



Effects of 1800 MHz and 2100 MHz mobile phone radiation on the blood–brain barrier of New Zealand rabbits

Abdullah Oğuz Kizilçay¹ · Bilal Tütüncü² · Mehmet Koçarslan³ · Mahmut Ahmet Gözel⁴

Received: 1 July 2024 / Accepted: 28 October 2024 / Published online: 16 November 2024
© International Federation for Medical and Biological Engineering 2024

Abstract

In this study, the impact of mobile phone radiation on blood–brain barrier (BBB) permeability was investigated. A total of 21 New Zealand rabbits were used for the experiments, divided into three groups, each consisting of 7 rabbits. One group served as the control, while the other two were exposed to electromagnetic radiation at frequencies of 1800 MHz with a distance of 14.5 cm and 2100 MHz with a distance of 17 cm, maintaining a constant power intensity of 15 dBm, for a duration equivalent to the current average daily conversation time of 38 min. The exposure was conducted under non-thermal conditions, with RF radiation levels approximately ten times lower than normal values. Evans blue (EB) dye was used as a marker to assess BBB permeability. EB binds to plasma proteins, and its presence in brain tissue indicates a disruption in BBB integrity, allowing for a quantitative evaluation of radiation-induced permeability changes. Left and right brain tissue samples were analyzed using trichloroacetic acid (TCA) and phosphate-buffered solution (PBS) solutions to measure EB amounts at 620 nm via spectrophotometry. After the experiments, BBB tissue samples were collected from the right and left brains of all rabbits in the three groups and subjected to a series of medical procedures. Samples from Group 1 were compared with those from Group 2 and Group 3 using statistical methods to determine if there were any significant differences. As a result, it was found that there was no statistically significant difference in the BBB of rabbits exposed to 1800 MHz radiation, whereas there was a statistically significant difference at a 95% confidence level in the BBB of rabbits exposed to 2100 MHz radiation. A decrease in EB values was observed upon the arithmetic examination of the BBB.

Keywords Electromagnetic radiation · GSM frequencies · Blood–brain barrier · New Zealand rabbit

1 Introduction

In recent decades, the ubiquitous use of mobile phones and the growing concern over potential health risks associated with their radiofrequency electromagnetic radiation emissions have sparked extensive scientific investigation [1–6]. Of particular interest is the effect of these emissions on the blood–brain barrier (BBB), a crucial physiological barrier

that plays a pivotal role in maintaining the central nervous system's microenvironment [5, 7, 8].

The blood–brain barrier (BBB) is formed by specialized brain microvascular endothelial cells (BMECs) that control the passage of substances into the brain. Tight junctions create high trans-endothelial electrical resistance (TEER) and restrict molecule diffusion, while efflux transporters like p-glycoprotein remove unwanted lipophilic substances. Although the BBB protects the brain, it poses challenges for drug development by limiting the absorption of most pharmaceuticals. When compromised, the BBB is linked to neurological disorders such as Alzheimer's disease, stroke, and multiple sclerosis, leading researchers to develop models for in vitro studies of its mechanisms [9, 10]. However, BBB permeability can be influenced by various factors, including pathological conditions, multiple sclerosis, stroke, and diabetes, as well as exposure to ionizing and non-ionizing radiation [11]. For instance, radiofrequency (RF) radiation has been shown to increase BBB permeability, allowing

✉ Bilal Tütüncü
bilaltutuncu@itu.edu.tr

¹ Department of Computer Engineering, Zonguldak Bülent Ecevit University, Zonguldak, Turkey

² Energy Institute, Istanbul Technical University, Istanbul, Turkey

³ Department of Sterilization, Dursun Odabaş Medical Faculty, Van Yüzüncü Yıl University, Van, Turkey

⁴ Department of Electrical and Electronics Engineering, Süleyman Demirel University, Isparta, Turkey

normally excluded substances to penetrate the brain, potentially impacting neurological health [5]. Furthermore, ultra-wideband electromagnetic pulses have demonstrated the ability to disrupt BBB integrity in animal models [8].

Understanding the interaction between mobile phone radiation and the BBB is essential, as any disruption in BBB integrity could have profound implications for brain health and function [12]. The two primary frequencies utilized in contemporary mobile telecommunications, 1800 MHz and 2100 MHz, have garnered substantial attention due to their widespread application in cellular networks worldwide [13, 14]. For example, in ref. [15], it has been demonstrated that radiation from mobile phones at 900, 1800, and 2100 MHz frequencies can increase oxidative damage in the frontal lobes of rat brain tissues, an increase in lipid peroxidation, and oxidative DNA damage. Additionally, exposure to 2100 MHz radiofrequency radiation has been shown to induce single-strand breaks in DNA. In ref. [16], it was observed and presented that exposure to 900–1800 MHz radiation caused oxidative stress in the tissues of pregnant mothers and their offspring. In ref. [17], it has been observed that radiofrequency radiation at 2100 MHz can damage the nasal septal mucosa and disrupt mucociliary clearance in rats. While numerous studies have explored the biological effects of radiofrequency radiation, the specific impact of these frequencies on BBB permeability remains an area of ongoing investigation [18–20].

This study aims to contribute to our understanding of the potential consequences of exposure to 1800 MHz and 2100 MHz mobile phone radiation on the BBB. New Zealand rabbits were chosen for this study as they are commonly used in neurobiological research due to their manageable size, well-characterized physiology, and suitability for blood–brain barrier (BBB) studies. Their consistent anatomy helps in generating reliable, reproducible results. Additionally, their larger brain size compared to smaller animals allows for more precise sampling and analysis of brain tissues. Using New Zealand rabbits as an experimental model, we conducted a controlled investigation, mimicking real-world exposure conditions to evaluate any discernible alterations in BBB permeability. By utilizing rabbits, a common animal model for neurobiological research, we sought to provide insights into the implications for mammalian brain health and the potential risks associated with chronic mobile phone usage. The experimental design involved exposing rabbits to radiation levels within the range of typical daily mobile phone usage while carefully monitoring the BBB's response. Subsequent analysis and statistical examination of collected data aimed to determine whether any significant changes in BBB integrity occurred as a result of exposure to 1800 MHz and 2100 MHz mobile phone radiation. Twenty-one New Zealand rabbits were used in the study, divided into three groups. Two groups were exposed to electromagnetic

radiation at different frequencies, maintaining a constant power intensity of 15 dBm, while one group served as a control. After the experiments, samples were taken from the rabbits' brains. Statistical analysis revealed a significant difference in the BBB of rabbits exposed to 2100 MHz radiation but not in those exposed to 1800 MHz radiation. This was confirmed by a decrease in EB values.

The findings from this study hold the potential to inform public health policies, contributing to the ongoing dialogue on mobile phone radiation safety. Additionally, they may provide valuable insights into the broader field of electromagnetic radiation and its influence on neurological health, offering a foundation for further research and potential risk mitigation strategies.

2 Materials and methods

2.1 Antenna selection and design

In this section, two identical antenna designs were implemented to apply electromagnetic waves to rabbits and determine the effects of these waves on rabbits based on frequency and power values.

Depending on the distance between the receiver and transmitter antenna, the EM field region is generally divided into reactive near field, radiated near field (Fresnel), and far-field (Fraunhofer) regions. These radiated field regions are calculated in relation to the dimensions of the antenna [21] as shown in the formula 1.

$$\lambda = \frac{c}{f} \Rightarrow \begin{cases} r \leq \frac{\lambda}{2\pi}, & \text{Reactive near field} \\ \frac{\lambda}{2\pi} > r \leq 2\lambda, & \text{Radiated near field} \\ r > 2\lambda, & \text{Far field} \end{cases} \quad (1)$$

Here, the distance between the receiver and transmitter antenna is r (m), the propagation speed of the EM wave in space is c (3×10^8 m/s), the operating frequency of the RF source is f (Hz), and the wavelength is expressed as λ (m). The dimensions of a microstrip antenna are calculated in direct relation to the operating frequency region. In urban areas, a tissue can be positioned in these three different regions depending on the distance to the transmitter antenna according to different scenarios. However, urban signals generated by sources such as continuous broadcasting base stations are often exposed in the far-field region.

A wideband circular monopole antenna design was developed, taking into consideration the frequency range to be used in the study and the far-field limits of the electromagnetic wave. Rogers AD255C material was used as the substrate material in the design of the developed monopole antenna. This material has electrical and physical properties

with a substrate thickness of 0.762 mm, a loss tangent value of 0.009, and a dielectric constant of 2.55. The parameters indicating the physical lengths of the designed antenna are shown in Fig. 1a, and the antenna produced is illustrated in Fig. 1b.

In this study, a circular monopole antenna design was preferred for its ability to operate in a wideband [22]. The geometry and physical length parameters of the microstrip circular monopole antenna design are illustrated in Fig. 1. As shown, the antenna consists of a circular patch with a radius of $R = 18$ mm. This radius allows for the calculation of the center frequency at which the antenna can operate effectively [23]. Additionally, the feeding line, which comprises the matching sections and consists of three segments, has lengths of $y_1 = 15$ mm, $y_2 = 15$ mm, and $y_3 = 27$ mm, along with widths of $x_1 = 3.4$ mm, $x_2 = 1.6$ mm, and $x_3 = 2$ mm. The antenna is designed on a substrate material with dimensions of $50 \times 90 \times 0.762$ mm³, which possesses electrical properties consistent with Rogers AD255C. Rogers AD255C laminates use a fluoropolymer resin system combined with ceramic materials and fiberglass, offering low loss, reduced thermal expansion, and minimized passive intermodulation (PIM).

Various techniques can be applied for impedance matching. Optimization of ground slots and feeding lines is considered a common approach [24–28]. In this design, different width and length microstrip lines and a ground slot with a width of $x_4 = 4$ mm are used to match the circular patch to the feeding line. The operating frequency band for

the designed antenna can be extended using these matching techniques or other methods. CST (Computer Simulation Technology) Microwave Studio software was employed for antenna design. The simulation results of the return loss (S11) for the design were compared with measurement results obtained using the FSH6 model of Rohde and Schwarz handheld spectrum analyzer with a directional coupler. The S11 graph, which depicts simulation and measurement results, is presented in Fig. 2. This graph also illustrates the frequency bands that can be covered by this antenna.

Figure 2 demonstrates that the return loss (S11) of the designed antenna is below -10 dB in the range of 1–6 GHz. This indicates that the antenna can transmit a minimum of 90% of the power sent to it and can receive RF signals from the environment with similar efficiency in this frequency range. The frequencies of 1800 MHz and 2100 MHz, planned for use in this study, are within the designed antenna's operating range. Since the receiver and transmitter antennas (Rx/Tx) used in this study are identical, these results are applicable to both antennas.

2.2 System design for RF signal generator and RF power level detection system

When selecting RF devices for the experimental setup, attention should be paid to the operating frequency range and RF power level values. Particularly considering the RF signal exposure generated by mobile phones, a voltage-controlled

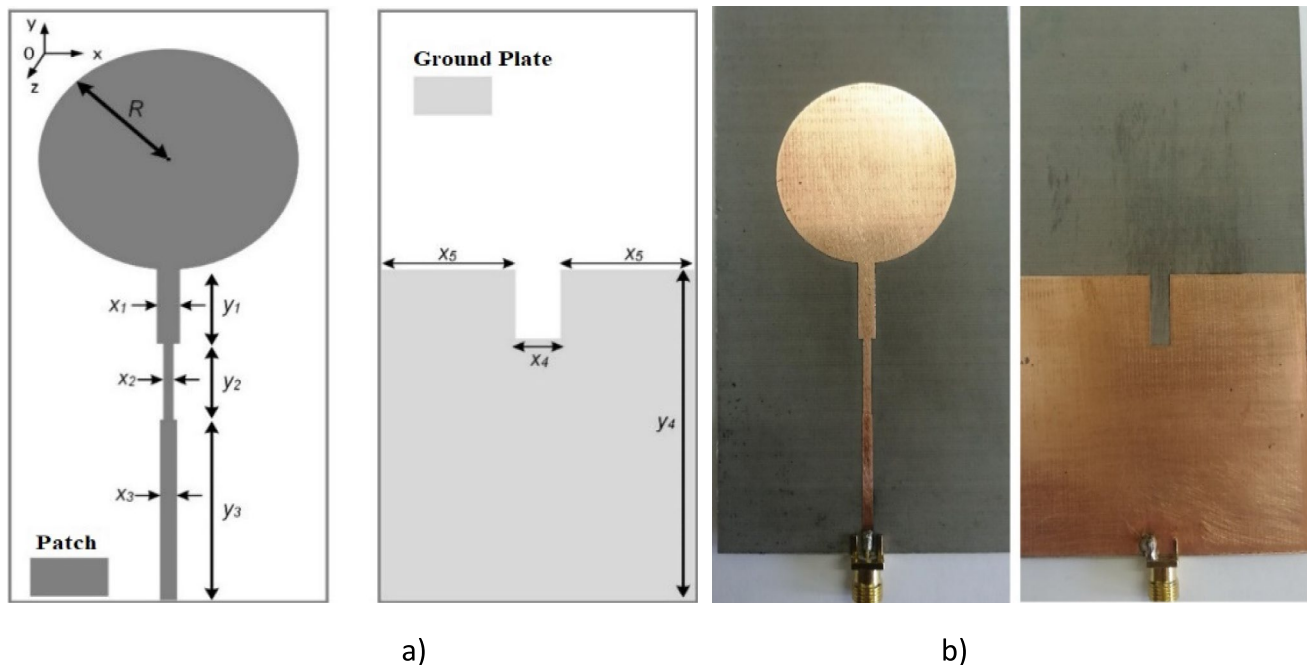
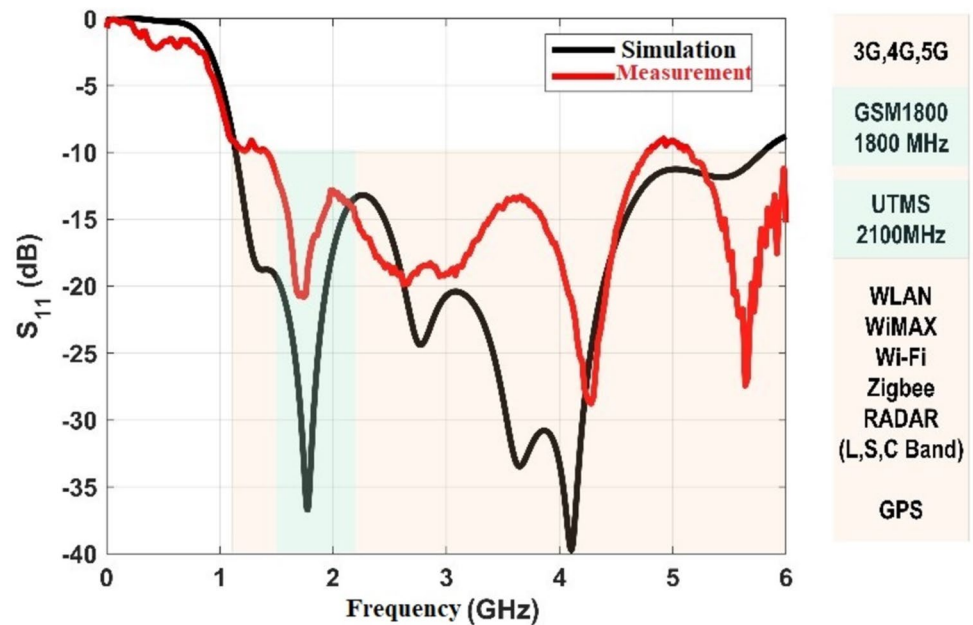


Fig. 1 Designed antenna: **a** physical dimensions and **b** manufactured image

Fig. 2 Return loss (S_{11}) of the Rx/Tx antenna



signal source capable of generating power levels ranging from -50 to 13 dBm at frequencies of 1800 MHz and 2100 MHz was used for this study. Additionally, a RF power detector, capable of operating in the 0 – 8000 MHz frequency range, was used to instantly detect and record the exposure of the generated signal on experimental animals. Furthermore, both transmitter and receiver antennas were employed to collect the generated RF signals and allow them to propagate as electromagnetic waves in the experimental environment. The working principle of the experimental setup comprises two main stages: the first part involves an RF oscillator, RF power amplifier, and a transmitting antenna for generating

and propagating RF signals, while the second part includes a receiving antenna, RF power detector, analog-to-digital converter (ADC), and a computer for data recording. Additionally, a DC voltage source powers the active circuits in the system, as depicted in Fig. 3 for the experimental setup.

The drawing created in Fig. 3a shows the location of the devices used in the measurement setup and the connection types of these devices to each other. In the experimental setup shown in Fig. 3, an RF oscillator circuit (Mini-Circuits ZX95-2500-S + model) is used to generate an RF signal at a frequency of 1800 MHz with a 6 dBm output power. The generated RF signal can be amplified to

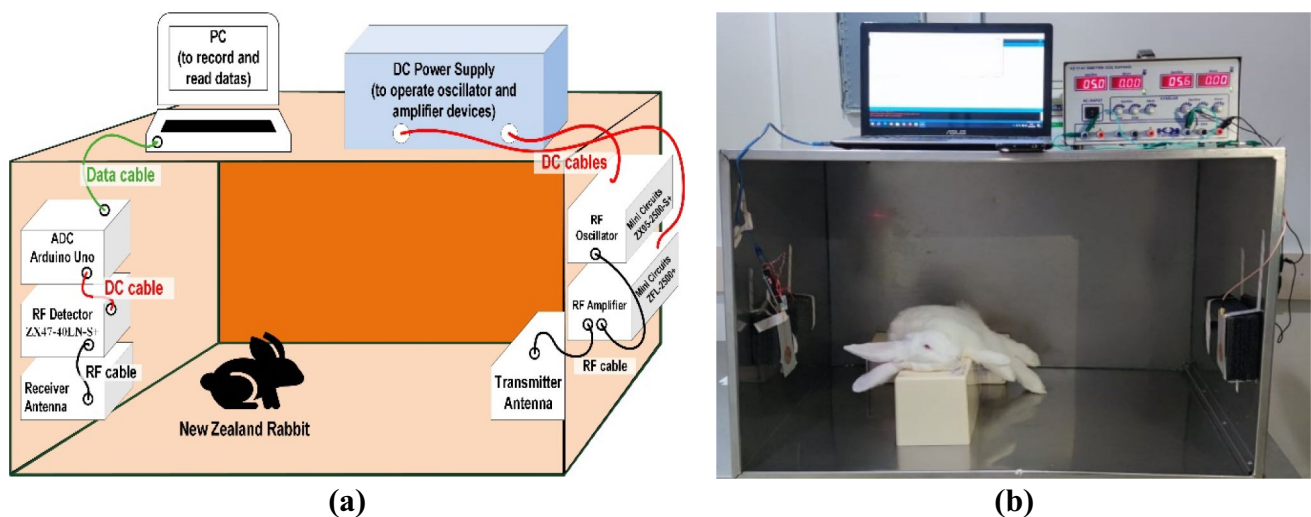


Fig. 3 Experimental environment and the RF system components. **a** Schematic and **b** real environment

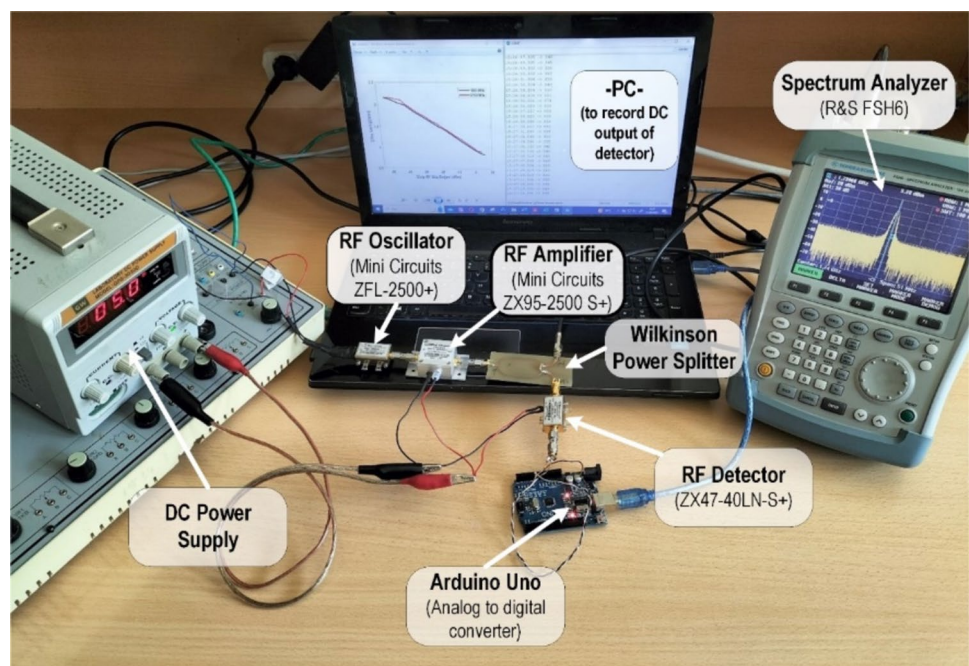
a power level of 15 dBm using an RF power amplifier. The produced RF signal is then sent to a transmitting antenna to propagate it into the air medium. To ensure that the measurements of the rabbit are not affected by other potential RF signals in the environment, the measurements were conducted in a laboratory environment with reduced electromagnetic interference, within a metal cage. The transmitting antenna was placed inside this cage using foam and aligned with the receiving antenna. The experimental rabbit exposed to the electromagnetic wave was positioned closer to the receiving antenna, between the two antennas. The power level of the RF signals obtained by the receiving antenna is determined to instantaneously identify the RF power to which the rabbit is exposed. The RF signal received by the receiving antenna is transferred to the RF power detector circuit. The RF power detector converts the RF signals it receives at the input into DC signals, generating a DC voltage at the output. The output voltage of the RF power detector is transferred to a computer environment via an ADC circuit and recorded. As a result, this system allows for the real-time detection of the RF power values of the signals sent into the environment. In existing systems, the output values of the devices used to expose experimental animals to RF signals are not tested in real-time. Therefore, it is not possible to monitor whether the experimental animals are continuously exposed to the same RF power levels for the desired duration. This deficiency could lead to errors in the experiments conducted. With this developed system, both the signal generation component at the desired frequencies and a setup capable of instantaneously detecting and recording the impact of

these signals on the experimental animals have been created. This allows for tracking the RF signals to which the experimental animals are exposed, thus enhancing the reliability of the experiments conducted.

The voltage values obtained at the output of the detector circuit are recorded in a computer environment at 1-s intervals. The recorded data represents voltage values in millivolts (mV) and the corresponding time at which these voltage values were obtained. The RF power detector used in this setup is the Mini-Circuits ZX47-40LN-S+ model, capable of operating in the frequency range of 0–8000 MHz and providing output voltages ranging from 2100 to 500 mV between –50 and 20 dBm output power levels. To determine the RF signal power received at the input based on the voltage values obtained at the output of this detector, an RF input power vs. output voltage graph has been created for the frequencies used in the experiment, specifically 1800 MHz and 2100 MHz. To generate this graph, the setup shown in Fig. 4 has been developed.

Figure 4 represents a system designed to determine the output voltage of the RF power detector within specific limits based on the input power at 1800 MHz and 2100 MHz frequencies. Through this detection, the RF input power levels can be inferred from the recorded output voltage values. Consequently, it becomes possible to monitor the real-time power levels of the RF signals received by the Rx antenna. In essence, this allows for tracking the instantaneous power values of the RF signal to which the experimental animal is exposed. Two different DC voltage sources have been used in this setup. These DC voltage sources were used to power active circuits such as the RF oscillator, power

Fig. 4 Setup developed for determining output voltage based on input power in the RF power detector circuit



amplifier, and RF detector circuit. The power levels generated by the RF oscillator circuit, ranging from -50 to 6 dBm, were increased to a maximum of 15 dBm using the RF power amplifier. RF signals generated in 1 dB increments between -50 and 15 dBm were split in half using a Wilkinson power splitter circuit, with one half directed to a spectrum analyzer and the other half sent to the RF detector circuit. The voltage values generated at the output of the RF detector circuit were transferred to a computer environment

and recorded. The DC voltage values displayed on the computer screen were compared with the RF power levels observed on the spectrum analyzer screen, and data were recorded for each 1 dB increment generated between -50 and 15 dBm. This allowed for the determination of the output voltage corresponding to the input power of the RF power detector within the range of -50 to 15 dBm. With this setup, the output voltage values corresponding to the input power of the RF power detector were separately identified for 1800 MHz and 2100 MHz, and a graph as shown in Fig. 5 was plotted.

The output voltage obtained using the graph shown in Fig. 5 was recorded for the desired frequency values, and the recorded output voltage data during the measurement time interval was used to determine the RF signal power applied to the experimental animal in the experimental environment. The results indicated that the power levels applied to the experimental animal remained constant during the experimental phase. Figure 6 displays the RF devices used in this experimental setup.

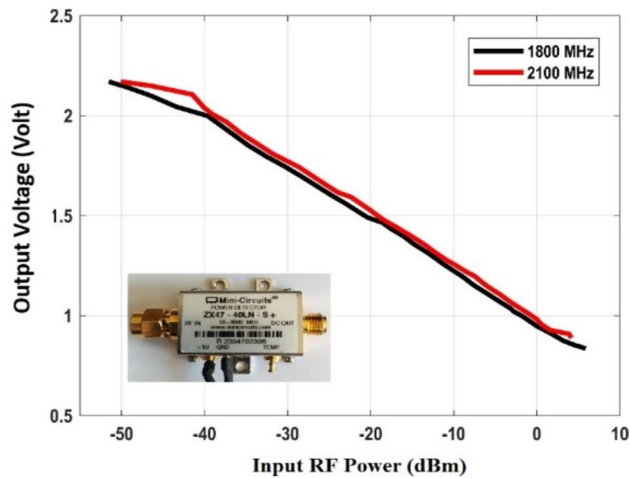


Fig. 5 Output voltage vs. input power graph for the RF power detector

2.3 Equipment utilized in the chemical study

In the course of our research, several pieces of laboratory equipment were employed to ensure accurate and precise measurements. These instruments included the Milton Roy Spectronic 3000 Array spectrophotometer, the Shimadzu AEG-220 balance, the WTW pH 315 pH meter, the Stuart 5A3 vortex mixer, micropipettes ranging from 100 to 1000

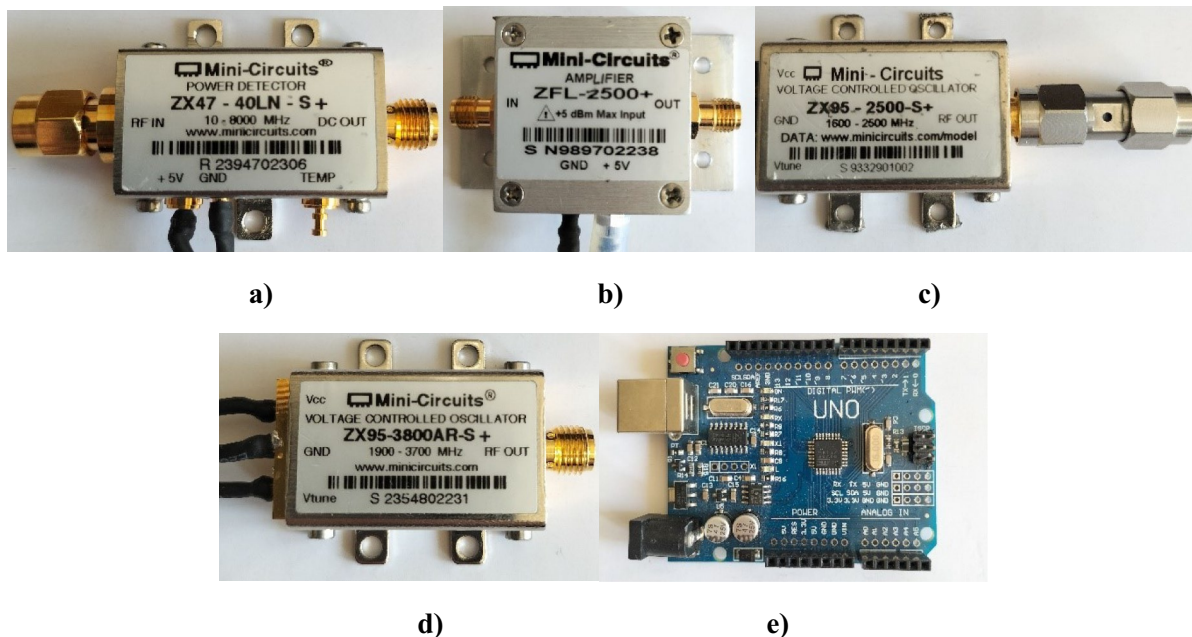


Fig. 6 RF devices used in this experimental setup: **a** RF power detector, **b** RF amplifier, **c** oscillator, **d** oscillator, and **e** Arduino Uno

μL , as well as other standard laboratory supplies. Additionally, the Hielscher UP 50 H ultrasonic homogenizer and the Nüve-NF 800 R centrifuge were integral to the experimental setup.

2.4 Chemicals employed in the research

Various chemicals were used throughout our investigation to facilitate our experiments. These included substances such as ketamine, xylazine, Evans blue (EB), physiological serum, Na_2HPO_4 , NaH_2PO_4 , and TCA (trichloroacetic acid).

2.5 Experimental animals

For our study, we utilized a total of 21 female New Zealand rabbits. These rabbits were divided into three groups, each containing seven subjects. The rabbits had an average weight of around 3 kg and were bred by the Experimental Research Laboratory of Atatürk University. Prior to the commencement of our experiments, these rabbits underwent an adaptation period lasting 1 to 2 weeks at the Yüzüncü Yıl University Experimental Research Center (YYÜDAM).

2.6 Experimental groups

Our research was conducted with three distinct groups, each consisting of seven female rabbits with an average weight ranging from 2 to 5 kg. These groups were categorized as follows: with “N” signifying the number of subjects in each group: Group I, control female group ($N=7$); Group II, 1800 MHz GSM group ($N=7$); and Group III, 2100 MHz GSM group ($N=7$).

2.7 Determining exposure duration

The exposure duration of rabbits to RF radiation was determined to be 38 min, taking into account the current average daily talk time of 19 min for mobile phone users [29]. This average duration reflects typical mobile phone usage patterns. To simulate a more realistic exposure scenario, we chose to double the daily conversation time. Additionally, considering the widespread use of 4.5G for internet connectivity, this extended duration allows us to better assess the potential effects of RF radiation on the BBB.

2.8 Method

Evans blue (EB) is a dye widely utilized in studies to assess BBB permeability. EB binds to plasma proteins, primarily albumin, allowing researchers to evaluate the

integrity of the BBB. EB is characterized by its high affinity for plasma proteins, water solubility, and the capability to be quantitatively measured using spectrophotometry at a wavelength of 620 nm. These properties make EB an effective tool in our experiments for evaluating the impact of RF radiation on BBB integrity. Two grams of EB was weighed and mixed with physiological saline to a total volume of 100 mL using a magnetic stirrer, as seen in Fig. 7a. This resulted in a 2% EB solution. In this dose, EB was intended to bind entirely to plasma proteins, especially albumin, resulting in the staining of albumin in a blue color. This solution was administered to the subjects under anesthesia through a yellow (No. 24) catheter at a dosage of 4 mL/kg just before exposure. It was injected into the ear vein over an average duration of 8 min [29], as seen in Fig. 7b.

Following that, the subjects were exposed to the RF field using the specified microstrip antenna at distances of 14.5 cm for 1800 MHz and 17 cm for 2100 MHz for a duration of 38 min (refer to Fig. 3 for the experimental setup and RF system components). After the 38-min RF field exposure, the subjects’ chest cavities were opened. Cardiac perfusion was performed by delivering heparinized physiological saline from the left ventricle, and a washing process continued until colorless fluid was obtained from the right atrium. Heparin ensured that the blood-Evans blue (EB) mixture, which had been cleared from circulation, did not clot. The subjects were then decapitated, and their brain tissues were removed. In total, two pieces of brain tissue were prepared from each subject, including the right hemisphere and left hemisphere. These tissues were preserved at -40°C for chemical analysis.

2.8.1 PBS—phosphate-buffered solution (0.2 molar)

We used an isotonic medium, a phosphate-buffered solution (PBS), to maintain the integrity and viability of the cells. 21.8 g of Na_2HPO_4 and 6.4 g of NaH_2PO_4 were weighed and dissolved in distilled water to make up a total volume of 100 mL. A magnetic stirrer was used to ensure complete dissolution, and the pH was adjusted to 7.4 [30].

2.8.2 TCA—trichloroacetic acid

To prepare a 60% TCA solution, 60 g of TCA were weighed and diluted with distilled water to a total volume of 100 mL [31]. Mixing was achieved using a magnetic stirrer.

We planned to prepare the tissues for spectrophotometer reading as follows: After preparing the PBS, we distributed 2.5 mL of it into empty centrifuge tubes (e.g., Reiner,

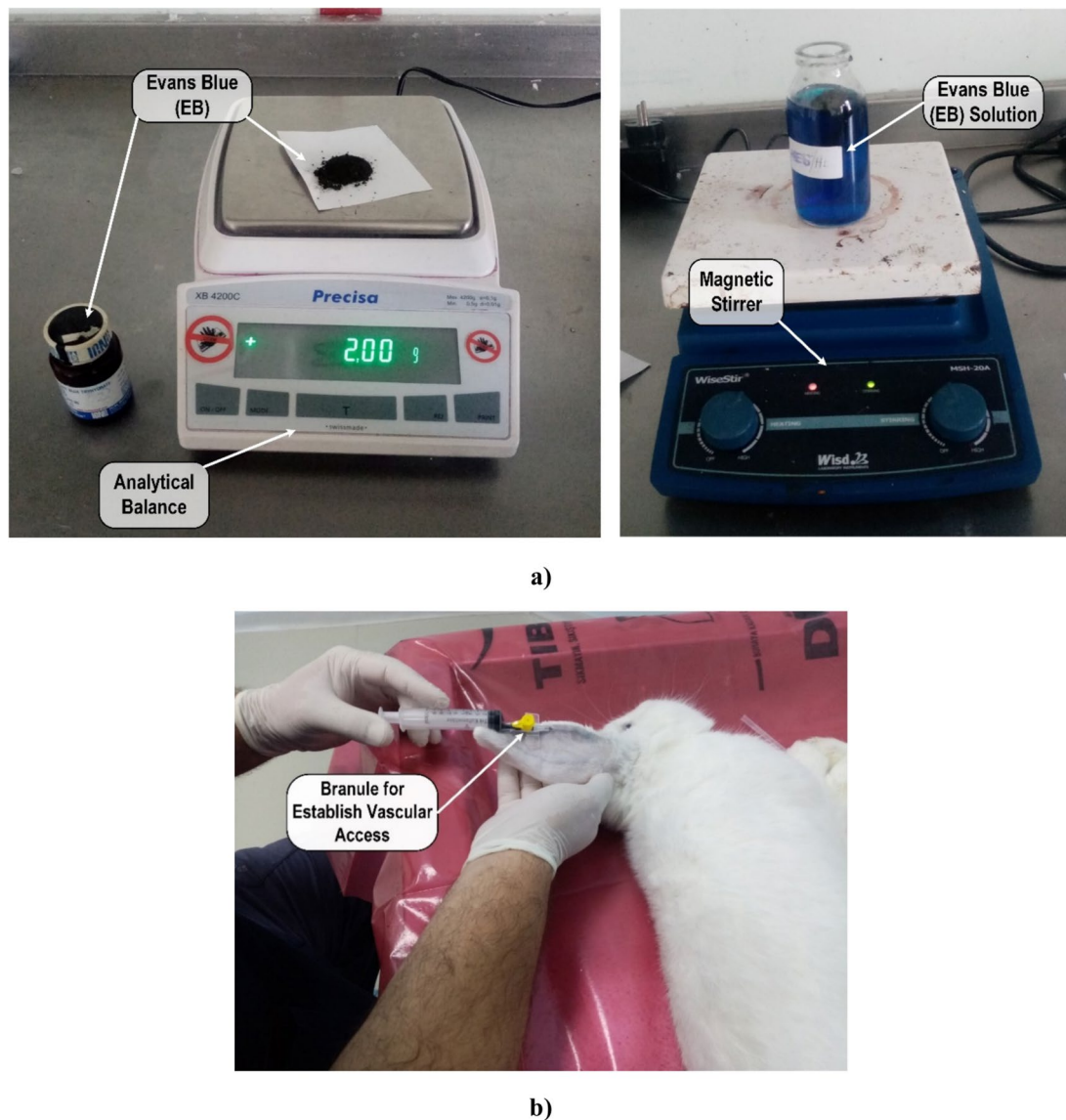


Fig. 7 **a** Preparation of EB and **b** insertion of the yellow (No. 24) catheter into the ear vein

12 mL capacity), leaving 2.5 mL of space in each tube. After transferring the tissues to the tubes, homogenization will be carried out. We then distributed the previously prepared 60% TCA solution into each tube, again with 2.5 mL in each tube [32]. To ensure the complete homogenization of the mixture, we vortexed it and subjected it to a refrigerated centrifuge at 3000 rpm for 30 min (+4 °C). After allowing the tissues to rest overnight at +4 °C, our measurements were carried out at a wavelength of 620 nm, following the standard curve we prepared [32]. Figure 8 shows the homogenization process after transferring the tissues to the tubes, while Fig. 9 depicts the centrifugation of the prepared tubes.

2.8.3 Stock solution and standard curve

A stock solution was prepared by dissolving 0.01 g of EB in 100 mL of PBS, resulting in a 10 mg/mL EB solution. Subsequently, dilutions were made from this solution to prepare liquids with concentrations of 0.5 mg, 1 mg, 1.5 mg, 2 mg, 2.5 mg, and 3 mg, and a standard curve was plotted using these solutions. During the sample readings and the creation of the standard curve, equal amounts of mixed (2.5 mL + 2.5 mL) PBS + TCA solutions were used in a blinded manner. EB values in mg% were calculated for the right brain and left brain using the standard curve. Figure 10 shows the stock solution and the blinded curve.



Fig. 8 Homogenization process

2.9 Statistical evaluation

To determine whether there was a difference between the two groups and the normal group, the Kruskal–Wallis test was conducted, and the significance of the differences was assessed using the Mann–Whitney U test. The Mann–Whitney U test is used to compare two independent groups when the assumptions of parametric tests are not met. Applying a test of significance for the difference between two means without meeting parametric test assumptions can lead to incorrect conclusions. When parametric test assumptions are not met, the Mann–Whitney U test is the most powerful test that can be used. p -values of <0.01 and <0.05 were considered statistically significant.

3 Results

3.1 Spectrophotometer reading results and amounts of EB in unit tissues

EB was selected as a marker for assessing BBB absorption due to its unique properties. EB binds tightly to plasma proteins, primarily albumin, facilitating a clear evaluation of BBB integrity. Under normal conditions, EB cannot penetrate brain tissue; however, if the BBB is compromised, EB can enter the brain, indicating increased permeability. We expect to observe changes in EB absorption levels in brain tissue samples from rabbits exposed to RF radiation, especially at the 2100 MHz frequency, compared to the control group. This expectation is supported by existing literature [7, 8] suggesting that RF radiation may disrupt BBB integrity, leading to increased EB penetration.

Table 1 provides the mean EB absorption and standard deviations for the left brain and right brain. These data were then discussed in detail with graphs.

All groups were compared internally for the differences in the right and left brain using the Mann–Whitney U test. Statistically, when compared to the 1800 MHz control group, the EB passage through the blood–brain barrier was found to be insignificant despite being lower. In the case of the 2100 MHz group, the EB passage through the blood–brain barrier was found to be lower in both groups, and the test results were considered significant.

3.2 Comparison of right and left brains in the 1800 MHz group

3.2.1 Right brain at 1800 MHz

Figure 11a illustrates the mean concentrations of EB in the right brain tissue of the New Zealand rabbit groups. As evident from the graph, there has been a marginal arithmetic decrease in the absorbance (Abs) values' distributions for both the 1800 MHz and normal groups. Nonetheless, given that Exact Sig = 0.902 exceeds $\alpha = 0.05$ at a 95% confidence level, the null hypothesis has been considered statistically insignificant. Figure 11b is a bar graph, Fig. 11c is a pyramid graph, and Fig. 11d is a histogram graph, all related to the right brain in both the 1800 MHz and normal groups. In Fig. 11c and the corresponding sections of the subsequent figures, the term “frequency” on the axes refers to the rate at which specific events occur and is represented as the number of observations in a given sample at specific frequencies. Therefore, it is unitless.

The brief explanation of the graphs presented in Fig. 11 and subsequently in Figs. 12, 13 and 14 for panels a, b, c, and d is as follows:



Fig. 9 Centrifugation of the prepared tubes

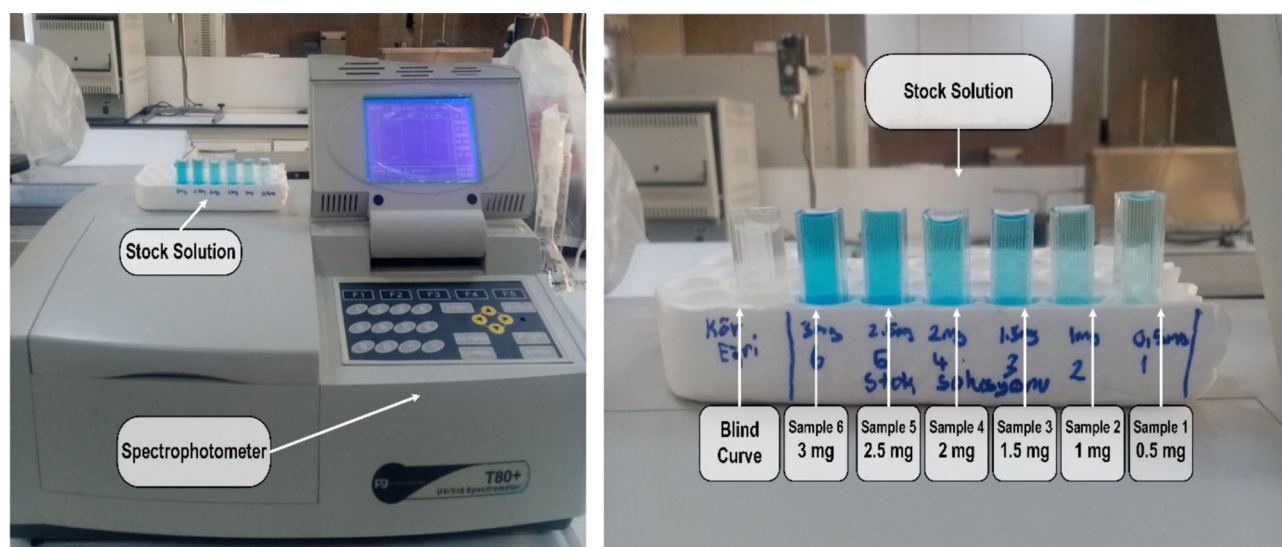


Fig. 10 Stock solution and blinded curve

Table 1 Comparison of the mean EB absorption and standard deviations for the left brain and right brain in all groups

	Right brain	Left brain
G-I: control group	0.1069 ± 0.03	0.1083 ± 0.04
G-II: 1800 MHz GSM	0.0877 ± 0.025	0.0844 ± 0.05
G-III: 2100 MHz GSM	0.039 ± 0.04	0.0276 ± 0.1

In panel a, these figures display the mean concentrations of EB in the brain tissue from all three groups.

Panel b displays bar graphs showing the Abs values obtained from the brain tissue samples (right or left brain) for each group. These graphs allow for a visual comparison between the Abs values of the control and experimental groups, illustrating the individual values rather than mean concentrations.

Panel c illustrates the Abs values obtained from the statistical comparisons between the two groups of rabbits, specifically showing the values within the range of 0.1

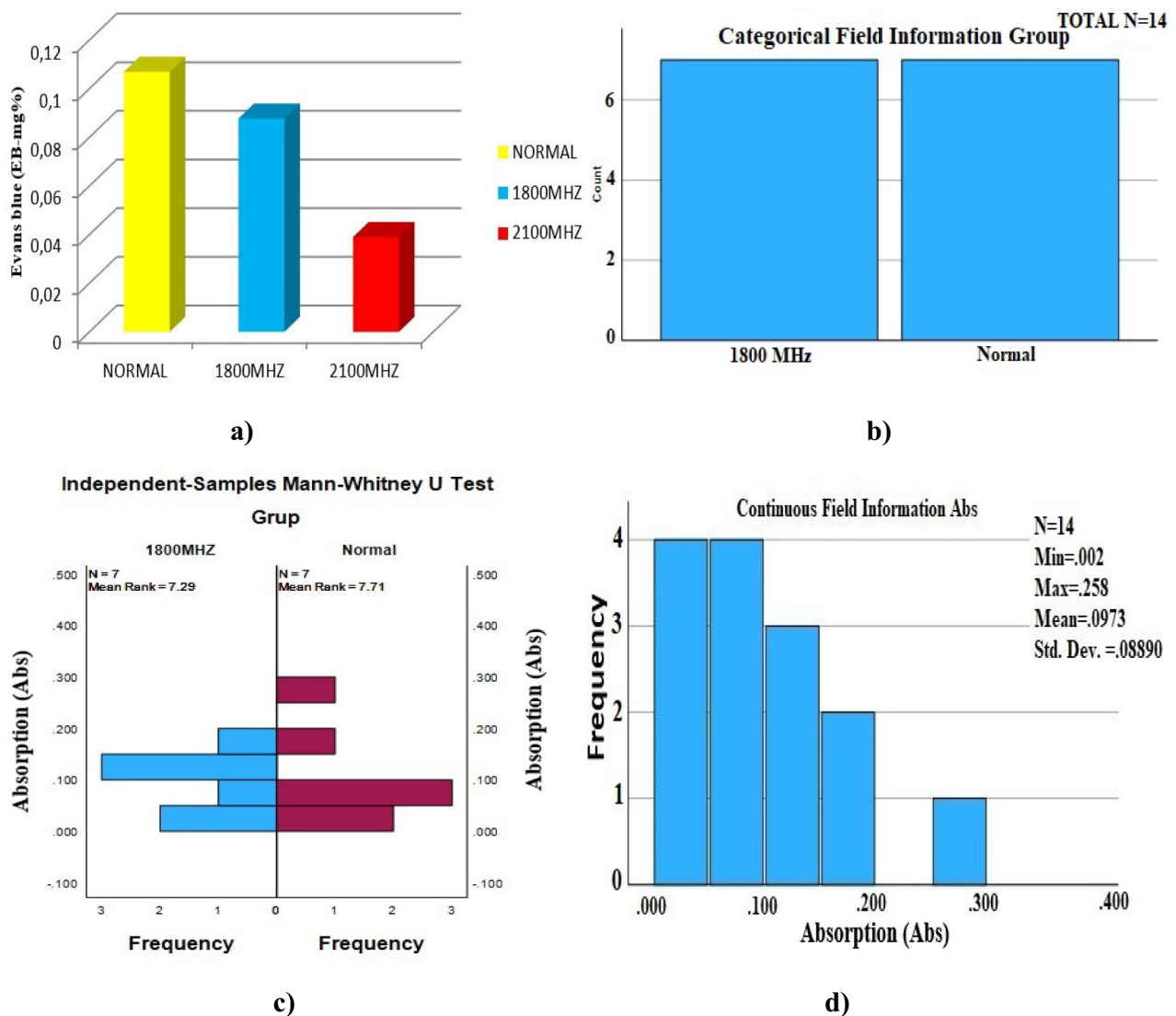


Fig. 11 Results for the right brain at 1800 MHz and normal groups. **a** EB levels. **b** Bar graph of 14 values. **c** Pyramid chart showing the number of observations. **d** Histogram graph of the 14 tested values

to 0.5. This serves as a form of classification. The term “frequency” refers to the observation frequency as it is displayed from the center of the graph toward the left or right. For example, in Fig. 11c, the 2 rabbits from Group 2 produced 2 frequencies in the 0.0 to 0.1 range, plus 1 frequency from another group, resulting in a total of 3 observations. In the 0.1 to 0.2 range, 3 frequencies from Group 2 plus 1 from another group yield 4 observations. Thus, we are discussing a total of 7 observations, highlighting how many rabbits fall within specific Abs value ranges.

Panel d shows the histogram of the combined Abs values from Group 2 (7 values) and Group 1 (7 values), totaling 14

Abs values displayed in a single histogram. This figure summarizes the values presented in panel c, as it showcases all 14 Abs values at once from left to right.

Analysis of the data and summary statistics are revealed in Table 2. There are a total of 14 observations. The Mann–Whitney *U* test value is 23, and the Mann–Whitney *U* test statistic is 0.902. Based on the statistical analysis conducted at a 95% confidence level ($\alpha=0.05$), the null hypothesis (H_0), which states that there is no significant difference in the Abs values (medians) between the 1800 MHz group and the normal group, cannot be rejected. Therefore, it is concluded that there is no statistically significant difference

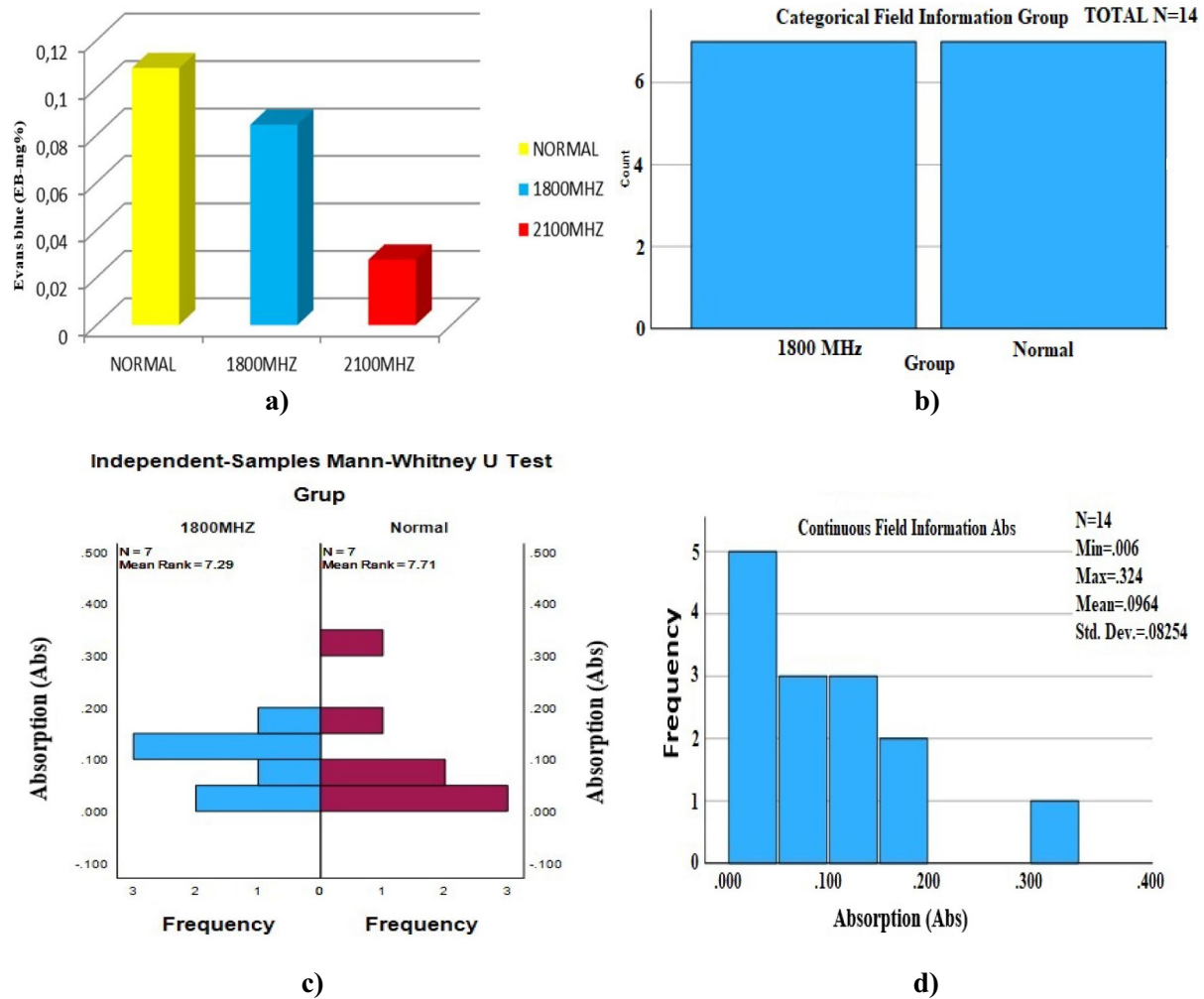


Fig. 12 Results for the left brain at 1800 MHz and normal groups. **a** EB levels. **b** Bar graph of 14 values. **c** Pyramid chart showing the number of observations. **d** Histogram graph of the 14 tested values

in the Abs values between the 1800 MHz group and the normal group.

3.2.2 Left brain at 1800 MHz

Figure 12a displays the average EB amounts in the left-brain tissue of New Zealand rabbit groups, with data provided below. As can be seen from the figure, the Abs values for 1800 MHz and normal have arithmetically decreased distributions, but statistically, the Exact Sig = 0.902 > $\alpha = 0.05$, indicating that at a 95% confidence level, the null hypothesis was found to be insignificant. A bar graph, a pyramid graph, and a histogram graph are provided in Fig. 12b–d, respectively, all related to the left brain in both the 1800 MHz and normal groups.

3.3 Comparison of right and left brain in the 2100 MHz group

3.3.1 Right brain at 2100 MHz

In Fig. 13a, the graph presents the average EB levels in the right brain tissue of New Zealand rabbit groups. As seen in the figure, within the 2100 MHz GSM modulation group, the Abs values for the normal group have shown a statistically significant arithmetic decrease in their distribution. The Exact Sig is 0.053, which is slightly greater than the alpha level (α) of 0.05 but still falls within the margin. Hence, it is considered statistically significant at a 95% confidence level. In Fig. 13b, a bar graph represents the 14 values of the right brain for both the 2100 MHz and Normal groups.

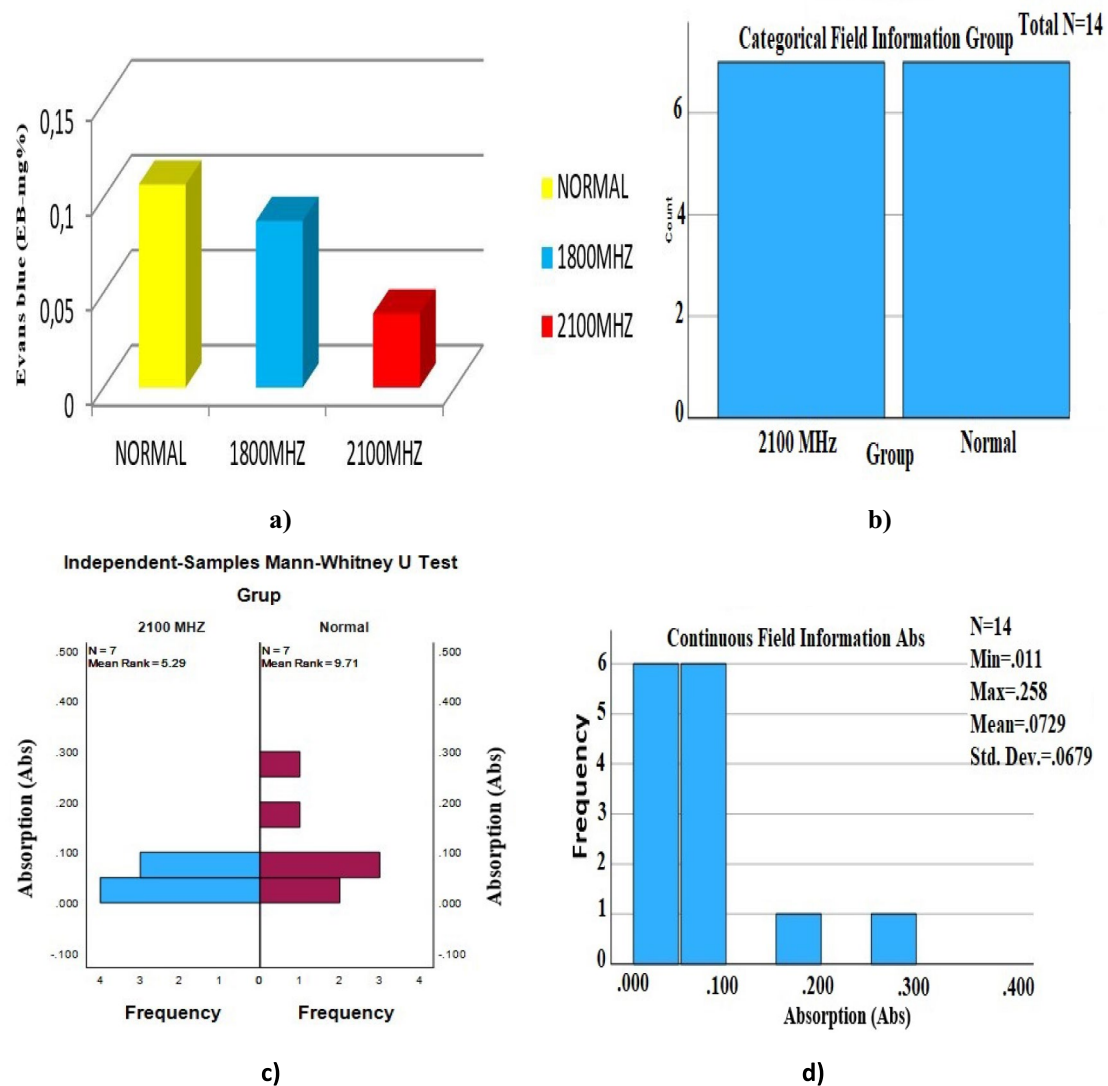


Fig. 13 Results for the right brain at 2100 MHz and normal groups. **a** EB levels. **b** Bar graph of 14 values. **c** Pyramid chart showing the number of observations. **d** Histogram graph of the 14 tested values

Figure 13c displays a pyramid graph illustrating the number of observations for the right brain in both the 2100 MHz and Normal groups, while Fig. 13d provides a histogram graph depicting the distribution of the 14 tested values for the right brain in both the 2100 MHz and Normal groups.

3.3.2 Left brain at 2100 MHz

In Fig. 14a, the graph depicts the average EB levels in the left-brain tissue of New Zealand rabbit groups. As observed from the figure, within the 2100 MHz GSM modulation group, there is a statistically significant decrease in the distribution of Abs values for the Normal group. The Exact Sig is 0.011, which is less than the alpha level (α) of 0.05.

Consequently, it is considered statistically significant at a 95% confidence level. A bar graph, a pyramid graph, and a histogram graph are provided in Fig. 14b–d, respectively, all related to the left brain in both the 2100 MHz and normal groups.

3.4 Comparison with literature

In recent years, extensive research has focused on the potential health effects of RF radiation, particularly in relation to brain health. This section aims to compare our findings with existing literature, providing a comprehensive overview of studies that analyze the impact of different radio frequencies on brain health, with an emphasis on

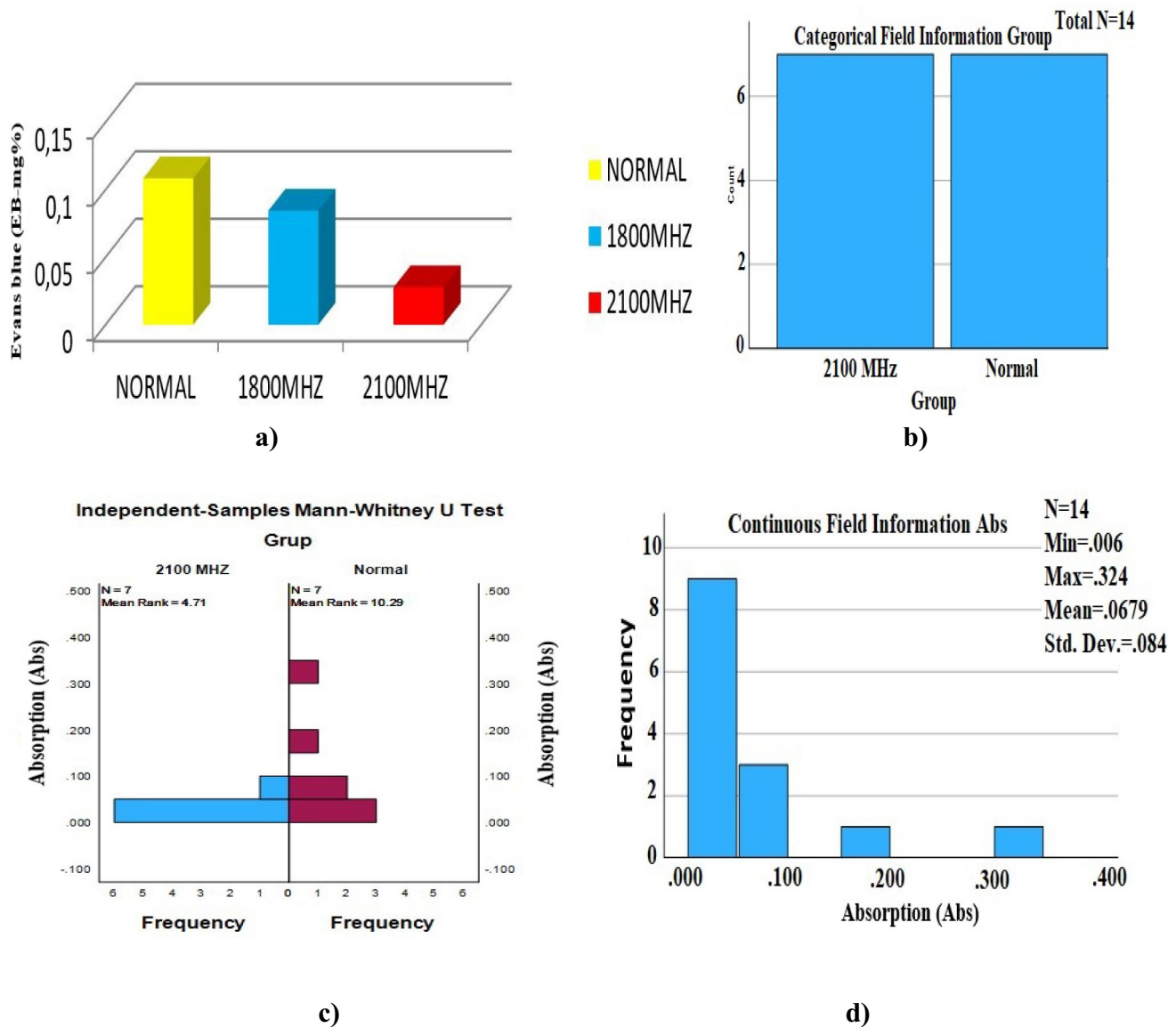


Fig. 14 Results for the left brain at 2100 MHz and normal groups. **a** EB levels. **b** Bar graph of 14 values. **c** Pyramid chart showing the number of observations. **d** Histogram graph of the 14 tested values

Table 2 Independent-samples Mann–Whitney *U* test summary*

Total <i>N</i>	14
Mann–Whitney <i>U</i>	26.000
Wilcoxon <i>W</i>	54.000
Test statistic	26.000
Standard error	7.826
Standardized test statistic	0.192
Asymptotic Sig (2-sided test)	0.848
Exact Sig (2-sided test)	0.902

*This table is provided here as it is valid for all subsequent analyses, and therefore, it is not repetitively presented in the following subsections

key parameters. Table 3 examines various studies analyzing how different radio frequencies impact brain health, focusing on parameters like frequency, exposure duration, and biological effects.

It is evident that various studies have investigated the impact of electromagnetic radiation at different frequencies on brain tissue. The analysis of these studies indicates that while lower frequencies may affect brain structure over a longer time frame, higher frequencies like 2.1 GHz have more immediate, statistically significant impacts, such as compromising BBB integrity. This comparison underscores the importance of further investigating the

Table 3 Effects of different frequencies on the brain

Ref	Model	Cage	Exposure duration	Freq. (GHz)	Effect
[33]	Mice	Yes	2 h/day	2.4	Causes oxidative and nitrosative stress, leading to p53 activation and subsequent apoptosis of hippocampal cells, which is linked to memory impairment
[34]	Human neuroblastoma and murine microglial cells	No	2 h/day	0.935	No observable effects on murine microglial cells (N9) and human neuroblastoma cells (SH-SY5Y)
[35]	Wistar rats	Yes	2 h/day	0.8–0.9	Induced epigenetic modulations in the hippocampus
[36]	Rats	N/A	15 min	2.856	Altered the metabolism of phospholipids and triglycerides (TG)
[37]	New Zealand rabbits	Yes	6 h/day	1.8	DNA damage was detected in brain tissues
[38]	Rats	Yes	8 h	2.115	Leads to oxidative stress in the brains of young rats, characterized by a significant rise in carbon-centered radicals and increased lipid peroxidation
[39]	Rabbit	No	30 min	1.8	Prolongation of certain auditory brainstem response (ABR)
This work	New Zealand rabbits	Yes	38 min	1.8–2.1	Significant effects on BBB permeability at 2100 MHz, no effect at 1800 MHz

threshold effects of different frequencies, especially those commonly used in mobile telecommunications.

4 Discussion and conclusion

This study posits the hypothesis that exposure to RF radiation at frequencies of 1800 MHz and 2100 MHz can alter the permeability of the BBB in New Zealand rabbits. Specifically, the 2100 MHz frequency may impact the electrical properties of endothelial cells, which are crucial for maintaining BBB integrity, potentially allowing substances that typically cannot enter the brain to penetrate. For this purpose, in this study, 21 New Zealand rabbits weighing between 2 and 5 kg were utilized. The rabbits were divided into three groups, with one group serving as the control, and the other two groups exposed to EM fields. In the RF exposure groups, rabbits were individually exposed to a homogeneous field. Anesthesia was administered using ketamine + xylazine, and 4 mL/kg of EB 2% solution was administered to the rabbits via a catheter inserted into the ear veins. The subjects were then exposed to the RF field using the specified microstrip antenna at 1800 MHz with a distance of 14.5 cm and at 2100 MHz with a distance of 17 cm for 38 min. The exposure was conducted under non-thermal conditions, with a radio frequency radiation level approximately ten times lower than the normal value, within a conductive cage and near-field exposure. After decapitating the rabbits, four brain tissue sections were prepared from each rabbit: the left and right brain. The tissues were stored at -40°C for further processing. After being subjected to analysis with TCA and PBS solutions, the EB amount was measured

at 620 nm using a spectrophotometer. A change in EB levels in the brain tissues of rabbits exposed to radiation, as compared to the control group, indicates that the BBB was compromised. Additionally, statistical analyses conducted using the Mann–Whitney *U* test demonstrated significant differences in EB absorption values between the experimental and control groups. These findings support the conclusion that exposure to RF radiation can disrupt BBB integrity.

The study results showed that there was no statistically significant difference at a 95% confidence level between the BBB permeability Abs value distributions in the right and left brain, for the 1800 MHz and normal group rabbits. However, a statistically significant difference at a 95% confidence level was observed in the BBB permeability Abs value distributions in the right and left brain for the 2100 MHz and normal group rabbits. If the confidence level is reduced to 90%, a significant difference can also be asserted for the right brain in this group. Although the BBB permeability values in the 1800 MHz and 2100 MHz groups differed arithmetically from the normal groups, it can be stated that statistically, the 1800 MHz group rabbits were not affected by EM radiation, while the 2100 MHz group rabbits were affected, and the BBB permeability changed. This observed downward change may lead to a disruption of the BBB integrity and could cause various neurological disorders. It is believed that the results obtained from this research will shed light on future similar studies. In terms of the contributions and novelty of this study, it can be stated that the measurement setup was introduced to minimize external noise signals that could affect the assessment of BBB permeability. A specialized cage environment was developed to isolate the experimental animal from RF signals of varying

frequencies present in the surroundings. The animal was exposed exclusively to RF signals at specified frequencies and power levels, while the ambient RF power levels were continuously monitored to detect any abnormal fluctuations. This innovative approach enhances the quality of the experiments and ensures controlled exposure conditions.

Funding This study was funded by the Scientific and Technological Research Council of Turkey (TUBITAK) ARDEB 1002 by Grant No 122E356.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval We obtained ethical approval for this study from the Animal Experiment Local Ethics Committee at Van Yüzüncü Yıl University (VAN YÜHADYK) by approval no:2021/01–08. The study was conducted in accordance with the ethical guidelines and standards for the use of animals in scientific research.

Conflict of interest The authors declare no competing interests.

References

- Hartwig V, Virgili G, Mattei FE, Biagini C, Romeo S, Zeni O, Giovannetti G (2022) Occupational exposure to electromagnetic fields in magnetic resonance environment: an update on regulation, exposure assessment techniques, health risk evaluation, and surveillance. *Med Biol Eng Comp* 60:297–320. <https://doi.org/10.1007/s11517-021-02435-6>
- Dasdag S, Akdag MZ, Bashan M, Kizmaz V, Erdal N, Emin-Erdal M, Yegin K (2022) Role of 2.4 GHz radiofrequency radiation emitted from Wi-Fi on some miRNA and fatty acids composition in brain. *Electromagnet Biol Med* 41(3):281–292. <https://doi.org/10.1080/15368378.2022.2065682>
- Maurya R, Singh N, Jindal T, Pathak VK, Dutta MK (2020) Machine learning–based identification of radiofrequency electromagnetic radiation (RF-EMR) effect on brain morphology: a preliminary study. *Med Biol Eng Compu* 58:1751–1765. <https://doi.org/10.1007/s11517-020-02198-6>
- Lameth J, Arnaud-Cormos D, Lévêque P, Boillée S, Edeline JM, Mallat M (2020) Effects of a single head exposure to GSM-1800 MHz signals on the transcriptome profile in the rat cerebral cortex: enhanced gene responses under proinflammatory conditions. *Neurotox Res* 38:105–123. <https://doi.org/10.1007/s12640-020-00191-3>
- Senturk F, Cakmak S, Kocum IC, Gumusderelioglu M, Ozturk GG (2022) Effects of radiofrequency exposure on in vitro blood-brain barrier permeability in the presence of magnetic nanoparticles. *Biochem Biophys Res Commun* 597:91–97. <https://doi.org/10.1016/j.bbrc.2022.01.112>
- Ibrani M, Hamiti E, Ahma L, Shala B (2016) Assessment of personal radio frequency electromagnetic field exposure in specific indoor workplaces and possible worst-case scenarios. *AEU-Int J Electron Commun* 70(6):808–813. <https://doi.org/10.1016/j.aeu.2016.03.007>
- Sırav B, Seyhan N (2016) Effects of GSM modulated radio-frequency electromagnetic radiation on permeability of blood–brain barrier in male & female rats. *J Chem Neuroanat* 75:123–127. <https://doi.org/10.1016/j.jchemneu.2015.12.010>
- Gao P, Chen Q, Hu J, Lin Y, Lin J, Guo Q, Guo G (2020) Effect of ultra-wide-band electromagnetic pulses on blood-brain barrier permeability in rats. *Mole Med Rep* 22(4):2775–2782. <https://doi.org/10.3892/mmr.2020.11382>
- Lippmann E, Azarin S, Kay J et al (2012) Derivation of blood-brain barrier endothelial cells from human pluripotent stem cells. *Nat Biotechnol* 30:783–791. <https://doi.org/10.1038/nbt.2247>
- Kandel ER, Schwartz JH, Jessell TM (2000) Principles of neural science. McGraw-Hill, New York
- Kozlira JM, Lockman PR, Allen DD, Mumper RJ (2006) The blood-brain barrier and brain drug delivery. *J Nanosci Nanotechnol* 6(9–10):2712–2735. <https://doi.org/10.1166/jnn.2006.441>
- Betta G, Capriglione D, Cerro G, Miele G, D’Amata MS, Šuka D, Simić-Pejović M (2020) On the measurement of human exposure to cellular networks. *IEEE Instrum Meas Mag* 23(9):5–13. <https://doi.org/10.1109/MIM.2020.9289066>
- Bozok S, Karaagac E, Sener D, Akakin D, Tumkaya L (2023) The effects of long-term prenatal exposure to 900, 1800, and 2100 MHz electromagnetic field radiation on myocardial tissue of rats. *Toxicol Ind Health* 39(1):1–9. <https://doi.org/10.1177/07482337221139586>
- Chandel S, Kaur S, Issa M, Singh HP, Batish DR, Kohli RK (2019) Appraisal of immediate and late effects of mobile phone radiations at 2100 MHz on mitotic activity and DNA integrity in root meristems of Allium cepa. *Protoplasma* 256:1399–1407. <https://doi.org/10.1007/s00709-019-01386-y>
- Alkis ME, Bilgin HM, Akpolat V, Dasdag S, Yegin K, Yavas MC, Akdag MZ (2019) Effect of 900-, 1800-, and 2100-MHz radiofrequency radiation on DNA and oxidative stress in brain. *Electromagn Biol Med* 38(1):32–47. <https://doi.org/10.1080/15368378.2019.1567526>
- BahreyniToossi MH, Sadeghnia HR, Feyzabadi MM, Hosseini M, Hedayati M, Mosallanejad R, AlizadehRahvar Z (2018) Exposure to mobile phone (900–1800 MHz) during pregnancy: tissue oxidative stress after childbirth. *J Maternal-Fetal Neonatal Med* 31(10):1298–1303. <https://doi.org/10.1080/14767058.2017.1315657>
- Aydoğan F, Aydın E, Koca G, Özgür E, Atilla P, Tüzüner A, Samim EE (2015) The effects of 2100-MHz radiofrequency radiation on nasal mucosa and mucociliary clearance in rats. *Int Forum Allergy Rhinol* 5(7):626–632. <https://doi.org/10.1002/alr.21509>
- Wang S, Song Z, Li H, Guo G, Xi X (2021) Numerical simulation and analysis of effects of individual differences on the field distribution in the human brain with electromagnetic pulses. *Sci Rep* 11(1):16504. <https://doi.org/10.1038/s41598-021-96059-3>
- Elschot EP, Backes WH, Postma AA, van Oostenbrugge RJ, Staals J, Rouhl RP, Jansen JF (2021) A comprehensive view on MRI techniques for imaging blood-brain barrier integrity. *Invest Radiol* 56(1):10–19. <https://doi.org/10.1097/RLI.0000000000000723>
- Zhou Y, Qiu LB, An GZ, Zhou JX, Du L, Ma YH, Ding GR (2017) Effects of electromagnetic pulse exposure on gelatinase of blood–brain barrier in vitro. *Electromagn Biol Med* 36(1):1–7. <https://doi.org/10.3109/15368378.2016.1140058>
- Gozel MA, Kahriman M (2024) Design and implementation of RF power levels measurement system from indoor to outdoor in Isparta province. *Sens Actuators A* 374:115458. <https://doi.org/10.1016/j.sna.2024.115458>

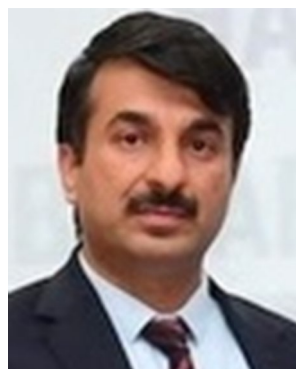
22. Okas P, Sharma A, Das G, Gangwar RK (2018) Elliptical slot loaded partially segmented circular monopole antenna for super wideband application. *AEU Int J Electron Commun* 88:63–69. <https://doi.org/10.1016/j.aeue.2018.03.004>
23. Stutzman WL, Thiele GA (2012) *Antenna theory and design*. John Wiley & Sons
24. Tütüncü B, Kösem M (2022) Substrate analysis on the design of wide-band antenna for sub-6 GHz 5G communication. *Wireless Pers Commun* 125(2):1523–1535. <https://doi.org/10.1007/s11277-022-09619-9>
25. Wang L, Fang L, Zhang X, Chi Y (2022) A compact broadband circularly polarized stacked microstrip antenna with parasitic elements. *Radio Sci* 57(6):1–8. <https://doi.org/10.1029/2021RS007401>
26. Tütüncü B (2020) Microstrip antenna for 5G communication: design and performance analysis. In *IEEE 2020 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA)*, pp 1–4. <https://doi.org/10.1109/HORA49412.2020.9152855>
27. İmeci ŞT, Tütüncü B, Hecceg L (2023) Performance-enhanced S-shaped slotted patch antenna for X band/Ku band applications. *Wireless Pers Commun* 129(2):1069–1082. <https://doi.org/10.1007/s11277-023-10174-0>
28. Tütüncü B, Torpi H (2017) Omega-shaped metamaterial lens design for microstrip patch antenna performance optimization at 12 GHz. In *IEEE 2017 10th International Conference on Electrical and Electronics Engineering (ELECO)*, pp 987–990. <https://ieeexplore.ieee.org/abstract/document/8266148>
29. BTK: <https://www.btk.gov.tr/uploads/pages/pazar-verileri/ceyrekraporu-2021-3-ceyre-6-1-22-kurum-disi.pdf>. Accessed 2023
30. Kaya M, Palanduz A, Kalayci R, Kemikler G, Simsek G, Bilgic B, Karadeniz A (2004) Effects of lipopolysaccharide on the radiation-induced changes in the blood–brain barrier and the astrocytes. *Brain research* 1019(1–2):105–112. <https://doi.org/10.1016/j.brainres.2004.05.102>
31. Kajiwar K, Ito H, Fukumoto T (1990) Lymphocyte infiltration into normal rat brain following hyperosmotic blood–brain barrier opening. *J Neuroimmunol* 27(2–3):133–140. [https://doi.org/10.1016/0165-5728\(90\)90062-R](https://doi.org/10.1016/0165-5728(90)90062-R)
32. Postaci I, Coskun O, Senol N, Aslankoc R, Comlekci S (2018) The physiopathological effects of quercetin on oxidative stress in radiation of 4.5 g mobile phone exposed liver tissue of rat. *Bratislavske Lekarske Listy* 119(8):481–489. https://doi.org/10.4149/bl_2018_088
33. Shahin S, Banerjee S, Singh SP, Chaturvedi CM (2015) 2.45 GHz microwave radiation impairs learning and spatial memory via oxidative/nitrosative stress induced p53-dependent/independent hippocampal apoptosis: molecular basis and underlying mechanism. *Toxicol Sci* 148(2):380–399. <https://doi.org/10.1093/toxsci/kfv205>
34. Zielinski J, Ducray AD, Moeller AM, Murbach M, Kuster N, Mevissen M (2020) Effects of pulse-modulated radiofrequency magnetic field (RF-EMF) exposure on apoptosis, autophagy, oxidative stress and electron chain transport function in human neuroblastoma and murine microglial cells. *Toxicol In Vitro* 68:104963. <https://doi.org/10.1016/j.tiv.2020.104963>
35. Kumar R, Deshmukh PS, Sharma S, Banerjee BD (2021) Effect of mobile phone signal radiation on epigenetic modulation in the hippocampus of Wistar rat. *Environ Res* 192:110297. <https://doi.org/10.1016/j.envres.2020.110297>
36. Xia Z, Li M, Tian Y, Li Y, Li B, Zhang G, Dong J (2021) Lipidomics of serum and hippocampus reveal the protective effects of fermented soybean lipid on rats of microwave-induced cognitive damage. *ACS Chem Neurosci* 12(12):2122–2132. <https://doi.org/10.1021/acscchemneuro.1c00042?goto=supporting-info>
37. Zhu S, Zhu Y, Li H, Zhang D, Zhang D (2020) The toxic effect of mobile phone radiation on rabbit organs. *All Life* 13(1):252–258. <https://doi.org/10.1080/26895293.2020.1763481>
38. Singh KV, Prakash C, Nirala JP, Nanda RK, Rajamani P (2023) Acute radiofrequency electromagnetic radiation exposure impairs neurogenesis and causes neuronal DNA damage in the young rat brain. *Neurotoxicology* 94:46–58. <https://doi.org/10.1016/j.neuro.2022.11.001>
39. Kaprana AE, Vardiambasis IO, Kapetanakis TN, Ioannidou MP, Nikolopoulos CD, Lyronis GE (2021) Experimental study of potential adverse effects on the auditory system of rabbits exposed to short-term GSM-1800 radiation. *Int J Radiat Biol* 97(3):421–430. <https://doi.org/10.1080/09553002.2021.1859152>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.



Abdullah Oğuz Kizilçay Received his B.Sc. degree in Computer Engineering from Middle East Technical University, Ankara, Turkey, and M.Sc. and Ph.D. degree in Electronics and Communication Engineering from Suleyman Demirel University. He is currently working as Assist. Prof. Dr. at Zonguldak Bülent Ecevit University. His research interests include applied electromagnetics, biomedical, and optimization.

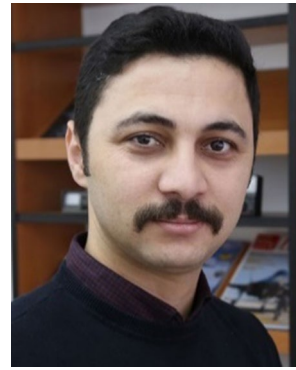


Bilal Tütüncü Received his B.Sc. degree in Electronics and Communication Engineering from Süleyman Demirel University, Isparta, Turkey, in 2003, and his Ph.D. degree in Electronics and Communication Engineering from Yıldız Technical University, Istanbul, Turkey, in 2018. He served as a lecturer at Bingöl University from 2009 to 2010. Between 2010 and 2020, he worked as an electronics engineer at the Istanbul Provincial Directorate of the Ministry of Health. Currently, he is an associate professor at Istanbul Technical University. His research interests include electromagnetic radiation, antennas, and metamaterials, and he has numerous academic publications in various journals and conferences in these fields.



Mehmet Koçarslan Graduated from the Nursing Department of the Health School at Yüzüncü Yıl University in 2013. In 2018, he obtained a B.Sc. degree in Electrical and Electronics Engineering from the Faculty of Engineering at Van Yüzüncü Yıl University. He further completed his M.Sc. degree in Electrical and Electronics Engineering at the same university in 2023. Since 2013, Mehmet Koçarslan has been working in the field of radiation sciences as a healthcare professional at the Dursun

Odabaş Medical Faculty of Van Yüzüncü Yıl University.



Mahmut Ahmet Gozel Received his B.Sc. degree in electronics and communication engineering in Suleyman Demirel University, Isparta, Turkey, in 2011, and then received M.Sc. and Ph.D. degrees in 2015 and 2020, respectively, in the same university. He is currently an assistant professor in the Department of Electrical and Electronics Engineering, Suleyman Demirel University, Isparta, Turkey. His research interests include antennas, RF energy harvesting, RFID, microwave active and pas-

sive circuit design, broadband technologies, and microwave resonator sensor for material characterization.