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Effect of high-frequency radiofrequency (6 GHz) electromagnetic radiation on oxidative stress and kidney morphology

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Abstract

This study aimed to investigate the effects of high-frequency (6 GHz) radiofrequency electromagnetic radiation (RF-EMR) exposure on oxidative stress markers and kidney morphology. Our study was designed with 3 groups, each containing 10 animals. These groups were: control, sham, and RF-EMR exposed group. No treatment was applied to the control group; the sham group was housed in the same room under the same conditions and for equal periods of time, except that the generator was turned off. The RF-EMR exposed group was exposed to 6 GHz RF-EMR emitted from the signal generator for 4 hours per day for 6 weeks. At the end of the experimental period, intracardiac blood was collected from animals and plasma oxidant (MDA), antioxidant (SOD, CAT and GSH) and cortisol markers were analyzed. After, the rats in all groups were sacrificed and kidney tissues were removed. Hematoxylin and eosin staining methods were applied histopathologically. Blood-plasma GSH, CAT, SOD and MDA levels (excluding cortisol) were lower in the RF-EMR exposed group compared to the control and sham groups ($p < .001$). No significant difference was observed in plasma levels GSH, CAT, SOD, MDA and cortisol activities between control and sham groups. In addition, we reported that the histological characteristics of kidney tissue were affected by RF-EMR. The results of our study indicated that 6 GHz RF-EMR can function as an environmental stress factor and can modulate oxidative stress in blood plasma and cause morphological changes in kidney tissue.

Keywords

RF-EMR, oxidants, antioxidants, oxidative stress, kidney morphology

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Highlights

- Histopathological and biochemical analyses were conducted to evaluate the effects of high-frequency (6 GHz) RF-EMR exposure on oxidative stress markers and kidney morphology in rats.
- Blood-plasma GSH, CAT, SOD, and MDA levels were lower in the RF-EMR exposed group compared with the control and sham groups. No significant difference was observed in plasma GSH, CAT, SOD, and MDA activities between control and sham groups. A partial but not significant increase in cortisol levels was observed in the RF-EMR exposed group compared to the control and sham groups. In addition, we found that the histological characteristics of kidney tissue were affected by RF-EMR.
- According to our findings, 6 GHz RF-EMR can function as an environmental stress factor and can modulate oxidative stress in blood plasma

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and cause morphological changes in kidney tissue.

Introduction

Wireless technologies have become quite common today and one of the extraordinary outputs of this technology is cell phones. With the increasing demand for these communication devices, the installation of a large number of base stations increases environmental exposure to electromagnetic radiation (EMR). The potential biological and health effects of radio-frequency (RF) energy from wireless communications have been debated by scientists and the public for many years, and there has been heated public debate on the safety of 5G systems in particular. While thousands of studies have been conducted on this topic, almost all of them have been conducted at frequencies below 6 GHz, where most current communication systems operate. Although the energy absorbed from cell phones cannot break chemical bonds in living organisms, the results of many studies have shown that EMR exposure can cause various biological effects such as oxidative stress (Emre et al., 2011; Oskouei et al., 2022; Schuermann and Mevissen 2021). Several studies have indicated that RF-EMR energy may have harmful effects on biological systems (Alkis et al., 2019; Elsawy et al., 2019; Hu et al., 2021; Ok et al., 2024; Ozguner et al., 2005). The impact of EMR on the body can vary depending on the frequency, intensity, and power of the radiation, making it challenging to categorize the effects of EMR parameters. While this is the case, cell phone technology is growing uncontrollably and rapidly beyond our ability to research. The mobile phone, which started with the first generation, is now in its fifth generation without thorough and systematic screening for any biological effects on humans or other animals.

Free radicals derived from oxygen metabolism are known as reactive oxygen species (ROS). ROS are involved in various physiological events such as cell signaling mechanisms, cell proliferation, growth, differentiation, and death (Juan et al., 2021). Low concentrations of ROS can be beneficial or even indispensable in processes such as intracellular signaling and defense against microorganisms. However, higher amounts of ROS are implicated in a range of diseases, including the aging process, cancer, ischemia, and failures in immune and endocrine functions. As a countermeasure against ROS accumulation, enzymatic and several non-enzymatic antioxidant activities exist (Matés et al., 1999). Cells use an antioxidant defense system based on enzymatic components such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) to protect themselves from cellular damage caused by ROS and their products (Deponte 2013).

Exposure to RF-EMR has been linked to the production of reactive oxygen species (ROS) and oxidative stress (OS), which can result in oxidative tissue damage, including DNA damage. RF-EMR has been shown to affect the energy levels and spin orientation of electrons in biological molecules, leading to the generation of free radicals, including ROS (Barnes and Greenebaume 2016; Georgiou and Margaritis 2021; Lai 2021; Schuermann and Mevissen 2021; Yakymenko et al., 2016). Similarly, it has been reported that when the cell is exposed to any agent that causes excessive ROS production, including EMR, the cell's radical homeostasis (oxidative balance) is disrupted, resulting in oxidative stress (Consales et al., 2012).

RF-EMR exposure has been documented to cause changes in antioxidant defense system parameters such as glutathione (GSH) concentration, GPx, SOD, and CAT activity in human cells (Moustafa et al., 2001) and rat cells (Aydin and Akar 2011). However, it can be said that the effects of RF-EMR mentioned above are still controversial, as there are several studies that have failed to find biological effects after RF-EMF exposure or contain some shortcomings or weak evidence, particularly in the investigation of genotoxic effects (Danese et al., 2017; Karipidis et al., 2021; Vijayalaxmi and Prihoda 2019). One reason for this debate is that the possible biophysical mechanisms of RF-EMF interaction with living cells have not yet been fully elucidated. Free radicals, antioxidants, and RF-EMR have become an important part of life and have gained increasing importance in recent years. Building on this, this study evaluated the effect of long-term exposure to high-frequency (6 GHz, SAR: 0.083 W/kg) anthropogenic RF-EMR on oxidant/antioxidant biomarkers and renal histopathology in rats.

Materials and methods

Animals

Thirty adult male Wistar Albino rats, weighing between 250 and 300 g, were used in the experiment. During the experiment, the rats were housed in a

laboratory environment with a temperature of 24 ± 2°C and humidity ranging from 35 to 50%. The rats were provided with ad libitum pellet feed and tap water, and their living conditions followed a 12-h light/dark circadian rhythm.

RF-EMR exposure system

We used a fixed-output frequency RF signal generator operating at 6 GHz to apply RF-EMR (Set Electronic, Co. model:FR6GX-2W, Sakarya, Turkey). The radio-frequency radiation (RFR) emitted power could be adjusted from 0 to 2 Watts. The modulation was in Continuous Wave (CW) format, and the specific model we used was FR6GX-2W. The RF generator's output and input impedance were 50 ohms, and the setting resolution was 0.001 Hz. In the study, we used a monopole antenna consisting of a single conductive sheet with a quarter wavelength (λ/4), evenly distributed in all directions emanating from the RF generator. This antenna was used to expose rats to RF-EMR. The exposure setup for rats is shown in Figure 1.

For the experiment, a special cage measuring 90 cm × 90 cm x 42 cm and divided into 4 equal compartments was used. It was designed to comfortably house both male and female rats while exposing them to RF-EMR. The cage was cleaned regularly to maintain a healthy environment for the rats and ensure the electromagnetic radiation effect was not compromised. The temperature and humidity of the cage were also kept constant to prevent any negative effects on the rats. The monopole antenna was positioned at the upper middle point of a Faraday cage before applying the RF-EMR. The antenna was fixed in the middle of the special cage to evenly spread the radiation at the same distance from the rats' bodies. The rats in the experimental group were continuously exposed to the far-field range of an antenna at 6 GHz with an electric field of 6.3 V/m, a magnetic field of 16.3 mA/m, and an RFR power density of 11.80 μW/cm^2. The antenna-rat distance in the vertical position was 30 cm. Due to movement, the antenna-rat distance varied between 7 and 10 cm during exposure. The exposure apparatus was heated by running it for 20 minutes to equilibrate the RF generator before RF exposure. The RF-EMR-exposed group was exposed to 6 GHz RF-EMR emitted from the signal generator for 4 hours per day for 6 weeks. The rats in the sham group were placed in another Faraday cage along with their standard cages to protect them from possible EMF sources in the external environment. Before the experiment, the RF generator was turned off, and the power supply was set to 1 Watt. Using the triaxial high-frequency electromagnetic field measuring device, ElectroSmog meter (TES 593, Taiwan), measurements were taken to determine the electric field (V/m), magnetic field (A/m), and RF power density (mW/cm^2) at the midpoint of the special application case near the monopole antenna. The measurements were taken from the four corners of the cage.



Figure 1. RF-EMR Exposure System. (a) 6 GHz RF-EMR-treated application cage. (b) Top view of the four-chamber application cage.

Experimental design

The rats used in the study were divided into three groups randomly: control, sham, and RF-EMR. The control group did not undergo any procedure. The sham group was kept in the same room in a sham cage for the same amount of time and under the same conditions, except that the generator was turned off. On the other hand, the RF-EMR group rats were exposed to 6 GHz RF-EMR radiation for four hours every day between 10:00 AM and 2:00 PM for a period of 6 weeks (Figure 1). All three groups of rats had unrestricted access to food, water, and movement during the study.

Field measurement and specific absorption rate calculation

The RF-EMA parameters were measured using a portable ElectroSmog meter. The meter has 3D capability and a high dynamic range, enabling it to measure a wide range of values (Karamazi et al., 2025). Measurements were taken multiple times from the area near the monopole antenna (the application cage's middle point) and the cage's four corners. The obtained values were normalized. Throughout the study, the RF generator was operated at a power of 1 W consistently. The electric field (E) was recorded as 6.30 ± 0.04 V/m, the magnetic field (H) was recorded as 16.31 ± 0.09 mA/m, and the power density (PD) was recorded as 11.80 ± 0.11 W/cm^2 from the RF-EMA parameters.

To solve the electric field distribution and evaluate the SAR, we used the Sim4Life 7.0.2 program based on the Finite-Difference Time Domain method (FDTD) of ZMT Zurich MedTech AG (Zurich, Switzerland). Three-dimensional model simulations of a volumetric pixel (voxel) rat were created using the ViZoo 1.0 (Virtual Zoo) program belonging to Zurich MedTech AG. The IEE/IEC62704-1 averaging method was used for simulation. The major reason for choosing this software is its comprehensive library of computable human and animal models provided by the IT'IS foundation. These models, known as ViP (Virtual Population) and ViZoo (Animal Models), were combined with the advanced tissue models required for this study. Several studies have indirectly demonstrated the accuracy and reliability of Sim4Life (Bai et al., 2022; Shah et al., 2022). A spatial-average SAR simulation was conducted on a voxel rat model with an average mass of 1 g. In our study, we determined the SAR value to be 0.083 W/kg for the whole body of adult rats (as shown in Figure 2). The calculated SAR value for 5G technology was used as a reference to measure the SAR value (Persia et al., 2018).

Collection of blood samples

After 6 weeks, Male Wistar rats were anesthetized with ketamine (100 mg/kg body weight) and xylazine (5 mg/kg body weight) by intraperitoneal injection. Blood samples of 2 mL were obtained from the subjects by cardiac puncture and transferred into vacuum tubes containing anticoagulant (preferably EDTA). After blood samples were collected, all tubes were immediately mixed by gentle 180° inversion to prevent microcoagulation. Post-experimental rats were sacrificed in accordance with international guidelines for animal care and ethical standards.

SOD activity assay

The SOD activity test was conducted following the method recommended by Sun et al. (Sun et al., 1988). When xanthine is transformed into uric acid by the xanthine oxidase enzyme, the superoxide radicals produced react with nitrobluetetrazolium (NBT) in the presence of NBT in the medium, resulting in the formation of the formazan compound. This compound has maximum absorbance at a wavelength of 560 nm. In the presence of SOD enzyme in the environment, the superoxide radicals are converted to H_2O_2, which leads to a decrease in formazan formation and consequently, a decrease in absorbance measured at 560 nm. The decrease in absorbance provides information about the activity of the SOD enzyme. The SOD enzyme activity in plasma is calculated as U/mL.

CAT activity assay

CAT activity was assessed using a modified version of the method described by Bergmeyer (Bergmeyer 1974), as outlined in Lartillot et al. (Lartillot et al., 1988). The specific absorption coefficient at 0.0392 cm^2 µmol-1 H_2O_2 was used to measure CAT activity spectrophotometrically at 240 nm. Catalase activity in plasma was determined and reported as U/mL plasma.

GSH activity assay

Glutathione levels in plasma were determined according to the method described by Tietze (Tietze 1969). The samples were rendered protein-free by

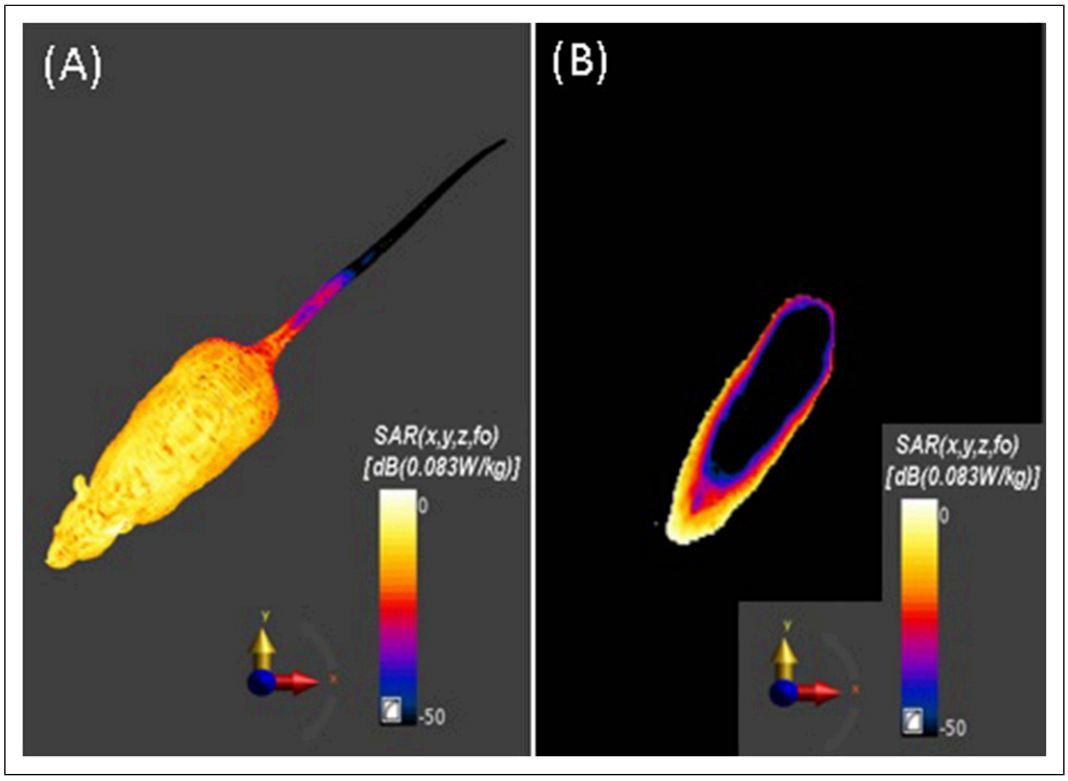


Figure 2. SAR simulations at 6 GHz. (a) Adult rat voxel model and (b) SAR distribution (for an average mass of 1g) for the whole body in an adult rat.

adding an equal volume of trichloroacetic acid (TCA) solution to the plasma. The color intensity resulting from the colorimetric derivatives formed by the sulfhydryl and primary amino groups in the samples with 5,5-dithiobis-2-nitrobenzoic acid (DTNB) was measured at 412 nm using the spectrophotometric method. Glutathione levels in plasma were calculated in μM/mL using the glutathione standard plot.

MDA activity assay

Lipid peroxide levels in plasma were determined by a method modified by Satoh (Satoh 1978) and Yagi (Yagi 1984). MDA, which can be measured by thiobarbituric acid (TBA), is formed in the peroxidation of fatty acids. The lipid peroxidation level was calculated as nmol/mL by measuring the color intensity of the colored complex formed by MDA, a fatty acid peroxidation end product, and TBA, at 532 nm.

Cortisol measurements

Rat blood plasma cortisol levels were evaluated by spectrophotometric analysis using a rat-specific ELISA (Enzyme-Linked Immunosorbent Assay) kit. Spectrophotometric analyses were performed in the Central Laboratory, which is accredited by the Joint Commission International. Plasma cortisol levels were determined using a commercial cortisol ELISA test kit (Cat. No: CK-bio-14447, Shanghai Coon Koon Biotech Co., Ltd, China) according to the manufacturer's instructions. Cortisol activity in plasma was determined and reported as nmol/L plasma.

Pathologic technique

Rats were sacrificed at the end of RF-EMR exposure according to the ethical standards of international guidelines. Kidney tissues were then collected for macroscopic and histopathological examination, divided in half, and fixed in a 10% formalin solution for 24 hours without compromising their integrity. Kidney tissues weighed an average of 0.5 g and were 1.4 × 1.1 × 0.8 cm in size. Kidney tissues subjected to routine follow-up were stored in alcohol, xylene, and paraffin solutions at increasing concentrations (70%, 90%, 100%). Paraffin-embedded tissues were cut into 4 μm sections and stained with routine hematoxylin-

eosin (H&E) staining. Histopathological examination was performed with H&E staining without identifying which tissue samples belonged to which group. Preparations were evaluated under a light microscope at different magnifications (×10, ×20, ×40). In hematoxylin-eosin sections prepared from kidney tissues, changes such as tubular tortuosity, tubular vacuolization, tubular regeneration, widening of the Bowman capsule, tubular necrosis, leukocyte infiltration of the vasa recta, interstitial inflammation, tubular atrophy, interstitial edema, lymphatic vessel dilatation, and tubular dilation were graded and determined.

Statistical analysis

The data set was analyzed by making comparisons between the rat group exposed to RF-EMR and the non-exposed rat groups. Our data set was analyzed on a statistical program (R studio, version 1.1.463). In total, there are four types of enzymes consisting of three antioxidative and one oxidative enzyme whereas two different groups such as the control, sham and experimental group are in existence. In order to investigate the significance of different groups over four enzyme concentrations, the one-way ANOVA (analysis of variance) method was employed, and that method was applied to each enzyme one by one. Before the execution of the one-way ANOVA method, outlier analysis was also included by deploying the box plot method to ensure more appropriate analysis removing the relevant outliers. So as to validate the one-way ANOVA method, residual analysis was also encompassed using the Shapiro-Wilk normality test and normal QQ plots. After the examination of assumptions pertain to ANOVA method, confidence intervals at the 95% level were also created for the mean values in each group.

Results

According to the results from the ANOVA method, it was evident that there is a significant statistical difference between the control, sham, and experimental groups in terms of CAT-GSH and MDA-SOD enzyme levels ($p < .001$, $n = 10$), as shown in Figures 3 and 4, respectively. Furthermore, it can be deduced that for all enzymes considered in this work, the concentrations significantly decrease in the experimental groups compared with the control groups. Additionally, when expressed as a percentage, the decrease in CAT is more dramatic compared to other enzymes (Figure 3). Apparently, a strong statistical difference prevails in the groups regarding those enzymes, but the percentage by which RF affects the concentration amount can be different with respect to enzymes. Average cortisol levels were calculated as control (48.99 ± 16.7 nM/L), sham (50.44 ± 15.2 nM/L) and RF-EMR group (55.42 ± 23.4 nM/L). There was no significant difference in mean cortisol levels between the control, sham, and RF-EMR groups ($p > .05$, $n = 10$).

According to cortisol results, no statistical significance was found between control and sham groups ($p > .05$), between control and experimental groups ($p > .05$), between sham and experimental groups ($p > .05$). Although there was a shift in the averages of the groups, it was determined that there were no statistically significant differences.

Histopathological examination for kidney

Histopathological evaluation of kidney tissues from the experimental groups, was performed (Figure 5(a)-(j)). In our analysis of histopathological slides, the 6 GHz RF-EMR exposure group showed expansion of the Bowman's capsule, leukocyte infiltration of the vasa recta, tubular regeneration, tubular dilatation, and interstitial inflammation compared to the sham and control groups (Figure 5).

Discussion

Despite the growing literature on the effects of RF-EMRs on human health, this topic remains highly controversial (Alkis et al., 2019; Emre et al., 2021; Ilgaz et al., 2025). We believe that evaluating renal histopathology in conjunction with oxidant/antioxidant capacity in relation to RF-EMR exposure would be a useful study to shed light on this topic. We aimed to fill this gap by investigating the effects of RF-EMRs on kidney tissue, which plays a critical role in free radical formation and the regulation of metabolic activities. Worldwide, the intensity of use, variety and geographical distribution of industrial RF-EMR sources (base stations, induction heaters, radio and television broadcasts, mobile phones, microwave ovens, 5G telecommunications networks) are increasing steadily (Bortkiewicz 2019). The use of these devices, coupled with the fact that the effects of RF-EMR exposure on oxidative stress and kidney tissue are not yet fully understood, and no common decision

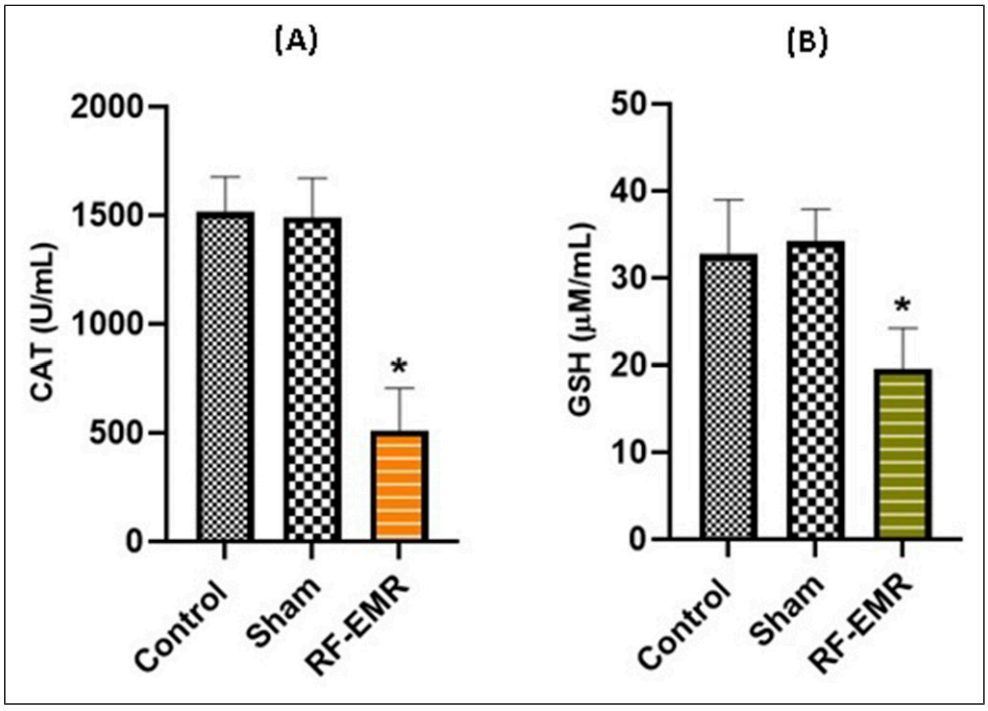


Figure 3. The effect of RF-EMR on plasma CAT levels and erythrocyte GSH levels. The data are presented as mean ± SD for ten animals per group and are significantly different (*$p < .001$). CAT and GPx values are expressed as means with 95% confidence intervals.

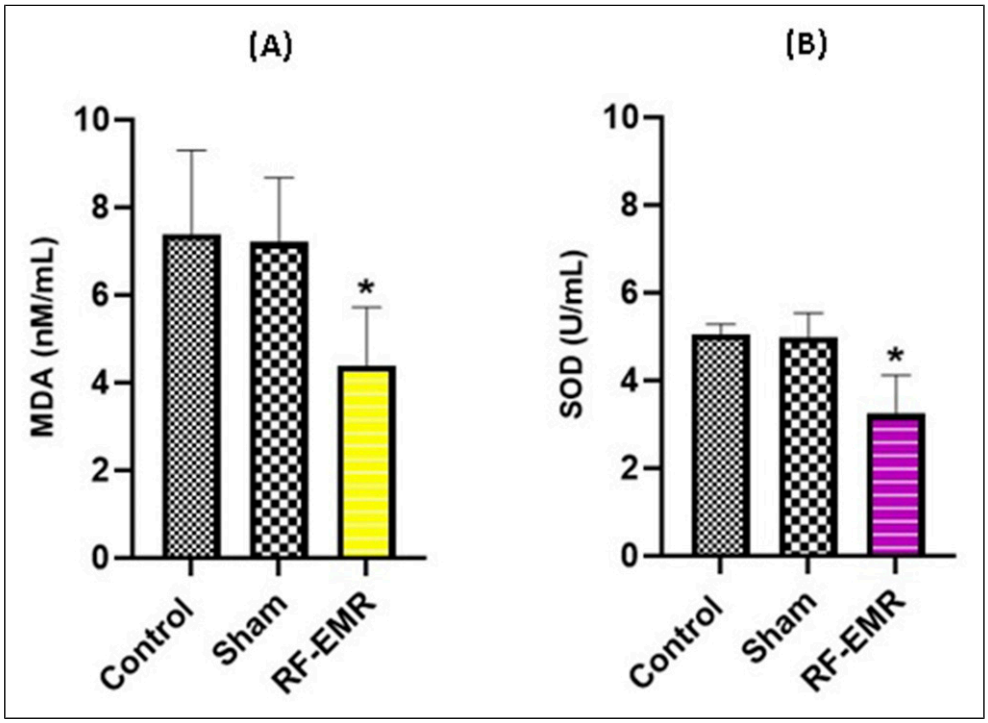


Figure 4. Shows the mean MDA and SOD levels in the control, sham and experimental (RF-EMR) groups (mean ± SD). MDA and SOD values are expressed as the mean with a 95% confidence interval (*P < 0.001).

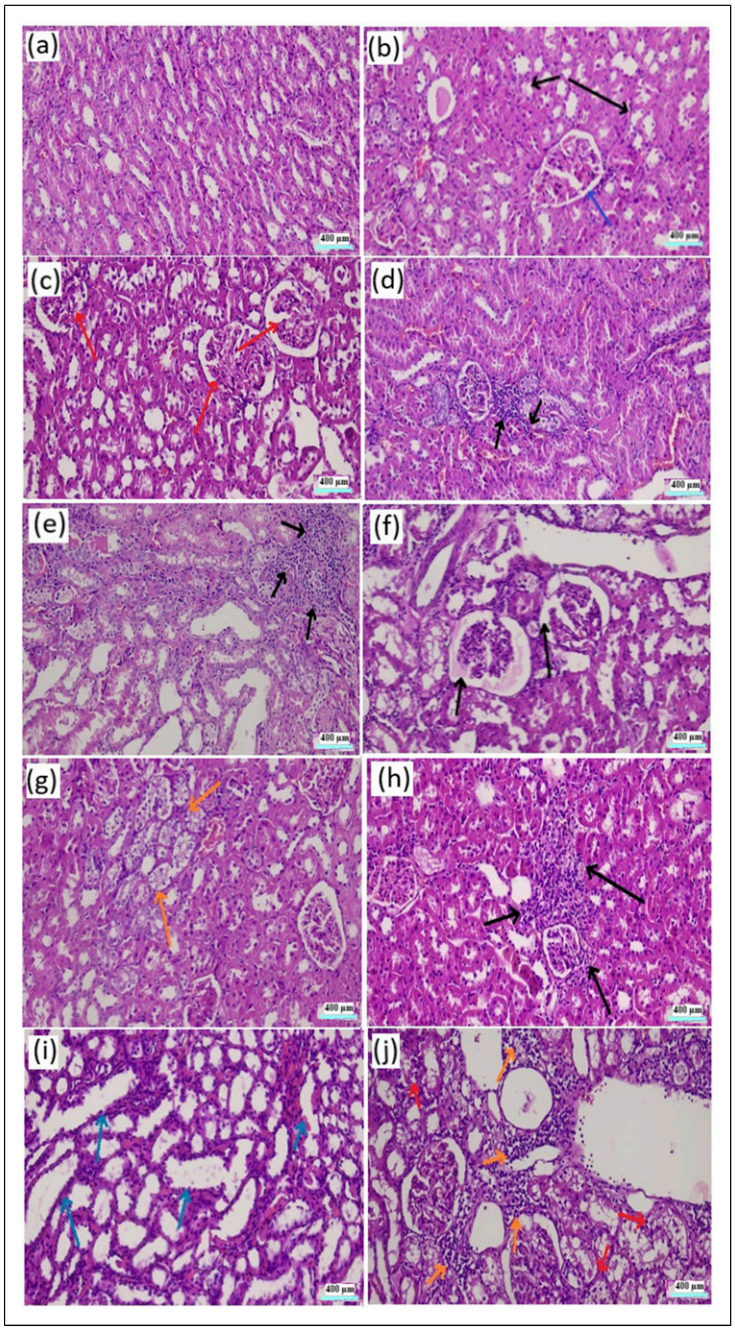


Figure 5. Histopathological images of kidney tissues from the experimental groups. (a) Histological sections of control kidney tissue show normal tubular epithelium (x400). (b) Histological sections of control kidney tissue show normal glomerular structures (blue arrow) and tubular epithelium (black arrow) (x400). (c) Histological sections of sham kidney tissue show normal glomerular structures (red arrow) and tubular epithelium (x400). (d) Histological sections of RF-EMR group kidney tissue show leukocyte infiltration in the vasa recta (black arrow) (x400). (e) Histological sections of RF-EMR group kidney tissue show leukocyte infiltration in the vasa recta (black arrow) as well as tubular dilatation (x400). (f) Histological sections of the kidney tissue of the RF-EMR group show widening of the Bowman capsule space (black arrow) (x400). (g) Histological sections of the kidney tissue of the RF-EMR group show tubular regeneration (orange arrow) (vacuolization, prominent nucleoli, mitosis) in the tubule cells (x400). (h) Interstitial inflammation (black arrow) is present in the histological sections of the kidney tissue of the RF-EMR group (x400). (i) Dilation of the tubules (blue arrow) is observed in the histological sections of the kidney tissue of the RF-EMR group (x400). (j) Histological sections of the kidney tissue of the RF-EMR group show leukocyte infiltration in the vasa recta (orange arrow) as well as regeneration of the tubules (red arrow) (x400).

on tolerable levels has been reached, is causing public concern (Berköz et al., 2018). Although there is a great deal of research on the effects of industrial and low-frequency EMR sources, very little is known about the potential effects of long-term and high-frequency EMR sources. Therefore, we aimed to identify the potential harmful effects that devices emitting RF-EMR at high frequencies (6 GHz) could have on health and to provide industrial support regarding the safe use of these devices.

Oxidative stress (OS), which occurs due to endogenous and exogenous factors (such as environmental toxicity), is defined as the imbalance between the body's antioxidant defense and the production of free radicals that cause peroxidation in the cell plasma membrane. OS plays an important role in the occurrence and development of many diseases, including cardiovascular diseases, diabetes, neurological disorders, psychiatric diseases, kidney disease, lung disease, aging, and cancer in both animal and human studies (Jomova et al., 2023).

ROS are continuously neutralized by antioxidants present in body tissues (Mittal et al., 2014). When ROS production exceeds the scavenging capacity of antioxidants, it leads to oxidative stress (Desai et al., 2009a). Recent reports have shown that electromagnetic radiation (EMR) from Wi-Fi devices and mobile phones can cause oxidative stress due to the overproduction of oxygen-derived free radicals (Bertuccio et al., 2023; Naziroglu et al., 2013). Long-term exposure to EMR is rapidly increasing day by day in human, animal, and plant habitats. Although numerous detrimental biological effects after EMR exposure have been identified, the potential hazards of the dizzyingly rapid increase of wireless devices on the occurrence of oxidative damage have still not been fully addressed. Therefore, in the present investigation, oxidative stress markers and antioxidants in blood were evaluated to confirm oxidative damage induced by 6 GHz RF-EMR. Various studies have reported that EMF exposure causes oxidative damage due to oxidative stress in many tissues of the body (Kivrak et al., 2017; Meyer et al., 2024; Pagadala et al., 2022).

Moreover, it is hypothesized that EMR may induce oxidative stress in various cell types and thus jeopardize human and animal health. In vivo animal studies have shown that OS develops in response to mobile phone radiation (Ahmadi Tameh et al., 2024; Balci et al., 2007; Kim et al., 2021; Meral et al., 2007). RF-EMR has been reported to cause a significant decrease in total antioxidant capacity by reducing SOD, CAT, and GSH-Px enzyme activity (Kamali et al., 2018; Hamam et al., 2022). Similarly, our findings are consistent with the results obtained by Salah et al. (Salah et al., 2013), who reported a significant decrease in SOD, CAT, and GSH-Px enzyme activities.

Our experimental data clearly demonstrate that exposure to 6 GHz RF-EMR leads to ROS generation, suggesting a possible effect on oxidative stress induced by increased ROS after continuous exposure to RF-EMR. In other words, decreased SOD, CAT, and GSH activities in response to increased ROS probably cause oxidative damage to macromolecules. In this context, depletion of antioxidants, changes in gene expression of antioxidants and/or inhibition of enzymatic antioxidant activity may be responsible for the persistence of oxidative stress in the case of continuous exposure to EMR.

Our study showed that prolonged exposure to 6 GHz RF-EMR caused a non-significant increase in plasma cortisol levels in rats, indicating the presence of OS. On the other hand, Ahmadi Tameh and colleagues showed that prolonged exposure to mobile RF significantly increased cortisol levels in adult rats (Ahmadi Tameh et al., 2024; Kim et al., 2021). However, some studies have shown that although cells exposed to prolonged, low-dose RF-EMR did not present any findings in contrast to control conditions, the changes observed during ultrastructural examination gave the impression that significant changes may occur if the study period is extended (Ntzouni et al., 2011).

On the other hand, studies designed to measure malondialdehyde (MDA) levels and superoxide dismutase (SOD) activity have shown contradictory results (Oral et al., 2006; Agarwal et al., 2008; Ribeiro et al., 2007). Our findings for measuring MDA activity showed contradictory results similar to the literature findings. It seems that chronic exposure to 6 GHz RF-EMR may partially reduce oxidative stress by decreasing MDA levels. Studies on human sperm have shown increased reactive oxygen species (ROS) production due to mobile phone radiation (Agarwal et al., 2008; De Iuliis et al., 2009). In particular, researchers have consistently shown that RF-EMR affects the plasma membrane in cells (Capri et al., 2004; Cleary et al., 1996; Desai et al., 2009b; Irmak et al., 2002; Yurekli et al., 2006). What is less certain is how RF-EMR is able to induce such cellular responses in the absence of a thermal induction mechanism. Cleary et al. suggested that RF-EMR may affect plasma

membrane signal transduction independently of thermal effects (Yurekli et al., 2006). Electromagnetic fields (EMFs) disrupt the electrochemical equilibrium of biological membranes, thus causing abnormal cation movement and impaired function of membrane voltage-gated ion channels. The resulting ion channel dysfunction can trigger an increase in oxidative stress and impairment of all cellular functions, including DNA damage and subsequent carcinogenesis (Georgiou and Margaritis 2021; Schuermann and Mevissen 2021). Recently, Friedman et al. reported that RF-EMR stimulates plasma membrane NADH oxidase in HeLa cells and causes extracellular superoxide production (Friedman et al., 2007). Subsequently, it was thought that this effect of RF-EMR on NADH oxidase may lead to oxidative stress and eventually carcinogenesis.

Emre et al. reported that 900 MHz RF-EMR exposure led to an increase in apoptotic cell rates in amniocytes (Emre et al., 2021). Capri et al. showed that exposure to 900 MHz RF-EMR was associated with a significant increase in annexin V-positive human lymphocytes (without any change in apoptotic cells) and mitochondrial membrane potential (Capri et al., 2004). All these findings suggest that RF-EMR may stimulate apoptosis by acting on the cell plasma membrane (Annexin receptor). In studies investigating the effects of RF-EMR on calcium dynamics in stem cell-derived neuronal cells, RF-EMR was shown to cause an increase in neuronal intracellular calcium, in other words, apoptosis (Rao et al., 2008). As can be seen, there are many studies supporting the theory that RF-EMR affects the plasma membrane (Irmak et al., 2002; Jomova et al., 2023). Literature data and our findings suggest that the plasma membrane may be a direct target of RF-EMR as well as having a secondary effect through the plasma membrane. Our findings and studies on the health effects of RF energy from communication systems have revealed that non-thermal effects should also be discussed. Considering the reports presented above and our findings, it is thought that RF-EMR induces plasma membrane and mitochondrial dysfunction, leading to high ROS production, resulting in a disturbed oxidant-antioxidant balance. Although thousands of studies have been conducted on the possible biological and health effects of RF energy, almost all of them have been conducted at frequencies below 6 GHz, where most of the current communication systems operate. In our study at 6 GHz, it was demonstrated that RF-EMR interacts with biological systems and that exposure may affect oxidative stress by reducing oxidant and antioxidant values in rats.

Owing to their high blood perfusion rates and aerobic mechanisms, kidneys are sensitive to EM radiation and produce significant levels of reactive oxygen species (ROS) with a limited antioxidant defense system (Ozbek 2012). Excessive free radical formation or a decrease in antioxidant levels leads to histological changes in kidney cell morphology (Saleh et al., 2023). The ability of RF-EMRs to cause oxidative stress in the kidneys strongly highlights the kidney's strong dependence on oxygen and its susceptibility to the toxic effects of reactive oxygen enzymes. In addition, RF-EMRs are more absorbable by pelvic organs, particularly the kidneys and testes, compared with many other internal organs. The primary cause of these adverse effects can be attributed to increased oxidative stress in the organs. These few observed changes are likely related to functional changes in renal nephrons following 42 days of 4 hours per day of RF-EMR exposure. However, these results were inconsistent with the oxidative and histopathological findings obtained by Parul Chauhan and colleagues after 35 days of radiation exposure (2.45 GHz, 2 h/day) in rats (Chauhan et al., 2017). The reason may be that such changes occurred because of the longer duration and higher frequencies of exposure in our study.

Conclusion

The results of the current study have revealed that prolonged exposure of rats to 6 GHz RF-EMR significantly affects oxidative stress and, consequently, the kidney tissue profile. Although there is consistent evidence from experimental studies that EMF causes ROS formation, a complete picture and scientific consensus regarding potential adverse and long-term health effects have not yet emerged. This is because the possible biophysical mechanisms of RF-EMF interaction with living cells have not yet been fully elucidated. Therefore, intensive research on this topic is necessary, with careful attention to the selection of appropriate biological models and well-controlled experimental conditions. We hope that this laborious process will ultimately lead to more definitive conclusions regarding the existence of RF-EMF's effect on oxidative stress and kidney.

Author contributions

ME and YK contributed to investigation, conceptualization, methodology, and project administration. ME revised and edited the manuscript. YK contributed to the proofreading of this study and the organization of the experimental process. YK and TE contributed to the statistical analysis and data curation of this study. TT contributed to the histopathological assessment of this study. YK obtained regularly records from the RF-EMR exposure systems with a electrosmog meter device. ME designed and organized RF-EMR exposure systems. NEV and GY contributed to the biochemical markers assessment. ME and GY contributed to the supervision and proofreading of this study. All authors reviewed and approved the final version of the manuscript.

Declaration of conflicting interests

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Ethical considerations

The study followed the guidelines of Decision No: 7/13, issued by the Çukurova University Animal Experiment Local Ethics Committee.

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Data Availability Statement

All the data and material of this study is available from corresponding author.

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Appendix

Abbreviations

RF-EMR	Radiofrequency Electromagnetic Radiation
EMR	Electromagnetic Radiation
SAR	Specific Absorption Rate
ROS	Reactive oxygen species
GSH	Glutathione
GSH-Px	Glutathione Peroxidase
CAT	Catalase
SOD	Superoxide dismutase
MDA	Malondialdehyd
OS	Oxidative stress