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Apparatus for exposure of cancer cell lines with extremely low frequency (ELF) alternating magnetic field

Remigiusz MYDLIKOWSKI[1]*, Krzysztof MANIAK[2], Patrycja GROSMAN-DZIEWISZEK[3], Benita WIATRAK[3], Paweł BIEŃKOWSKI[4], and Tomasz GĘBAROWSKI[5]

[1] Faculty of Electronics, Photonics and Microsystems, Wroclaw University of Science and Technology, Wrocław, Poland
[2] National Institute of Telecommunications, Warsaw, Poland
[3] Department of Pharmacology, Faculty of Medicine, Wroclaw Medical University, Wrocław, Poland
[4] Department of Telecommunications and ICT, Wroclaw University of Science and Technology, Wrocław, Poland
[5] Department of Animal Physiology and Biostructure, Wrocław University of Environmental and Life Sciences, Wrocław, Poland

Abstract. This paper presents the design of a laboratory stand that facilitates the study of the effects of exposure to magnetic induction of extremely low frequency on cultures of cancer cell lines. The designed laboratory bench is adapted to operate in the frequency range of up to 300 Hz and the maximum settable magnetic induction of 2.5 mT. Tests are conducted on cellular test plates of 24, 48, or 96 wells where it is possible to evaluate the combined effect of magnetic field and cisplatin on cancer cells. The conducted tests determined the uniformity of field distribution inside the constructed solenoid establishing the optimal space for cellular research. Preliminary studies of the effect of the magnetic field on the response of cancer cells treated with cisplatin were conducted on the built stand. The study shows that a magnetic field with certain parameters can significantly affect the response of cancer cells to cisplatin treatment. The application of a magnetic field can either promote cell proliferation or, with appropriately selected parameters, lead to increased cytotoxicity. Continued research will allow us to find the appropriate drug concentration parameters when using magnetic field exposure with given parameters.

Keywords: alternating magnetic field; extremely low frequencies; cancer cells; cell viability; effect of cisplatin.

1. INTRODUCTION

The use of extremely low frequency (ELF) electromagnetic field (EMF) is a non-standard way of treating cancer. Its interaction at the cellular as well as molecular level affects various biological processes in cells such as proliferation, metabolism, and the cell cycle and thus those that play the most important role in the development of cancer cells. Intercellular interactions based on the electromagnetic field generated by microsomes regulate cell migration, their differentiation process, and morphogenesis, such as peripheral nerves, among others. These processes are closely linked to centrosome function and intercellular communication [1, 2]. EMF induces apoptosis and increases the sensitivity of drug-resistant tumor cells to cytostatics. Two different mechanisms appear to be important in its effects on cancer cells. The first is the effect on the cell cycle. The second mechanism by which EMF affects cells is its actions on apoptosis, proliferation, and angiogenesis, processes that play an important role in cancer development [2].

Among the various frequency ranges of electromagnetic fields, ELF, or signals with frequencies below 300 Hz are mentioned as having the greatest effect on cancer cells. In this case, the anticancer effect is independent of the thermal effect of the field. It was shown that EMF can increase apoptosis and inhibit angiogenesis or proliferation of cancer cells. Such effects promote tumor inhibition. With the application of an EMF with certain parameters, there can be sensitization of tumor cells to phase-specific cytostatics, such as 5-fluorouracil. In addition, an ELF-EMF exacerbates DNA damage caused by cytostatic agents such as cisplatin and paclitaxel. This damage then causes tumor cells to die through the process of apoptosis. Proteins such as p53 and p21 participate in this process [3, 4]. ELF-EMF also affects the activity of mitochondria in the cancer cell and, as a result, can increase the production of reactive oxygen species [5]. It was also shown that by affecting the expression of E-cadherin in breast cancer cells, which participate in the epithelial-mesenchymal transition, ELF-EMF may have a role in suppressing metastasis [6].

Also, human studies confirm the anti-cancer effects of electromagnetic fields. A field with frequencies in the range of 200–300 Hz can activate the transcription of certain genes, e.g., jun, myc, hsp70 [7, 8]. In addition, reactive oxygen species ROS may also be formed as a result of this interaction. A negative effect on the antioxidant activity of melatonin was also ob-

*e-mail: remigiusz.mydlikowski@pwr.edu.pl

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served in an experiment conducted on AT478 squamous cell carcinoma cell lines [9]. It is noteworthy that cytostatics such as paclitaxel and platinum compounds also increase ROS levels in cancer cells, a synergistic effect with ELF [10–13]. Such effects were confirmed both in vitro and in vivo. The effect of the magnetic component of an electromagnetic field in the ELF range at 50 Hz and 1 mT on cancer cells incubated with cisplatin was described. In the study, exposure to magnetic induction of the EM field exacerbated the effects of cisplatin by increasing oxidative stress in cancer cells and increased ROS production causing DNA damage [14]. The use of appropriate parameters of low energy emission therapy should be selected for a given type of cancer based on the biofeedback method, which allows the determination of appropriate EM field parameters [15–18].

The use of EMF in cancer therapy appears to be a promising direction. Particularly important is the sensitization of cancer cells to cytostatics using EMF. To be able to appropriately select EMF parameters that are specific for a given cancer type and the effect on appropriate cytostatics, especially in drug-resistant cancers, these studies should be conducted on cell cultures [19–22].

To study the effects of electromagnetic fields on cell cultures on various cancer cell lines (including those taken from the patient), a laboratory test bench was designed. On the stand, it is possible to study the effect of a specific value of the magnetic induction of the electromagnetic field in the ELF frequency band, to determine the optimal time of exposure to the field and to apply anti-cancer drugs in the appropriate concentration. The central element of the stand is a solenoid in the working space of which, it is possible to place cell culture plates with 24, 48, or 96 cells. The bench is designed for low frequencies of up to 300 Hz and a maximum taskable magnetic induction of 2.5 mT.

According to current European standards and recommendations [23], the value of induction obtained at the test bench significantly exceeds the permissible value of continuous human exposure to magnetic fields. For example, for a frequency of 60 Hz, the safe level of magnetic induction is 0.084 mT [23]. However, the recommended levels are related to the negative impact of the EM field and its thermal effect, which is defined by the specific absorption rate (SAR).

2. DESIGN OF APPARATUS FOR EXPOSURE TO AN ALTERNATING MAGNETIC FIELD

To research cancer cells, a research apparatus was constructed that allows exposure to an alternating electromagnetic field in the extremely low-frequency range. The main component of the system is a solenoid fed from a signal generator via a power amplifier.

The ability to set a specific value of magnetic induction and control its value is realized by a graduated voltmeter of the output signal from the power amplifier. To simplify the measurement system, the ammeter was dispensed by scaling the voltmeter by setting a scaling constant B [mT]/U [V]. The block diagram of the test bench is shown in Fig. 1.

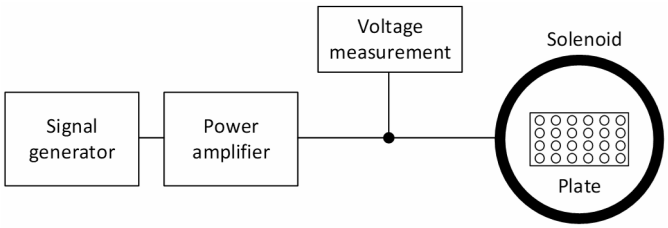


Fig. 1. Block diagram of the test stand for exposure to an alternating inductive field

2.1. Solenoid

On the designed laboratory bench, the cancer cells under study are placed inside a cylinder made of plastic, on the outer wall of which is wound a coil that generates a preset magnetic field (MF) – a solenoid. This solution is dictated by the study of cells placed on only one cell plate. With a larger number of cell plates under study, it would be expedient to build a station based on Helmoltz coils [24]. The use of two coils in a Helmoltz system allows the preset magnetic field induction to be maintained over a larger area. Tests could then be conducted simultaneously on several cell plates placed in this space.

Based on the design guidelines for conducting exposure to MF tests on a single 24, 48, or 96-cell plate and maximum field strength of about 2 mT, a solenoid design with appropriate parameters was conducted. To conduct tests on selected cell plates, a coil carcass with an outer diameter of 22.5 cm and a height of 10 cm was used. To determine the value of magnetic induction at the observation point P of the solenoid with N turns, radius R, the resultant length of the tightly wound winding denoted as l, and the current flowing through the coil with a current of I, the designations in Fig. 2 were used.

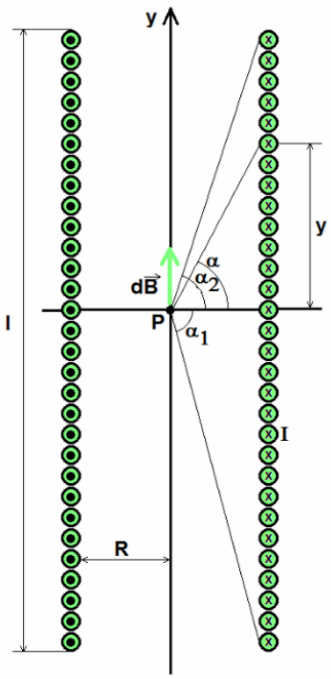


Fig. 2. Accidental magnetic field at point P on the axis of the solenoid

For the coil system as in Fig. 2, we determine the value of magnetic induction at the observation point P from the relationship [25, 26]

$$\vec{B} = \frac{\mu_0 \cdot I \cdot N}{2 \cdot l} \hat{j} \int_{\alpha_1}^{\alpha_2} \cos\alpha \, \mathrm{d}\alpha = \frac{\mu_0 \cdot I \cdot N}{2 \cdot l} (\sin\alpha_2 - \sin\alpha_1) \hat{j}, \quad (1)$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m – magnetic permeability of a vacuum, $\hat{j}$ – a vector of unit length (versor).

Considering coils of infinite length l, whose length is much larger than the radius R, we have the following values of angles $\alpha_1 = -\pi/2$ and $\alpha_2 = \pi/2$. For such conditions, equation (1) will take the form

$$\vec{B} = \frac{\mu_0 \cdot I \cdot N}{2 \cdot l} \hat{j} \cdot \left[\sin\left(\frac{\pi}{2}\right) - \sin\left(\frac{\pi}{2}\right) \right] = \frac{\mu_0 \cdot I \cdot N}{l} \hat{j}. \quad (2)$$

The design uses a cylindrical carcass made of plastic with dimensions: l = 10 cm, Ø = 22.5 cm. For these dimensions: $R = Ø/2 = 11.25$ cm, $y = l/2 = 5$ cm.

Taking the observation point P centrally in the center of the carcass, we get

$$\sin\alpha_2 - \sin\alpha_1 = 2 \cdot \sin \frac{y}{\sqrt{y^2 + R^2}} \approx 0.798. \quad (3)$$

After substituting this value into (1), finally

$$\vec{B} = 0.399 \cdot \frac{\mu_0 \cdot I \cdot N}{l} \hat{j}. \quad (4)$$

The solenoid was wound as a two-layer coil with a 1 mm diameter winding wire. With an active coil length of l = 10 cm, a total number of turns of N = 200 (100 per layer) was obtained. When forcing the maximum current flow (for 1 mm wire) at the level of I = 2.5 A ensuring the excitation of the solenoid with a sinusoidal waveform, the maximum value of magnetic induction determined from (4) is B = 2.5 mT. The theoretical results were confirmed by tests in an accredited testing laboratory. For the actual test system, a magnetic induction of B = 2.5 mT was obtained with a forced current flow in a 2.5 A solenoid.

The total length of the winding wire d used for the coil

$$d = 2 \cdot \pi \cdot R \cdot N = 141.4 \text{ m}. \quad (5)$$

Other solenoid parameters like resistance R and inductance L were determined from the formulas below

$$R = \frac{\rho \cdot d}{s} = 3.2\ \Omega, \quad (6)$$

$$L = \mu_0 \frac{N^2 \cdot S}{l} [H] \approx 20 \text{ mH}, \quad (7)$$

where $\rho = 1.68 \cdot 10^{-8}$ Ωm – copper resistivity, s – surface area of winding wire with a diameter of 1 mm, S – surface area of a solenoid with a diameter of 22.5 cm.

2.2. Power amplifier

A commercial device with a nominal power rating of 25 W with three-point frequency response correction. By design, the system should generate a magnetic field in the low-frequency ELF range (50–300 Hz). To increase the gain of the commercial amplifier, additional frequency response correction was used in the low-frequency range. Figure 3 shows the frequency characteristics of the power amplifier with the lower part of the frequency response emphasized. The characteristics were measured under laboratory conditions with no load on the system.

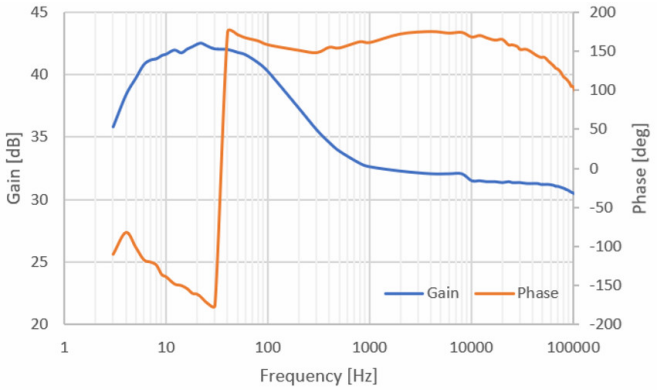


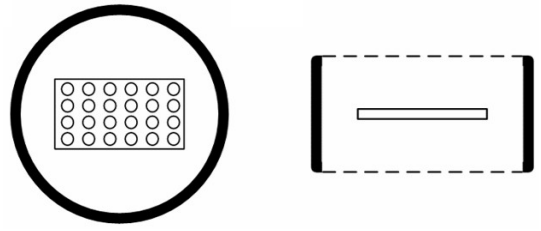
Fig. 3. Characteristics of gain and phase as a function of frequency of a power amplifier

An analysis of the obtained gain (amplitude) characteristics shows that with frequency correction applied, the amplifier operates with increased gain. The obtained increased gain in the frequency range from 5 to 200 Hz (about 42 dB compared to 31 dB in the rest of the range), reaches the level of output to the load at a maximum of 30 W. At the maximum gain value, there is a phase shift for frequency values around 40 Hz, which is characteristic of band-pass filter systems [27, 28].

3. TESTING THE UNIFORMITY OF MAGNETIC INDUCTION EXPOSURE IN THE SOLENOID

To confirm the obtained values of the magnetic field in the designed solenoid, tests were conducted to determine the value of magnetic induction and its distribution in the space of the exposure system. The induction tests were conducted in the accredited testing laboratory LWiMP AB-361 with the ESM-100-meter No. 972153 (manufacturer Maschek, calibration certificate AP-078 LWiMP/W/061/23 dated 15.02.2023). The distribution of magnetic induction in the space of the system was made by measuring it point-wise in a 1 cm × 1 cm × 1 cm grid using a GM-08 meter with measuring probe No. PT-7350 (manufacturer Hirst, calibration certificate AP-078 LWiMP/W/064/23 dated 15.02.2023).

A carcass with a wall thickness of 1 cm was used to construct the solenoid. This means that the available test space for displaying cellular samples has an inner diameter of 20.5 cm and a height of 10 cm. In this space, a cell test plate with 24, 48, or 96 cells of 86 mm × 128 mm × 22 mm (17 mm – 96 cells) is placed at its central point – Fig. 4.



(a) (b)

Fig. 4. Display layout of the designed solenoid: (a) top view, (b) cross-section

The test bench solenoid is supplied with a 60 Hz sinusoidal signal from a generator via a power amplifier. The choice of this frequency value is dictated by the ubiquitous influence of 50 Hz electromagnetic disturbances. These disturbances originate from the electric power grid and the devices powered by it. The results of magnetic induction distribution for 60 and 50 Hz are remarkably close to each other (practically the same), but at 60 Hz the results show less fluctuation and are easier to read.

In the laboratory stand, the ability to set a specific value of MF is controlled by a graduated voltmeter of the output signal from the power amplifier (Fig. 1). The normalized distribution of magnetic induction B/Bcenter at a frequency of 60 Hz in the workspace is shown in the graph of Fig. 5, where Bcenter is the induction value at the central point of the solenoid. The graph shows the distribution of induction inside the solenoid in the horizontal x-axis and vertical y-axis (consecutive planes) relative to the geometric center of the coil.

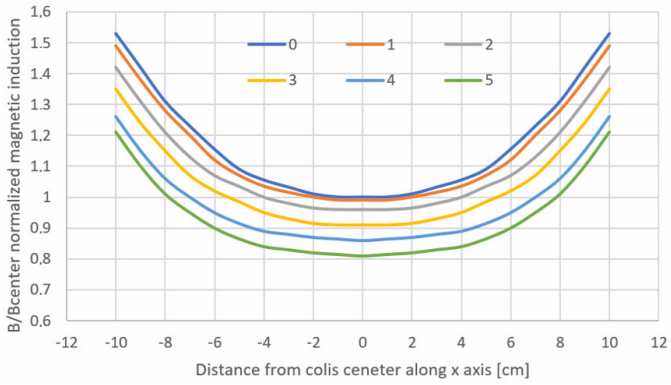


Fig. 5. Relative distribution of normalized magnetic induction B/Bcenter in the exposure coil along the horizontal x-axis and vertical y-axis (0, 1, 2, 3, 4, 5 – y-axis distance from the center point of the coil [cm])

Laboratory measurements of magnetic induction conducted when forcing a current flow in the solenoid of 2.5 A, confirm the calculated maximum value of magnetic induction at the geometric center of the coil of 2.5 mT (formula (4)).

At a distance of ±5 cm from the central point of the coil along the x-axis, the magnetic induction reaches inhomogeneities not exceeding +10%. For a greater distance of the x-axis, these inhomogeneities strongly increase to more than 50%. For values of ±2 cm in the y-axis, the decrease in induction does not exceed 5%. This results in recommendations to place a cell culture plate subjected to uniform exposure to magnetic induction near the geometric center of the coil. Reliable measurement results should be analyzed from the center cells of the plate within a radius of no more than 5 cm from the central point of the solenoid.

To confirm the laboratory results of the uniformity of exposure in the central line of the solenoid, magnetic induction tests were conducted for the coil placed in the incubator used to grow the cell lines. The metal shelf (aluminum) and the finishing of the incubator do not noticeably affect the distribution of induction inside the coil, i.e., the research area of cancer cells. The results obtained in the central axis of the coil (curve 0 Fig. 5) fully coincide with those obtained under laboratory conditions.

4. RESEARCH EXPERIMENT ON CULTURES OF CANCER CELL LINES

4.1. Experimental design

Research on the effect of magnetic fields on the growth of human cancer cells was conducted using a specialized laboratory setup. The cancer cell lines LoVo (colon cancer), MCF7 (breast cancer), and A431 (epidermoid cancer) were tested. Cultures were placed in 96-well plates, positioned at the center of a solenoid. Cells from the central wells (within 5 cm of the center) were exposed to a constant magnetic field and analyzed. Each test plate contained a single concentration of cisplatin, a commonly used cytostatic drug.

Simultaneously, control cultures were treated with cisplatin alone, without exposure to the magnetic field, and maintained in a separate incubator. Both test and control cultures were kept under identical environmental conditions (37°C, 5% CO2, 95% humidity). The incubator with the solenoid was dedicated exclusively to the test cultures, while the control cultures were kept in a standard incubator, ensuring they were not exposed to the magnetic field. This setup allowed the only variable between the two groups to be the presence or absence of the magnetic field. Although the control and test cultures were maintained in separate incubators to eliminate direct magnetic field exposure for the control group, additional measurements to confirm the absence of stray magnetic fields outside the solenoid are warranted. Future studies could involve systematic monitoring of low-level magnetic induction in adjacent areas around the solenoid during operation. Such data would ensure that potential stray fields do not inadvertently influence the biological response of nearby cultures.

Additionally, a control group, labeled E_0, consisted of cells cultured in the recommended medium for each cell line, without cisplatin or magnetic field exposure. All experiments were performed in four independent replicates, with both test and control cultures originating from the same passage.

4.2. Cell lines and culture conditions

Cell lines used: LoVo (CCL-229), MCF-7, and A431 were obtained from ATCC (Lonza, Basel, Switzerland). Cells were cultured in the recommended media for them: LoVo in DMEM

F-12, MCF-7 in MEM, A431 in DMEM, and NHDF in DMEM without phenol red. All media were supplemented with 10% FBS, 2 mM L-glutamine, and 25 µg/ml gentamicin. Cell lines were cultured in an incubator at 5% CO_2, 37°C, and 95% humidity (Fig. 6).

Fig. 6. View of the designed solenoid placed inside the incubator

4.3. Tested compound

Cisplatin was dissolved in physiological saline to concentrations of 10 mM. Concentrations from 20 to 400 µM were prepared for testing in media recommended for cell lines.

4.4. Viability assay

The plates were incubated overnight at 37°C with 5% CO_2 to allow for cell adhesion to the substrate. The next day, cisplatin concentrations were prepared in the appropriate media for each cell line. The supernatant was removed from the cells, and the tested cisplatin concentrations were added. The control cell cultures were incubated under standard conditions at 37°C and 5% CO_2, while the test cultures were additionally exposed to ELF-EMF with specified parameters for 8 hours. After this period, morphological changes in the cells were examined microscopically. The medium was then removed, the cells were rinsed with PBS, and an MTT solution (1 mg/ml) dissolved in MEM without phenol red was added. The plates were incubated at 37°C with 5% CO_2 for 2 hours. After incubation, the MTT solution was removed, and isopropanol was added to each well to dissolve the formazan crystals. The plates were shaken in the dark for 30 minutes. Absorbance was measured at $\lambda = 570$ nm using the Variuscan Go microplate reader. Cell viability was calculated using the following formula

$$\text{cell viability}_{\%} = \frac{\text{mean } E \text{ of cells exposed to ELF EMF}}{\text{mean } E \text{ of control cells}} \cdot 100\%, \quad (8)$$

where E represents absorbance.

4.5. Statistical analysis

Statistical analysis was performed for the results obtained. The normality of the data distribution and the equality of variances were confirmed with the Shapiro-Wilk and Levene tests, respectively. Consequently, statistical differences for a given drug concentration between treatment with and without a magnetic field were assessed using a parametric paired t-test. A p-value of <0.05 was considered statistically significant and denoted by an asterisk (*). Data were presented as the E/E_0 ratio and standard deviation, where E represents the average absorbance under experimental conditions and E_0 denotes the average absorbance of the control. Evaluation of cell viability is shown in Figs. 7 and 8.

4.6. Experimental results

In the experiment conducted, the effect of magnetic induction with a frequency of 60 Hz and values of 1.25 mT (Fig. 7) and

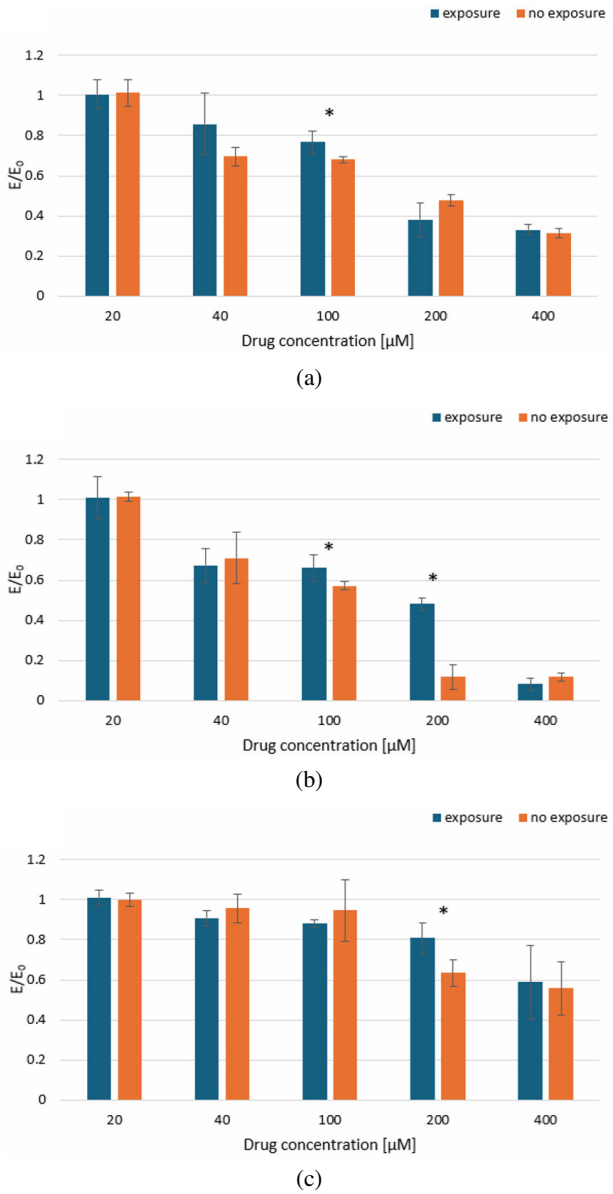


Fig. 7. Evaluation of the viability of cells exposed to 60 Hz and 1.25 mT magnetic field in cycles of 30 minutes of daily exposure conducted for five consecutive days: (a) MCF-7 cells; (b) LoVo cells; (c) A431 cells. The orange bars represent cisplatin-treated cells relative to the untreated control (E_0), while the blue bars represent cells treated with both cisplatin and EMF relative to the same untreated control (E_0). Statistical significance ($^*p < 0.05$) is shown for differences between cisplatin+MF and cisplatin-alone groups. Error bars represent the standard deviation

2.5 mT (Fig. 8), respectively, on cisplatin-treated cancer cell cultures was evaluated. Three different cancer cell lines were tested: breast cancer (MCF-7), colon cancer (LoVo), and skin cancer (A431). The concentrations of cisplatin used in the study ranged from 20 μM to 400 μM. The commonly recommended MTT assay, which is widely used to measure cell metabolic activity, was used to assess cytotoxicity and cell viability [29]. Laboratory tests were performed on tumor cells exposed to magnetic fields in a cycle of daily 30-minute exposure conducted for five consecutive days. Experiments for tumor cells exposed to cytostatics of different concentrations were performed in four independent replicates.

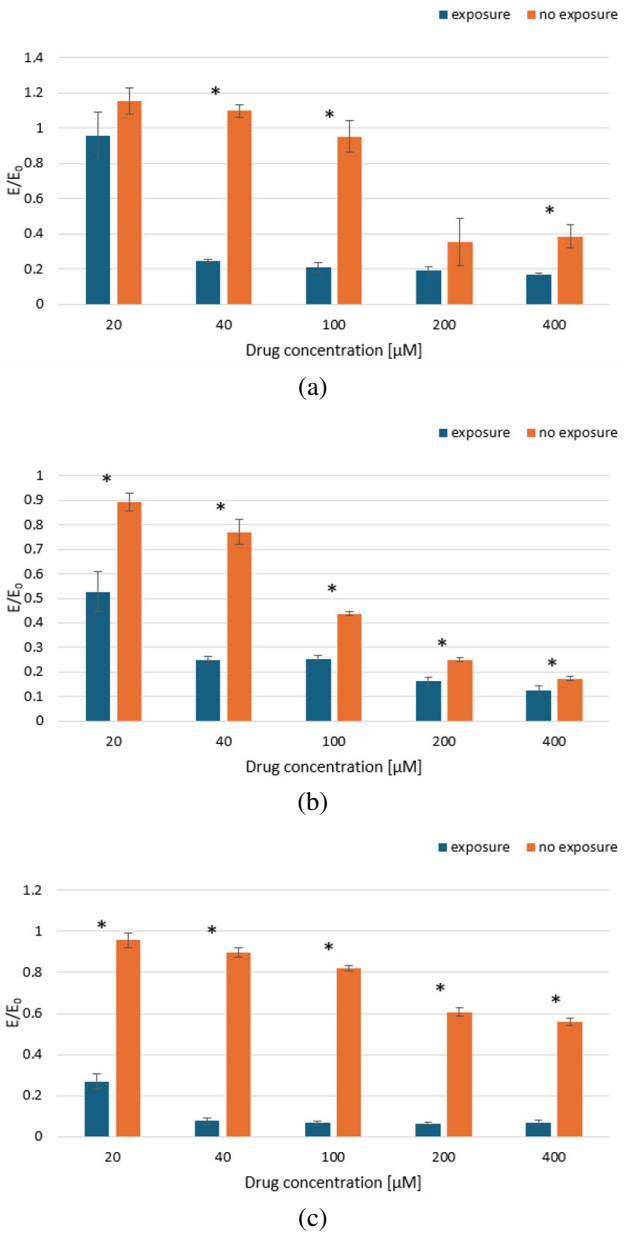


Fig. 8. Evaluation of the viability of cells exposed to 60 Hz and 2.5 mT magnetic field in cycles of 30 minutes of daily exposure conducted for 5 consecutive days: (a) MCF-7 cells; (b) LoVo cells; (c) A431 cells. The orange bars represent cisplatin-treated cells relative to the untreated control (E_0), while the blue bars represent cells treated with both cisplatin and EMF relative to the same untreated control (E_0). Statistical significance ($*p < 0.05$) is shown for differences between cisplatin+MF and cisplatin-alone groups. Error bars represent the standard deviation

The results shown by the orange and blue bars in Fig. 7 and Fig. 8 represent the absorbance ratio (E/E_0), where E corresponds to the mean absorbance of cells treated with cisplatin only or with both cisplatin and MF, respectively, and E_0 denotes the baseline absorbance of control cells without cisplatin treatment or EMF exposure. Specifically, the orange bars reflect the results for cisplatin-treated samples without EMF exposure (E) relative to the untreated control (E_0). The blue bars show the impact of both cisplatin and MF exposure (E) relative to the same untreated control group (E_0). This approach ensures that the effects of cisplatin and EMF are clearly distinguished, while the untreated control group serves as a consistent baseline.

Figure 7 shows the effects of the magnetic field on cancer cells treated with cisplatin at concentrations ranging from 20 μM to 400 μM.

In the MCF-7 (breast cancer), LoVo (colon cancer), and A431 (skin cancer) cell lines, a statistically significant pro-proliferative effect was observed at some cisplatin concentrations. Specifically, at 100 μM, 200 μM, and 400 μM, cells exposed to both cisplatin and the magnetic field exhibited higher viability compared to those treated with cisplatin alone, but only at selected points was this effect statistically significant. However, for certain concentrations (e.g., 200 μM for MCF-7 and 100 μM for A431), the opposite trend was observed, although the differences were not statistically significant. These observations suggest that the variability in cell viability might be related to measurement uncertainties or biological variability rather than consistent biological effects.

Similar effects were observed for the LoVo (colon cancer) cell line, where a statistically significant increase in cell viability was observed at 100 μM and 200 μM cisplatin concentrations in the presence of the magnetic field compared to cisplatin alone. This indicates that, under specific conditions, the magnetic field may enhance the proliferative response of LoVo cells to cisplatin treatment, particularly at intermediate drug concentrations.

In the experiment shown in Fig. 8, the magnetic induction value was increased to 2.5 mT. The increased exposure value led to a significant modification of the response of tumor cells to cisplatin treatment, resulting in a significant reduction in tumor cell viability. In this case, the pro-proliferative effect observed in Fig. 7 did not occur, and the cytotoxic effect of cisplatin was significantly enhanced by the altered magnetic field parameters. These results demonstrate that increasing magnetic field induction significantly enhances the cytotoxic effects of cisplatin treatment. While the observed cytotoxicity suggests a potential synergistic effect of high magnetic field induction, further studies are needed to determine whether specific field parameters could be optimized to achieve differential outcomes, such as proliferation or cytotoxicity, under safer and more clinically applicable conditions.

The observed increase in cell viability at low cisplatin concentrations (20 and 40 μM) in the group not exposed to MF (Fig. 8a) may arise from several factors. One possible explanation is the stimulation of cell metabolism in response to mild

cytotoxic stress induced by low doses of cisplatin. At such low concentrations, cells may activate adaptive mechanisms, such as increased energy production in mitochondria or activation of pro-survival pathways [30, 31]. This effect requires further investigation to determine the exact mechanisms underlying this phenomenon, for example, by analyzing oxidative stress markers and mitochondrial activity.

The conducted studies demonstrate that a magnetic field with specific parameters can significantly influence the response of cancer cells to cisplatin treatment. The application of a magnetic field may either promote cell proliferation at higher cytostatic concentrations or, with appropriately adjusted parameters, lead to enhanced cytotoxicity.

It was confirmed in the literature that the magnetic field affects healthy cells differently than cancer cells and is specific to a given type of cancer [32].

These observations were also confirmed by in vivo studies conducted on mice implanted with tumors. The group receiving cisplatin and exposed to ELF-MF had a longer survival time than the group treated with cisplatin alone, without exposure to MF. However, in the same experiment, in mice treated with cyclophosphamide, such an effect was not observed. It can also be concluded that the action of ELF-MF is related to the mechanism of action of cisplatin and increases the production of free oxygen radicals [33].

The effect of ELF-MF also depends on the type of cancer. For example, MCF-7 cells treated with cisplatin and bleomycin and exposed to MF at a frequency of 50 Hz showed greater susceptibility to cytostatics compared to cells not exposed to MF. However, such an effect was not observed for SH-SY5Y neuroblastoma cells [34].

The research has potential limitations. All cell lines were exposed to the same field parameters and concentrations of the same cytostatic cisplatin. It would be reasonable to extend the studies to other cytostatics in the future. This may show whether EMF will affect drugs with other mechanisms of action in an equivalent way. The experiment was performed on cell cultures and not in vivo, but the advantage of this study is that animals are not exposed because these are preliminary studies. A better choice would also be 3D cultures rather than 2D, but these are preliminary studies, aimed at evaluating the device and parameter settings, and in the future, they may be repeated on 3D cultures.

One limitation of the study is that, while care was taken to separate control and test samples by culturing them in two independent incubators, further studies could include additional measurements to confirm the absence of stray magnetic fields in adjacent areas of the solenoid. These measurements would ensure that even low-level magnetic induction outside the solenoid does not influence the results. An additional limitation is the lack of direct measurements verifying the absence of stray magnetic fields outside the solenoid operational area. While the experimental design minimized this risk, future investigations should include such measurements to ensure the isolation of test and control environments.

What is more, the study was performed using magnetic field induction levels that far exceed accepted safety standards for human exposure. Thus, while the results are promising in demonstrating enhanced cytotoxic effects, the direct translation of these findings to clinical applications would require further validation using lower, clinically acceptable field strengths.

In addition, the biological variability of cancer cell lines used in the study could also influence the observed effects. Variability between cell lines and even between passages of the same cell line may affect the reproducibility of the results. Furthermore, translating in vitro findings into clinical applications remains a significant challenge, as the tumor microenvironment in vivo is far more complex and dynamic than in controlled cell culture conditions.

5. CONCLUSIONS

A universal laboratory bench has been designed to test the exposure of the magnetic component of the MF to cultures of cancer cell lines, placed on 24, 48, or 96-cell plates. On the stand it is possible to set any value of magnetic induction up to a maximum level of 2.5 mT in the extremely low frequency range up to 300 Hz. The bench facilitates testing the effectiveness of various cytostatic agents of selected concentrations, along with studying the effect of the electromagnetic field on the reduction of cancer cell viability. The results confirm that higher magnetic field induction correlates with increased cytotoxicity in cancer cells treated with cisplatin. While this finding supports the potential for magnetic field applications in adjuvant therapy, it is important to emphasize that the study was conducted under conditions of relatively high magnetic field induction, which exceeds established safety thresholds. Therefore, the ability to fine-tune field parameters for clinical applications remains speculative and requires further investigation.

On the laboratory bench setup, preliminary research experiments were conducted on cancer cells with a 60 Hz signal and a preset magnetic induction of 1.25 mT and 2.5 mT. Cultures of human cancer cells of the LoVo (colon cancer), MCF-7 (breast cancer), and A431 (skin cancer) lines were tested. From the results obtained, it is noticeable the molar concentrations of the cytostatic for which reduced viability of tumor cells is observed in comparison with the control group not subjected to magnetic field exposure.

The conducted studies show initially that a magnetic field with specific parameters can significantly affect the response of cancer cells to cisplatin treatment. It is possible that the use of a magnetic field can either promote cell proliferation at higher cytostatic concentrations or, with appropriately adjusted parameters, lead to increased cytotoxicity.

For the designed solenoid, tests were conducted on the uniformity of magnetic induction exposure in its inner space. Based on the research, recommendations are made to place the cell culture plate near the geometric center of the solenoid. The test results obtained for further medical analysis are considered only from the center cells of the plate within a radius of no more than 5 cm from the central point of the solenoid. Only the cells in this area can be considered to have undergone uniform exposure with inhomogeneities not exceeding +10%.

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