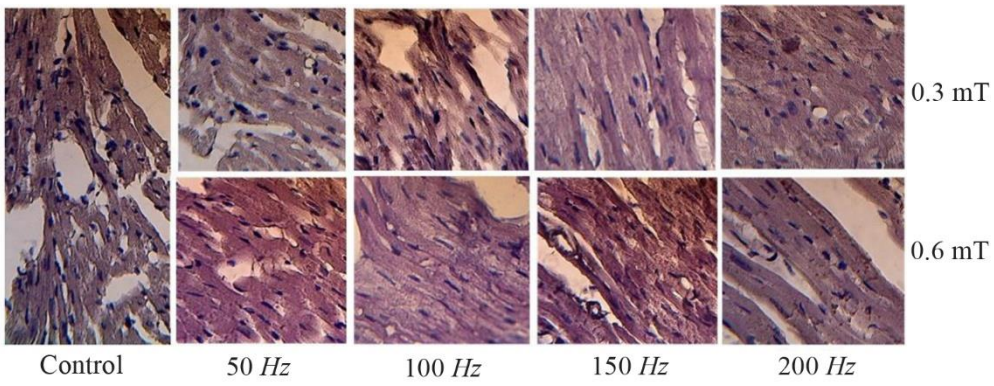

Figure 10. Histology of the control heart and hearts exposed to magnetic fields at frequencies of 50-200 *Hz*.

netic fields at a frequency of 50 *Hz* tends to decrease cell density, whereas at 150 *Hz* and 200 *Hz*, cell density increases, as shown in figure 10.

Limitations

This study has several methodological limitations in the characterization of the magnetic field. Numerical simulations using the Finite Element Method (FEM) and three-dimensional magnetic field mapping were not performed. The magnetic field distribution within the exposure chamber was assumed to be homogeneous based on theoretical solenoid calculations, without experimental validation through detailed spatial measurements. The coil's efficiency in generating a uniform field-including the effects of resistance and inductance-was also not comprehensively modeled.

In terms of dosimetry, the magnetic exposure dose (B=0.3 *mT* or 0.6 *mT*) received by each subject was based solely on the nominal magnetic field calculated at the solenoid center. This study did not quantify the influence of edge effects, including field spreading and decay at the coil ends, on subjects located in those regions. Additionally, variations in animal positioning during exposure-such as movement away from the center or closer to the coil walls-were not considered in the dosimetric calculations.

Conclusion

Exposure to low-flux, low-frequency alternating magnetic fields has potential for diabetes therapy. Such exposure may promote cell recovery or cause damage in blood cells, kidneys and heart. However, the optimum conditions of cholesterol levels, glucose, hemoglobin, viscosity, number of erythrocytes, erythrocyte conditions, kidney and heart cells do not always occur at the same frequency and flux density. Therefore, further research is still highly needed.

Ethical consideration

The use of mice as experimental subjects was approved by the Ethics Commission of the Faculty of Science and Technology, State Islamic University of Maulana Malik Ibrahim Malang (No. 04/EC/KEP-FST/2024), with approval granted on May 4, 2024.

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Conflict of Interest

The authors declare no conflict of interest.

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