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ElektrosmogReport

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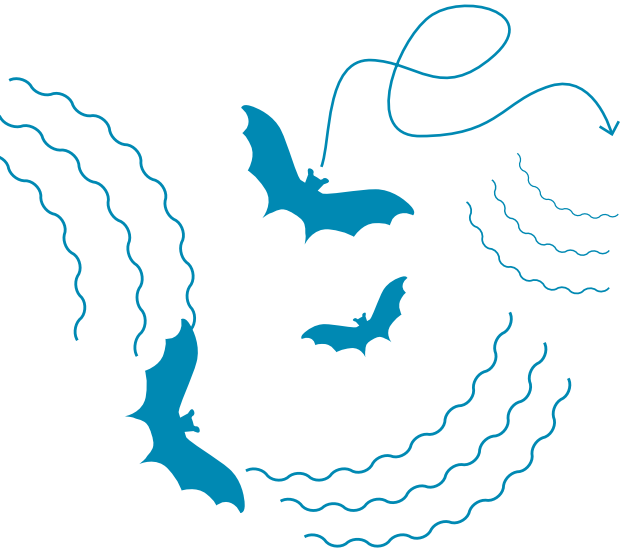

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EMF exposure disrupts magnetic compass of bats

Disruptive effects of brief radiofrequency noise exposure on migratory bat navigation

Lindecke O, Schneider WT, Vintulis V, Jordan N, Cellarius F, Marggraf LC et al. (2026). Disruptive effects of brief radiofrequency noise exposure on migratory bat navigation. *Science,* 392(6801), 977–979. https://doi.org/10.1126/science.adq4418

A new study from the University of Oldenburg examines whether frequencies that are known to disrupt bird navigation also affect bat navigation. Previous research has shown that very weak broadband signals in the 50 to 85 MHz range disrupt the light-dependent magnetic compass of songbirds, which relies on cryptochromes in the retina. While this frequency range does not overlap with that of mobile communication technologies, it is more prevalent in urban than in wilderness areas due mostly to power lines and FM radio. Disorienting effects were observed at levels well below current ICNIRP reference levels. Although it has been clearly demonstrated that the magnetic compass of birds is based on cryptochrome 4 (CRY4), the magnetic sense in mammals has been studied less extensively. Some studies on rodents and other mammals suggest the use of cryptochrome 2 (CRY2). Therefore, it is important

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to understand how wild mammals respond to electromagnetic radiation that is considered safe for humans according to ICNIRP guidelines. Thus far, the effects of artificial electromagnetic fields on humans and animals have primarily been studied under conditions of direct exposure. It remains unclear whether exposure could cause behavioral effects even after the field has faded. Bats are an ideal model species for this type of research because they share many similarities with small, nocturnal migratory birds, including the distances they travel and the ecological challenges they face.

Study design and implementation:

The experiments were conducted over the course of four fall migration seasons along the Baltic Sea coast from 2021 to 2024. A total of 165 adult *Pipistrellus pygmaeus* bats were captured at the Pape Ornithological Station in Latvia. For the experiments, the scientists selected two sites overlooking the Baltic Sea that were about 100 m apart. To prevent the bats from seeing the sky before or after treatment, the scientists carefully covered them with black linen bags, except when they were in the exposure cages. In 2021 and 2022, electromagnetic noise exposure occurred at sunset during the calibration phase. In 2023, EMF exposure took place after sunset. Thus, all bats were able to observe the sunset from the same location. In the 2024 season, EMF exposure was limited to the initial phase. The same equipment was used for EMF exposure in all four seasons. The setup remained identical during the first three seasons. The bats were placed in a non-magnetic box 1 m from a transmitting antenna (a double-turn induction loop). The transmitting antenna was connected to a signal generator that emitted electromagnetic noise (0.01–300 MHz, field strength 1 nT or 0.3 V/m). However, in the fourth season, the experimental setup was modified so that the bats were only exposed to EMF noise after being released from an orientation apparatus, a circular arena inside a converted Mongolian yurt. After placing a bat inside the yurt, the experimenter released the animal from outside. This setup allowed the experimenter to determine the bat's orientation based on the footprints it left on a thin layer of chalk covering the arena's entire circumference. The mean orientations of all groups were analyzed using Oriana software for circular statistics. The Rayleigh test was used to assess whether any of the data sets of a tested group deviated from a uniform circular distribution. To evaluate the overall navigation of the bats, an analysis of data dispersion was conducted across all years of the study. Hypothesis: The authors expected the "sunset" and "departure" groups to exhibit impaired orientation and fly off in random directions later in the night. (Previous studies by the same research group on this species of bat revealed that the bats must calibrate their magnetic compass based on the sun's position at sunset to ensure proper functioning.) Conversely, the authors predicted that the bats in the "after sunset" group would orient themselves similarly to the control animals because they had uninterrupted access to environmental cues during the critical phase at sunset and during their subsequent flight that night.

Results:

In the first year of the study, the bats in the control group flew northward. In the second, third, and fourth years, however, their average flight direction was southeast, southwest, and south, respectively. Significant deviations from a uniform pattern were observed in each of the control groups across the four migration seasons, but not in the treated groups. Bats that observed a natural sunset while exposed to EMF subsequently flew off in random directions in both seasons (uniform circular distribution). Contrary to the hypothesis, the bats did not exhibit oriented takeoff behavior after experiencing a sunset under natural geomagnetic field conditions followed by exposure to EMF and release within 2 to 6 hours. Their flight directions were indistinguishable from a uniform distribution. This contrasts with the control group, whose distribution resembled a symmetrical, southward-oriented pattern. A clear difference was observed between the combined control and treatment groups across all years of the study.

Conclusions:

The experiments described here demonstrate that exposure to low-level electromagnetic noise disrupts the orientation of bats for several hours after exposure. This has far-reaching consequences and raises numerous questions. The results imply that residual effects of weak broadband radiofrequency (RF) noise influence the movement behavior and navigational decisions of animals. The fact that orientation is disrupted regardless of whether exposure occurs during the critical calibration phase or afterward suggests that the result is based on an interaction between the effect on the magnetoreceptor and the subsequent behavioral interpretation of that effect. However, the exact mechanisms by which brief exposure to electromagnetic noise can cause the magnetic compass of an animal to malfunction for several hours remain unclear. According to the simple cryptochrome-based magnetic compass model involving radical pairs, this should not be possible. Therefore, this discovery highlights a discrepancy between quantum mechanical predictions and animal behavior or between theory and experiment. The effects of such exposure on bats are largely unknown yet could play a role in phenomena such as the so-called "invasions" of pipistrelle bats. These invasions have been observed with increasing frequency in European cities since the late 20th century. The authors point out one limitation: they tested migrating bats in a flight chamber without orientation cues. In other words, the bats had no access to other navigational cues, such as the stars or natural sounds. Therefore, it is possible that additional orientation cues in a natural environment could mitigate the disorientation caused by radiofrequency radiation. Regard-

less of the cause of the observed carryover effect, the potential ecological consequences of the demonstrated disruption are concerning because current exposure limits apply exclusively to humans. This leaves wildlife vulnerable even within these limits.

Editor's note:

A cryptochrome-based magnetic compass is generally only useful during the day (and in dry weather) because cryptochrome requires sunlight to activate. Whether blue or red light is needed depends on the type of cryptochrome present (CRY2 or CRY4). Some insects have a mechanism that circumvents this limitation, although the details are still unknown [1]. Since the Earth's magnetic field has undergone catastrophic reversals throughout geological history, and since solar flares can disrupt the Earth's natural magnetic field (and Schumann resonance) for an average of several days each year, most animals seem to possess two types of magnetic sensor: cryptochromes and magnetite crystals. Animals also use various (sensory) methods to calibrate their magnetic compass, such as the position of the sun or constellations in the night sky. This new study of bats produced results similar to those of previous studies of migratory birds, suggesting that bats, like birds, use cryptochrome (specifically CRY2, which is found in both mammals and birds, but not CRY4, which is only found in non-mammalian species, such as birds, reptiles, amphibians, and fish) to navigate using a magnetic compass. Several species, including turtles, termites [2], and humans [3, 4], possess both a cryptochrome compass and a magnetite compass. Of concern is the fact that disruption of the magnetic sense in migratory birds, as shown here in bats, occurs at very low field strengths, such as 1 nT , 0.3 V/m, and approximately 240 µW/m² for radio waves in the FM band and longer wavelengths at lower frequencies. It is also concerning that the disruption persists for several hours after EMF exposure. Further research into the magnetic sense of bats and other mammals would certainly be worthwhile, given that humans also belong to this group. (AT)

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Magnetic sense of homing pigeons

Homing pigeon navigation relies on superparamagnetic macrophages under overcast conditions

Lisowski C, Quetting M, Klaus D, Lazarevski L, Seep L, Germer M et al. (2026). Homing pigeon navigation relies on superparamagnetic macrophages under overcast conditions. *Science,* 392(6801), 985–991. https://doi.org/10.1126/science.ady2486

Birds have long been considered an excellent model system for studying navigation. For example, songbirds migrating at night or under cloudy skies can maintain a magnetically calibrated flight direction established at sunset for hundreds of kilometers. Despite decades of intensive research, the mechanisms of magnetoreception remain a mystery and are the subject of intense debate, especially when compared to the sensory systems of other vertebrates. To date, three main theories regarding magnetoreception in pigeons have been proposed: the cryptochrome theory, the magnetite theory, and the theory of an undefined mechanism based on voltage-gated ion channels. A new German study supports a fourth theory, which is based on the collective sensing ability of superparamagnetic macrophages, primarily found in the liver, that enable perception of geomagnetic direction.

Study design and implementation:

To identify tissues in pigeons with magnetic properties, scientists examined various organs, including the liver, spleen, muscles, and the inner and outer beaks, using a technique called vibrating sample magnetometry (VSM). VSM measures the magnetic properties of samples by determining the current induced when the sample moves through magnetized coils. The scientists then used immunohistochemistry with cell type-specific antibodies to isolate the cell type exhibiting magnetic properties. They stained iron(III) with Prussian blue because aside from magnetite crystals, which are made of iron, other forms of iron are the only naturally occurring strongly magnetic elements found in animals. (Although nickel is magnetic, it is incompatible with vertebrate biology.) The scientists isolated the iron-accumulating cell type by exploiting its ability to bind to columns during magnetic cell separation, as previously reported by the same research group. Using gene sequencing and expression patterns, the scientists identified the iron-containing cells and their function. First, they tested clodronate, a toxin specific to the liver macrophages identified in previous steps, in vitro and then on live pigeons to verify whether liver macrophages are essential to the magnetic sense of pigeons.

Thirty-four pigeons were individually trained to fly home over a 19-km route from west to east. After ten successful training flights, the birds were randomly assigned to receive either intra-

venous clodronate liposomes (n = 18) or control liposomes (n = 16). The following day, the pigeons were released individually under completely overcast skies and tracked using real-time GPS devices.

Results:

A strong magnetic blocking effect was observed in the livers and spleens of the pigeons, and a weaker effect was observed in their muscle tissue and beaks. These results suggest the presence of superparamagnetic particles in these organs. However, in the liver and spleen, these signals were masked by significantly stronger ferrimagnetic signals. Previous studies of other animal species, such as horses and mice, have detected ferritin nanoparticles that are predominantly localized in splenic macrophages. In the present study, the magnetic signals indicate a significant accumulation of iron-based nanomagnets in pigeon livers and a significantly lower accumulation in spleens. Prussian blue staining overlapped with MHC-II staining, which is specific to immune cells such as macrophages, dendritic cells, and B lymphocytes. After separating the magnetic cells using a magnetic column, gene sequencing revealed that the cells were macrophages. In addition, high expression of genes associated with iron metabolism was observed. One of these genes encodes a transcription factor that is essential for the development of macrophages in the red pulp of the mammalian spleen. These results suggest that the sorted MHC-II+ cells are involved in erythrocyte clearance and iron(III) and ferritin accumulation. In pigeons injected with the macrophage-specific toxin clodronate, the previously identified highly magnetic liver cells could not be detected 24 hours later when the same tests as above were performed again.

These tests and further investigations confirmed that pigeon livers contain macrophages that accumulate iron, thereby acquiring superparamagnetic properties. Next, the authors investigated how these macrophages might relay (navigational) signals to the brain. Using various staining methods and microscopic techniques, they determined that the brain is directly connected to peripheral nerve fibers in the liver. Within the liver, they frequently found macrophages in close proximity to nerve fibers (≤ 2 µm), which enables paracrine signal transmission or direct cell-to-cell contact.

All of the pigeons that were given the placebo found their way home within 70 minutes. However, none of the birds treated with clodronate returned on days when the skies were persistently cloudy. Instead, they exhibited random spatial orientation. Notably, pigeons with a macrophage deficiency could find their way home as soon as the sun became visible through the clearing clouds.

Conclusions:

Taken together, these results suggest that pigeons can perceive magnetic direction independently of a potential visual, cryptochrome-mediated magnetic sensing system. The results also suggest that macrophages are necessary for determining magnetic direction when the sun and landmarks are unavailable. The authors hypothesize that liver macrophages detect changes in the Earth's magnetic field and relay this information to the brain via the vagus nerve. They assume that magnetoreception requires a signal at the cell population level, rather than the single-cell level, to reach the threshold for neuronal activation. Liver macrophages are well-suited for this role because they accumulate iron(III) during erythrocyte clearance and are closely connected to autonomic nerves.

It is unclear whether macrophages transmit magnetic information mechanically or via a soluble mediator or hormone. However, it is known that macrophages use the paracrine pathway to transmit other types of information to the brain. One advantage of this new model is its potential to explain magnetoreception in animals that lack functional cryptochromes or that inhabit environments with little to no light, including bats, blind moles, and sharks.

Editor's note:

This new study is refreshing because it draws on the full scientific "toolbox," presents an entirely new and unexpected hypothesis, and largely proves the hypothesis through experimentation. The only remaining questions are how liver macrophages (mechanically or hormonally) transmit magnetic orientation information to the brain and how the brain processes this information. The discovery of a different type of magnetic compass, in addition to retinal cryptochrome and magnetite (mostly found in the brain), raises the question of whether superparamagnetic macrophages (in the liver or spleen) also mediate magnetoreception in other species. Further experiments are needed to determine if this is the actual function of magnetoreception in species that were previously thought to depend on cryptochrome or magnetite. In addition, we must consider which species possess multiple mechanisms of magnetic field sensitivity. (Some species of birds of prey and songbirds, for example, appear to use retinal cryptochromes. Is the homing pigeon an exception or is this the norm?) Finally, we must determine which external electromagnetic field parameters can disrupt this magnetoreception. (AT)

Mobile phone use and brain tumors – Epidemiological evidence supports tumor promotion

Interpretation of epidemiological studies on the relationship between mobile phone use and cancer

Kundi M, Hutter H-P (2026). Interpretation of epidemiological studies on the relationship between mobile phone use and cancer. *Epidemiologia*, 7(3), 86. https://doi.org/10.3390/epidemiologia7030086

The latency period for malignant brain tumors averages over 20 years. Since widespread mobile phone use did not begin until the mid-1990s, virtually all patients included in case-control studies had already developed an undetected tumor before they started using mobile phones. Therefore, a tumor-initiating effect is unlikely. The authors hypothesize that mobile phone use accelerates the growth of pre-existing tumors, resulting in earlier diagnoses. There are three possible mechanisms of action on a pre-existing tumor: 1) the tumor becomes more aggressive, 2) a regressing tumor recurs, or 3) the tumor grows faster. A central element of the study is the age-incidence function. This function shows how many new cases occur per 100,000 people in each age group. If an agent accelerates tumor growth, the entire curve shifts to the left along the age axis toward younger ages. In adults, this curve typically rises with age. A condition that would not be diagnosed until age 55 in non-users may occur as early as age 52 in users. However, in childhood and adolescence, the curve declines, meaning the incidence of cancer decreases with increasing age. A condition that would not be detected until age 16 in non-users is detected at age 15 in users. Consequently, fewer cases are recorded at a fixed comparison age among users than among non-users. (In the above examples, arbitrary numbers were used; editor's note.)

Study design and implementation:

The authors modeled the age-incidence function using age-dependent degeneration probability, Weibull-distributed latency, and survival probability (SEER data from 1992 to 2000). They examined three datasets: a meta-analysis of four case-control studies in adults, the MOBI-Kids study in 10- to 24-year-olds, and the Million Women Study in perimenopausal women. The extent of the shift was expressed as a proportion of the duration of use (32% corresponds to a 3.2-year shift for 10 years of use).

Results:

For adults, a 32% shift corresponds to a pooled odds ratio (OR) of 1.22. For MOBI-Kids, a 20% shift yields predominantly values below one, including a significantly reduced value in the middle age group (15 to 19 years). For the Million Women Study, whose curve initially rises and then declines, a 32% shift results in a hazard ratio of 0.98. The published value for gliomas was 0.89.

Conclusions:

The authors conclude that the standard interpretation is flawed as soon as an agent begins to act after tumor development begins. According to the standard interpretation, a relative risk (RR) > 1 indicates risk, whereas an RR < 1 indicates no risk. All three datasets are consistent with increased tumor progression. The common objection that a sharp increase in users should have led to a visible rise in incidence does not hold up either. According to the authors' model, such an increase would fall within the normal range of annual incidence fluctuations. The authors draw specific conclusions regarding non-ionizing radiation protection. Since the tumor-promoting effect only persists while vulnerable tissue is exposed to mobile phone radiation, usage recommendations should aim to minimize the exposure duration and intensity to these tissues. They specifically identify bone marrow, meninges, and brain tissue. Consequently, the authors criticize the limitations of RF dosimetry. SAR is only relevant for vulnerable tissues, not for adjacent tissue types. Currently, SAR is averaged across all tissue types. The authors argue that research should focus more on cellular growth and intracellular signaling pathways, and less on genotoxicity.

Editor's note:

The key finding of this publication has significant implications for interpreting epidemiological studies. If mobile phone radiation affects a pre-existing tumor, the direction of the risk measure depends solely on the slope of the age-incidence function. In other words, an increased odds ratio indicates tumor promotion when the age-incidence function increases, as it does for adults between 20 and 70 years of age. Conversely, if the function decreases, as it does for adolescents aged 15 to 19, then a decreased odds ratio suggests tumor promotion. This undermines the argument that an absence of incidence trends proves safety. At the same time, it supports the requirement that exposure parameters, particularly the SAR value, be tissue-specific rather than averaged across adjacent tissues. The widespread assumption that carcinogenic agents pose a greater threat to public health than tumor-promoting agents is a fallacy. Undetected precancerous lesions occur far more frequently than diagnosed tumors, so even a slight shift toward malignant development can strongly impact disease rates. (RH)

Modulated RF fields damage cancer cells without heat

Non-temperature-induced anti-tumor effects of amplitude-modulated radiofrequency: Molecular and functional synergies with radiotherapy

Veltsista PD, Walther W, Torke S, Ivanov A, Dieper A, Beule D et al. (2026). Non-temperature-induced anti-tumor effects of amplitude-modulated radiofrequency: Molecular and functional synergies with radiotherapy. *Cancers,* 18(10), 1613. https://doi.org/10.3390/cancers18101613

In oncology, radiofrequency electromagnetic fields (RF-EMFs) are used for hyperthermia. This method heats tissue to temperatures above 41°C. Recently, more attention has been given to non-thermal field effects, which are poorly understood. This study examines whether amplitude modulation can enhance these effects in oncology and whether it can be combined with radiation therapy (RT). The authors compared the effects of amplitude-modulated radiofrequency radiation (AMRF) and unmodulated radiofrequency radiation (RF) under strict temperature control in vitro, both alone and in combination with RT.

Study design and implementation:

Two colorectal cell lines (HT29 and SW620) and two glioblastoma cell lines (U138 and U343) were exposed using an Oncotherm system operating at 13.56 MHz (AMRF was used as the band-limited 1/f noise and the modulation index was set to 50%). The cells were isothermally exposed at 42°C for 65 minutes to achieve a SAR value between 200 and 240 W/kg. The temperature was controlled via water flow and continuously monitored. To eliminate the influence of thermal effects when comparing to the 42°C control group, each exposed group was paired with an isothermal water bath control group at 37, 42, or 44°C. To simulate co-exposure to ionizing radiation (radiotherapy), the cells were irradiated with 8 Gy of gamma radiation immediately before exposure. Proliferation, apoptosis (Annexin V), and necrosis (YOYO-3) were assessed over 96 hours using live-cell imaging. We also performed a transcriptome analysis using RNA sequencing for the SW620 and U138 cell lines.

Results:

The cytotoxicity of the exposure combinations depended on the cell line. For the HT29 cell line, the combination of RT and AMRF was the most effective at combating tumor cells. Compared to the 42°C control group, there was a statistically significant decrease in cell proliferation, while apoptosis and necrosis increased significantly. The increase in apoptosis was greater than that observed in the suprathermal 44°C control group. AMRF and RF+RT did not have a statistically significant effect on proliferation. However, RF alone increased proliferation, thereby having an antitherapeutic effect. For the SW620 cell line, necrosis increased significantly above the suprathermal control level in all four treatment scenarios. Cell proliferation decreased only under the RF+RT combination. For the U138 cell line, only AMRF and RF+RT influenced all three parameters of cytotoxicity (proliferation, apoptosis, and necrosis) in a manner conducive to tumor regression. Neither RF alone nor AMRF+RT had a statistically significant effect on proliferation. For the U343 cell line, AMRF monotherapy was the most effective, with all three parameters confirming cytotoxicity. All other combinations were either completely ineffective or significantly less effective. At the transcriptomic level, which was examined only in the SW620 and U138 cell lines, an even more pronounced cell line-specific response was observed. In SW620 cells, AMRF triggered the strongest response, peaking immediately after exposure and subsiding after 24 hours. RF and RF+RT had only moderate effects, and AMRF+RT fell somewhere in between. Compared to the hyperthermia control, AMRF activated gene expressions that heat alone did not trigger. These included metal detoxification, mitochondrial respiration, oxidative phosphorylation, amino acid starvation, and eIF2-mediated stress responses. U138, on the other hand, showed hardly any changes in gene expression despite strong phenotypic cell death responses.

Conclusions:

According to the authors, AMRF and AMRF+RT exert a biological, non-thermal cytotoxic effect on tumor cell lines. They favor a mechanism of field-induced rectification at ion channels. The radiofrequency field is rectified by ion channels, which generates a sustained direct current (DC) voltage across the membrane. This drives ion fluxes, particularly calcium influx, which could trigger apoptosis and necrosis without transcriptional changes. Since glioblastoma cells have altered "oncochannels" (Kir4.1, KCa3.1, and TRPV4), this effect may be amplified in U138 cells. This could explain the discrepancy between phenotype and transcriptome.

Editor's note:

The design of the constant temperature water bath appropriately separates RF and thermal effects. The fact that AMRF alone induces more severe necrosis than the suprathermal control suggests that a thermal mechanism of action is unlikely. The authors present their ion channel mechanism as a falsifiable hypothesis rather than a confirmed finding. However, the lack of blinding in the analysis and in the experimental setup provided by the device manufacturer is concerning. Caution should be exercised when applying the results of this study to non-ionizing radiation protection. The effective SAR value of 200 to 240 W/kg is orders of magnitude higher than the exposure one receives from everyday Wi-Fi or cellular networks. A cytotoxic effect at these intensities does not speak to the subtle effects of everyday fields. Nevertheless, evidence of non-thermal RF effects is relevant. (RH)

5G exposure during pregnancy can damage kidneys

Prenatal 3.5 GHz radiofrequency exposure induces renal histological changes and DNA damage in 6-month-old rats

Gelenli Dolanbay E, Canturk Tan F, Bektas H, Koc S, Varol S, Kilic O et al. (2026). Prenatal 3.5 GHz radiofrequency exposure induces renal histological changes and DNA damage in 6-month-old rats. *Histochemistry and Cell Biology,* 164, 56. https://doi.org/10.1007/s00418-026-02504-7

Most animal studies on the effects of wireless communication technologies have focused on 3G, 4G, and Wi-Fi frequencies (900, 1,800, and 2,450 MHz). However, little relevant data is available for the 3.5 GHz band, which is being widely used for 5G technology. Since developing kidney tissue is sensitive to environmental toxins, this study investigates the effects of exposure exclusively during the prenatal period on kidney tissue in adult offspring.

Study design and implementation:

Twenty-four pregnant Wistar rats were used and divided into three groups (n = 8): a control group with sham exposure, a group exposed during the last two weeks of gestation (D2T), and a group exposed throughout gestation (D3T). Each group was exposed for two hours daily at 3.5 GHz. The field strength in the cage ranged from 24 to 28 V/m. This resulted in specific absorption rate (SAR) values of 0.066 and 0.038 W/kg in the uterus, depending on the averaging method used. One male offspring was randomly selected from each litter and examined at six months of age (adulthood). The following were evaluated: renal histology (H&E), autophagy markers Beclin-1 and LC3 (autophagy = the breakdown of damaged cellular components), and DNA double-strand breaks (comet assay). The evaluation was conducted in a blinded manner.

Results:

Compared to the sham-exposed control group, significant pathological changes were observed in the kidney tissue. These changes were more pronounced in the D3T group than in the D2T group. Of the five examined histological parameters, four were abnormal: reduced glomerular size (glomerular atrophy), increased vacuoles in renal tubules (vacuolization), dilated renal tubules (tubular dilation), and increased cast formation in the renal tubule lumen where proteins precipitate (cylindruria). However, there was no statistically significant change in hemorrhage. Autophagy markers Beclin-1 and LC3 were significantly elevated in both exposed groups. The comet assay revealed statistically significant increases in DNA damage parameters.

Conclusions:

The authors interpret their results as evidence that exposure in utero may cause structural changes in the kidneys, including genotoxic effects and altered autophagy. The experimental animals were unable to recover from the changes that occurred during embryonic development. However, since the authors did not directly measure autophagic turnover, they caution that the marker findings should be interpreted with caution. They cite the following limitations: restriction to male offspring; use of a single exposure protocol regarding frequency, intensity, and duration; and lack of functional analyses, including oxidative stress markers. Future studies should include these analyses and vary frequencies and intensities to provide insights into thresholds (dose–response relationships) and underlying mechanisms.

Editor's note:

The study design and blinding, particularly the exposure setup with its low field intensity, deserve special mention. The significant effects observed at field strengths below the official whole-body exposure limit of 0.08 W/kg have far-reaching implications for the debate on biological effects and current exposure limits. As early as 2025, the research group published results on the effects of prenatal exposure on male fertility using the same animal cohort [1], which is why only male test animals were used (see ElektrosmogReport 1/2026). However, it is questionable how p-values in the order of 10^{-17} were obtained for eight test animals in the histopathological analysis. Such high significance values suggest that individual cells or tissue sections served as reference values rather than entire animals. This point is not mentioned in the text. (RH)

1. Gelenli Dolanbay E, Mert T, Caliskan Bender G, Bektas H, Uslu U, Fernandez-Rodriguez CE et al. (2025). Male reproductive and cellular damage after prenatal 3.5 GHz radiation exposure: One-year postnatal effects. *Annals of the New York Academy of Sciences,* 1554(1), 140–52. https://doi.org/10.1111/nyas.70116

Effects of 5G and GSM on neurons and skin cells

Effects of simultaneous in vitro exposure to 5G-modulated 3.5 GHz and GSM-modulated 1.8 GHz radiofrequency electromagnetic fields on neuronal network electrical activity and cellular stress in skin fibroblast cells

Hurtier A, Patrignoni L, Canovi A, Orlacchio R, Tjiou H, Gannes FP et al. (2025). Effects of simultaneous in-vitro exposure to 5G-modulated 3.5 GHz and GSM-modulated 1.8 GHz radio-frequency electromagnetic fields on neuronal network electrical activity and cellular stress in skin fibroblast cells. *Bioelectromagnetics,* 46(7), e70026. https://doi.org/10.1002/bem.70026

The widespread deployment of 5G cellular networks alongside existing GSM technologies underscores the urgent need to investigate the potential biological effects of exposure to multiple radiofrequency electromagnetic fields (RF-EMFs) simultaneously. A new French study examined how simultaneous exposure to 5G-modulated 3.5 GHz and GSM-modulated 1.8 GHz signals affects the electrical activity of neurons, mitochondrial reactive oxygen species (ROS) production, and cellular stress protein responses in neurons and skin fibroblasts. At carrier frequencies between 1 and 4 GHz, which are typical for GSM and low-band 5G, the penetration depth into biological tissue is approximately 1 cm. Therefore, skin cells and the central nervous system, particularly neurons in the cerebral cortex, are of primary interest. Previous studies on sequential exposure suggest that the biological effects of multifrequency exposure may be more pronounced than those of single-frequency exposure. These studies underscore the need to understand how RF-EMFs interact at multiple frequencies.

Study design and implementation:

Primary cortical neurons and immortalized human skin fibroblasts were exposed to RF-EMFs at specific absorption rates (SAR) of 1 and 4 W/kg for 15 minutes and 24 hours, respectively. Neuronal activity was analyzed using multielectrode arrays, and mitochondrial production of reactive oxygen species (ROS) was measured using MitoSOX Red. The authors investigated the activity of stress proteins using bioluminescence resonance energy transfer (BRET) assays that target RAS, PML, and HSF1 proteins. BRET is a cell-based technique that enables the real-time observation of protein-protein interactions and conformational changes in proteins. HSF1 (heat shock factor 1) is a stress-responsive transcription factor that activates the expression of heat shock proteins, such as HSP70 and HSP90, in response to protein denaturation or damage. RAS proteins act as molecular switches that control cell proliferation and division. PML regulates apoptosis, senescence, and antiviral responses.

The EMF exposure setups were based on two systems: a cell culture incubator that was converted into a Hall chamber exposure system for skin fibroblasts and an open transverse electromagnetic (TEM) cell exposure system for neurons. Signals from two generators were combined, amplified, and emitted into the Hall chamber and TEM cell. The 3.5-GHz signal used in this study is a genuine 5G New Radio (NR) signal, not just a pure 3.5-GHz sine wave. The same applies to the GSM signal.

Results:

Simultaneous exposure at 4 W/kg (2 W/kg per signal) did not significantly impact the burst and firing rates of cortical neurons. These results are consistent with previous findings by the same research group, which revealed that 5G-modulated 3.5 GHz signals with SAR values of 1 and 3 W/kg did not alter neuronal firing or burst rates in vitro [1]. However, a previous study demonstrated considerable inhibition of neuronal electrical activity at significantly higher SAR levels (28 W/kg). The underlying molecular mechanisms remain to be elucidated.

The present study found no effects on mitochondrial ROS production in fibroblasts at 1 or 4 W/kg. In BRET assays, minor effects were observed at 1 and 4 W/kg on basal activity of RAS and PML, as well as the maximal efficacy of PMA- and As_2O_3-induced RAS and PML activation (only at 1 W/kg for RAS and at both 1 and 4 W/kg for PML).

Combined exposure at 1 and 4 W/kg decreased the RAS basal activity according to BRET by 13% and 26% compared to the maximum potency of the specific toxin PMA on the RAS BRET probe. Similarly, exposure at 1 and 4 W/kg triggered slight increases in the PML BRET probe value, corresponding to approximately 16% and 13% of the maximum potency of the arsenic trioxide toxin. However, the maximum potency of PMA and arsenic trioxide in activating RAS and PML was slightly reduced (both are toxins that maximally activate these stress proteins).

No effects of combined 5G and GSM exposure on the basal activity of HSF1 were observed.

Conclusions:

According to the abstract, there is no conclusive evidence of significant biological effects from simultaneous exposure to 5G and GSM. Any observed deviations were small and likely within the range of experimental variability. However, in their discussion, the authors present a more nuanced picture. They provide a detailed comparison of numerous similar studies, including some from their own French research group. They point out that many studies have detected subtle effects that often contradict earlier findings. The authors view these contradictory results as evidence of the highly complex interactions between RF-EMFs and biological systems. In studies that detect effects, it remains unclear how these effects arise.

Regarding ROS production in mitochondria, the present study found no effects at either 1 W/kg or 4 W/kg. This con-

trasts sharply with earlier findings that exposure to 5G-modulated RF-EMFs alone at 1 W/kg decreased mitochondrial ROS levels in fibroblasts [2], while exposure to 4 W/kg had no effect. Overall, these observations suggest that the combination of 5G and GSM signals modulates mitochondrial ROS production and stress protein signaling differently than exposure to a single frequency does. However, the heterogeneity of the results makes it difficult to draw clear conclusions, as the observed effects appear to depend not only on the type of signal (5G alone, GSM alone, or 5G+GSM), but also the specific SAR value, the cell type studied, and possibly other unidentified factors.

Editor's note:

This is a well-planned and well-conducted study that identifies low-amplitude effects (compared to the effects of potent toxins that fully activate the investigated stress response pathways). Although the authors downplay this aspect somewhat, their results may reflect reality. It is possible that the effects of 5G+GSM exposure on isolated cells are only slightly harmful. But is it wise to ignore weak toxins? Why do many in vivo studies show stronger harmful effects than cell culture studies [3, 4]? One potential limitation of this study is its focus on pure neuron cultures. Numerous studies have demonstrated that neurons interact with astrocytes and other brain cells, such as microglia. Often, isolated neurons react differently than actual brain tissue. Tri-cultures would better simulate brain tissue.

The study authors provide a nuanced overview and summarize many earlier experimental findings. This illustrates why the field of electromagnetic fields has thus far been characterized by complexity, confusion, and insufficient causal relationships. These questions will likely only be resolved once the precise mechanisms by which electromagnetic fields influence biology are better understood. (AT)

1. Patrignoni L, Hurtier A, Orlacchio R, Joushomme A, Poulletier de Gannes F, Lévêque P et al. (2024). Evaluation of mitochondrial stress following ultraviolet radiation and 5G radiofrequency field exposure in human skin cells. *Bioelectromagnetics,* 45(3), 110–29. https://doi.org/10.1002/bem.22495

2. Canovi A, Orlacchio R, Poulletier de Gannes F, Lévêque P, Arnaud-Cormos D, Lagroye I et al. (2023). In vitro exposure of neuronal networks to the 5G-3.5 GHz signal. *Frontiers in Public Health*, 11, 1231360. https://doi.org/10.3389/fpubh.2023.1231360

3. Souchelnytskyi S (2025). Human cells response to electromagnetic waves of radio and microwave frequencies. *The Ukrainian Biochemical Journal,* 97(6), 5–22. https://doi.org/10.15407/ubj97.06.005

4. Weller SG, McCredden JE, Leach V, Chu C, Lam AK (2025). A scoping review and evidence map of radiofrequency field exposure and genotoxicity: Assessing in vivo, in vitro, and epidemiological data. *Frontiers in Public Health,* 13, 1613353. https://doi.org/10.3389/fpubh.2025.1613353

Wi-Fi and fetal development

A primary study on rat fetal development and brain-derived neurotrophic factor levels under the control of electromagnetic fields

DastAmooz S, Broujeni ST, Sarahian N (2023). A primary study on rat fetal development and brain-derived neurotrophic factor levels under the control of electromagnetic fields. *Journal of Public Health in Africa,* 14(6), 2347. https://doi.org/10.4081/jphia.2023.2347

Brain-derived neurotrophic factor (BDNF) is a growth factor that plays a crucial role in forming synaptic connections and repairing nerve cells. BDNF also promotes the growth and differentiation of these cells. Furthermore, functional mutations in the BDNF receptor have been associated with conditions such as depression and obesity. Previous studies have demonstrated a direct link between fetal growth and brain health. According to these studies, BDNF modulates patterns of fetal development, particularly with regard to weight. This study measured the body dimensions and BDNF concentrations of offspring from pregnant rats to determine the effect of Wi-Fi exposure on their growth.

Study design and implementation:

Twenty pregnant albino Wistar rats were randomly assigned to either the Wi-Fi group or the control group. After birth, 12 male fetuses were randomly selected from each group. The pregnant rats were housed in separate temperature-controlled rooms: an unshielded room for the Wi-Fi group and a room shielded with aluminum foil for the control group. A commercially available 2.4 GHz Wi-Fi modem was placed on a table 1 m away from the cages of the Wi-Fi group. The pregnant rats were exposed to Wi-Fi radiation for 6 hours daily for approximately 20 days (throughout the entire gestation period). Body length, tail length, and body weight were measured at birth and on the 21st and 56th postnatal days. An ELISA kit was used to measure BDNF levels toward the end of the experiment.

Results:

On day 56 after birth, the body weight of newborn rats exposed to electromagnetic fields (Wi-Fi) was approximately 10% lower (approx. 207 g) than that of the control group (approx. 230 g). However, this difference was not statistically significant. In contrast, the body length of the Wi-Fi group at birth was significantly greater than that of the control group: 51.0 mm versus 45.6 mm. The Wi-Fi group's tail length at birth (20.0 mm) was also significantly longer than the control group's (17.2 mm). However, by the 21st day after birth, the control group's tail length was significantly longer (by approx. 45%) than that

of the Wi-Fi group: 67.3 mm versus 46.3 mm. By day 56, the control group's tail length had increased by 14%, reaching 156.2 mm, while the Wi-Fi group's remained at 136.5 mm. Fifty-six days after birth, the concentrations of brain-derived neurotrophic factor (BDNF) were statistically significantly lower in the Wi-Fi group (6.8 ± 0.2 ng/mL) than in the control group (7.08 ± 0.16 ng/mL), representing only a 4% reduction.

Conclusions:

This study was limited by the small sample size, the lack of growth hormone level measurements, the short exposure duration (6 hours per day for 20 days), and the lack of BDNF measurements at birth.

Editor's note:

Leptin and BDNF interact through complex signaling pathways that regulate energy homeostasis, mood, and neurological development. In the adult brain, leptin acts as a potent regulator of BDNF expression, particularly in the hippocampus. In rodents, an increase in leptin occurs after birth (which can compensate for reduced in utero BDNF levels). However, this increase does not occur in humans. Overall, leptin and BDNF form a critical adipose tissue–brain axis. In adults, leptin signaling modulates BDNF expression. In fetuses, however, maternal levels of both factors contribute to the programming of metabolic and neural development. The findings following Wi-Fi exposure (at an estimated low, non-thermal power density of 10 mW/m²) are interesting. At the very least, the differences in body length suggest significant and problematic disruption of the normal growth process. However, it is unclear to what extent this is due to BDNF levels because they were only measured on day 56 (when the rats were sacrificed). At that time, there was only a 4% reduction in BDNF levels measured in the Wi-Fi group, which is likely an irrelevant amount. This study should be repeated/replicated with a larger number of experimental animals and additional hormone measurements, such as leptin and growth hormone levels. BDNF levels should also be determined at birth and on day 21. In addition, BDNF levels in pregnant females should be measured because BDNF in the mother's blood reaches the developing fetuses via the placenta. Therefore, it is not yet clear at what level (mother or fetus) Wi-Fi can affect BDNF levels. (AT)

5G modulates stress proteins without heat

Testicular heat-shock protein expression in rats following 3.5 GHz and 24 GHz RF-EMF exposure

Syed Taha SMA, Jaffar FHF, Hairulazam A, Vijay S, Jamaludin N, Zulkefli AF, et al. (2026). Testicular heat-shock protein expression in rats following 3.5 GHz and 24 GHz RF-EMF exposure. *International Journal of Molecular Sciences,* 27(8), 3452. https://doi.org/10.3390/ijms27083452

The fifth generation of mobile technologies (5G) uses mid-band frequencies of 3.5 GHz and will use millimeter waves of 24 to 28 GHz in the future. Since testicular tissue is sensitive to environmental stressors and since previous studies have identified the harmful effects of radiofrequency electromagnetic fields, this study examines the impact of 5G mid-band and millimeter wave frequencies on molecular stress responses in the testes of rats. (The focus is on heat shock proteins, which, despite their name, are upregulated by a broad spectrum of cellular stressors, such as oxidative stress or toxins. These chaperones primarily assist other proteins in folding into their correct three-dimensional structures; editor's note.)

Study design and implementation:

Thirty-six male Sprague-Dawley rats were exposed to 3.5 GHz, 24 GHz, or a sham field for 1 or 7 hours daily over 60 days (n = 6). The 3.5 GHz signal was generated by a signal generator without frequency modulation. The 24 GHz signal, on the other hand, was generated by a commercial radar sensor designed for presence detection. This signal exhibits frequency modulation, but it does not correspond to that of typical cellular networks (neither time-pulsed nor focused). The sources were mounted 20 cm above the cages. The specific absorption rate (SAR) was simulated using a rat voxel model and extrapolated to a distance of 20 cm using a power law. Testicular tissue was examined histologically and immunohistochemically for heat shock proteins (HSP27, HSP70, and HSP90). Depending on the exposure duration, either a one-way ANOVA or a Tukey test was performed.

Results:

The whole-body SAR was 0.06 W/kg at 3.5 GHz and 1.8×10^{-7} W/kg at 24 GHz at a distance of 20 cm. Histologically, the seminiferous tubule structure remained largely intact, showing only slight, isolated changes with no widespread or advanced tissue damage. In contrast, heat shock protein expression was significantly altered in a frequency- and duration-specific manner. With 1-hour daily exposure, a significant reduction in HSP70 production was observed at both frequencies compared to the control group that was sham-exposed. This effect was not present with 7-hour exposure. However, the 7-hour exposure

induced a significant increase in HSP90 at 3.5 GHz. HSP27, on the other hand, increased significantly after the 7-hour exposure, specifically at 24 GHz.

Conclusions:

The authors conclude that low-level, 5G-relevant fields can alter stress signaling pathways in the testes while leaving the tissue structurally intact. The HSP70 response, which is considered atypical, involves downregulation after 1 hour per day of exposure and no difference after 7 hours per day. The absence of a sustained difference suggests that the initial response normalized or remained below the threshold for permanent induction. The increase in HSP90 after 7 hours of exposure per day at 3.5 GHz indicates proteostatic adaptation to low-threshold stress stimuli rather than direct cellular damage. This finding is consistent with the lack of histological evidence. Since millimeter waves are primarily absorbed at the surface and cannot penetrate deeper tissue layers, the significantly increased HSP27 production observed after 7 hours per day at 24 GHz indicates a distinct stress adaptation.

Editor's note:

The safety of 5G exposure is called into question since the intensities used in the present study are below the limits for continuous exposure of the general population (SAR 0.08 W/kg). Heat shock proteins (HSPs), particularly HSP70 and HSP90, play a key role in normal spermatogenesis and not just the stress response. They are therefore of particular relevance to reproductive biology. Previous studies indicate that radiofrequency radiation can alter HSP expression in other tissues as well [1] (see ElektrosmogReport 03/2021). However, this publication may underestimate the biological effects of the 5G signal because it used unmodulated (3.5 GHz) and radar-modulated (24 GHz) signals. Recently published studies suggest that the biological effects of cellular network technologies are enhanced by their modulation patterns [2] (see ElektrosmogReport 02/2026). (RH)

1. Othman H, López-Furelos A, Leiro-Vidal JM, Ammari M, Sakly M, Abdelmelek H et al. (2021). Exposure to 2.45 GHz radiation triggers changes in HSP-70, glucocorticoid receptors and GFAP biomarkers in rat brain. *International Journal of Molecular Sciences*, *22*(10), 5103. https://www.mdpi.com/1422-0067/22/10/5103

2. Panagopoulos DJ, Litovsky R, Chamberlin K (2026). Recording the extremely low frequency pulsations of wireless communication electromagnetic fields. *Electromagnetic Biology and Medicine*, 1–10. https://doi.org/10.1080/15368378.2026.2654072

Wi-Fi disrupts HPA axis

The effect of 2.45 GHz radiofrequency electromagnetic radiation on components of the hypothalamic–pituitary–gonadal (HPA) axis in male rats

Vijay S, Ibrahim SF, Osman K, Zulkefli AF, Mat Ros MF, Jamaludin N et al. (2026). The effect of 2.45 GHz radiofrequency electromagnetic radiation on components of the hypothalamic–pituitary–gonadal axis in male rats. *International Journal of Molecular Sciences*, 27(10), 4582. https://doi.org/10.3390/ijms27104582

The brain and the testes are connected by the hypothalamic–pituitary–gonadal (HPG) axis. Both organs are susceptible to the effects of radiofrequency electromagnetic fields (RF-EMFs). This connection begins in the hypothalamus, where gonadotropin-releasing hormone (GnRH) is produced. The secretion of GnRH is regulated by the neuropeptide kisspeptin (Kp). GnRH then prompts the pituitary gland to release luteinizing hormone (LH) and follicle-stimulating hormone (FSH). These hormones regulate testosterone production and spermatogenesis in the testes. Testosterone then exerts negative feedback on the hypothalamus and pituitary gland, reducing the release of kisspeptin, GnRH, FSH, and LH. This maintains physiological testosterone levels and spermatogenesis. This study examines the impact of 2.45 GHz Wi-Fi radiation on this hormonal cascade, including the upstream kisspeptin pathway, in male rats.

Study design and implementation:

Eighteen adult male Sprague-Dawley rats were randomly divided into three groups (n = 6): a control group sham-exposed to an inactive router and two groups exposed for 4 or 24 hours daily. A commercially available Wi-Fi router served as the source, emitting Wi-Fi radiation through its 2.45 GHz antennas for 60 days. The 5 GHz band was turned off. The cages were positioned 20 cm away from the router, which was kept active via a ping protocol (10 pings per minute). The manufacturer specified the router's maximum power density as 0.141 W/m², and the whole-body specific absorption rate (SAR) was determined to be 0.41 W/kg. After the exposure period ended, kisspeptin production was examined at the mRNA level in the hypothalamus. At the same time, kisspeptin levels were measured in serum (protein level). In addition, the concentrations of GnRH, FSH, LH, and testosterone in serum, as well as testosterone in testicular tissue, were quantified using ELISA. One-way ANOVA with a Tukey post hoc test was used for statistical analysis.

Results:

The serum GnRH concentration was statistically significantly higher in both exposed groups. The testosterone concentration in testicular tissue was significantly lower in the 24-hour group than in the control group. Furthermore, a statistically signifi-

cant reduction in serum testosterone levels was observed in the 24-hour group compared to the 4-hour group, though not compared to the control group. No statistically significant findings were observed for any of the other examined parameters.

Conclusions:

Chronic exposure to 2.45-GHz Wi-Fi radiation (e.g. from commercial Wi-Fi routers) below current exposure limits may interfere with certain components of the HPG axis. The authors suggest that an increase in GnRH with unchanged kisspeptin levels indicates a kisspeptin-independent, non-thermal effect. They discuss oxidative stress in the hypothalamus as a possible mechanism. They attribute the absence of an LH and FSH response to the rise in GnRH to desensitization of the GnRH receptors because intermittent release of GnRH is essential for its physiological effects. The discrepancy between reduced testicular testosterone levels and elevated serum testosterone levels suggests delayed testosterone breakdown in the kidneys or impaired hormone transport, rather than increased synthesis.

Editor's note:

The finding that subthermal RF-EMF exposure can damage the HPG axis is not a new discovery. The present study replicates existing publications on this topic [1–3]. The editorial team finds the hypothesis that Wi-Fi radiation may impair testosterone breakdown is particularly interesting. Testosterone is metabolized by cytochrome P450. Radiofrequency radiation has been associated with mitochondrial dysfunction and increased oxidative stress. Cytochrome b5 has been identified as a critical mediator of biological EMF effects [4]. However, the authors acknowledge the study's limitations, including its small sample size, the lack of blinding, and the lack of relevant biochemical markers (e.g. oxidative stress, enzymatic or kinetic parameters for testosterone breakdown). In addition, measuring kisspeptin in serum is methodologically limited because centrally produced Kp cannot cross the blood–brain barrier. (RH)

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2. Jaffar FHF, Osman K, Hui CK, Zulkefli AF, Ibrahim SF (2022). Long-term Wi-Fi exposure from pre-pubertal to adult age on the spermatogonia proliferation and protective effects of edible bird's nest supplementation. *Frontiers in Physiology,* 13, 828578. https://doi.org/10.3389/fphys.2022.828578

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4. Kim J, Hwang Y, Kim S, Kwon D, Park J, Cho B, et al. (2026). Electromagnetic field-inducible in vivo gene switch for remote spatiotemporal control of gene expression. *Cell,* 189(11), 3465-3480.e23. https://doi.org/10.1016/j.cell.2026.03.029

Wi-Fi frequencies damage immune cells

Radiofrequency fields at 2.45 GHz reprogram mitochondria–lysosome crosstalk and modulate the survival/death of macrophages exposed to LPS and/or the SARS-CoV-2 spike protein

Sueiro-Benavides RA, Leiro-Vidal JM, Rodríguez-González JA, Ares-Pena FJ, López-Martín E. (2026). Radiofrequency fields at 2.45 GHz reprogram mitochondria–lysosome crosstalk and modulate the survival/death of macrophages exposed to LPS and/or the SARS-CoV-2 spike protein. *International Journal of Molecular Sciences,* 27(9), 3813. https://doi.org/10.3390/ijms27093813

Macrophages are a key component of the innate immune response and are sensitive to oxidative stress. However, the ability of non-ionizing radiofrequency electromagnetic fields (RF-EMFs) to alter the immune response to bacterial or viral stimuli remains largely unexplored. Bacterial lipopolysaccharide (LPS) activates the production of nitric oxide (NO) via the TLR4 receptor, which regulates mitochondria, lysosomes, and cell survival. The SARS-CoV-2 spike protein (CSP) can amplify these same signaling pathways. Since communication between mitochondria and lysosomes involves ROS and RNS signaling pathways, as well as degradation processes, these organelles are considered sensitive receptors of combined radiofrequency radiation and inflammatory stimuli in macrophages. This study examines the impact of exposure to 2.45 GHz RF radiation and LPS/CSP proteins on RAW 264.7 macrophages.

Study design and implementation:

The RAW 264.7 murine macrophage cell line was exposed to unmodulated 2.45 GHz radiation in a GTEM chamber for 6, 24, or 48 hours. The temperature was maintained at 37 ± 0.2°C to prevent thermal artifacts. The mean specific absorption rate (SAR) was 0.174 W/kg, corresponding to a field strength of 102.8 V/m and a power density of 28 W/m². During this time, the cells were treated with LPS, CSP, or both (hereafter referred to as "treated cells," as opposed to "exposed cells;" editor's note). The following parameters were analyzed: cell viability (using trypan blue and propidium iodide), lysosomal and mitochondrial activity (using fluorometry), nitric oxide (NO) production (using the Griess reaction), and the levels of apoptotic and necrotic cells. Statistical analysis was performed using two-factor ANOVA with Bonferroni or Holm–Sidak post hoc test.

Results:

After 6 hours of exposure, all three viability assays demonstrated a consistent reduction in viability in the untreated controls (including one trypan blue assay and two propidium

iodide assays. The propidium iodide assay was performed in parallel with the lysosomal and mitochondrial activity assays, editor's note.) After 24 hours, a treatment-dependent effect was observed in the trypan blue assay. The combination of CSP and LPS reduced viability compared to the control group (CSP+LPS sham-exposed). However, after 48 hours, this effect reversed under identical treatment conditions. The viability of the exposed CSP+LPS cells was significantly higher than that of the sham-exposed CSP+LPS cells, whose viability plummeted. Initially, exposure had a damaging effect, but then it had a protective effect. Nitric oxide production relative to cell count increased significantly after 24 hours in the LPS and CSP+LPS groups compared to the untreated control group. A field-dependent effect was observed only in the LPS group. The exposed group produced significantly more nitric oxide than the non-exposed group. This pattern changed after 48 hours. In all treated and exposed groups, nitric oxide production decreased significantly. Lysosomal activity increased sharply and significantly in all groups after 6 hours of exposure, regardless of treatment. The lysosomal inhibitor blocked exposed and sham-exposed cells equally, confirming that the effect of exposure is specific. Mitochondrial activity decreased significantly only in the LPS group after 6 hours. After 24 hours, mitochondrial activity decreased across all groups, regardless of exposure. After 24 hours, exposure provided statistically significant protection against apoptosis in all three treatment groups. (As shown by the bar charts, the number of apoptotic cells decreased by at least half, indicating an exceptional level of protection; editor's note). A similar trend was observed for necrosis after 24 hours. However, RF radiation demonstrated a statistically significant protective effect only in the LPS group. After 48 hours, the effect of the field was inconsistent. In some cases, the number of necrotic cells increased to over 60%, occurring independently of treatment and unrelated to RF exposure.

Conclusions:

The authors concluded that exposure to 2.45 GHz does not act as a non-specific toxin but rather reprograms the interaction between mitochondria, lysosomes, nitric oxide (NO), and cell death (apoptosis and necrosis) in a time- and stimulus-dependent manner. They also found that a drop in NO levels after 48 hours indicates an overwhelmed antioxidant defense system due to the interaction between electromagnetic fields (EMFs) and inflammatory stimuli. The shift in thresholds at mitochondrial and lysosomal checkpoints, which initially favors apoptosis and later necrosis, demonstrates that RF-EMFs influence the life-or-death decision of the immune cell lines rather than directly damaging the cells.

Editor's note:

This study stands out due to its carefully controlled exposure system, defined dosimetry in the GTEM chamber, and active thermoregulation. These features eliminate any room for objections regarding thermal effects. Furthermore, the use of two orthogonal viability assays and several functional markers, measured at three time points in some cases, is noteworthy. The authors' key finding – that exposure modulates the cells' response in conjunction with the inflammatory stimulus rather than non-specifically killing cells – is supported by the increase in lysosomal activity after 6 hours and the reversal of the vitality trend during CSP+LPS co-treatment (damage after 24 hours and protection after 48 hours). The authors describe this phenomenon as "time- and stimulus-dependent," yet they do not propose a mechanism of action. The nitric oxide analysis replicated the scientists' 2020 results [1], showing maximum NO production after 24 hours. These results were reported in ElektrosmogReport 01/2021. The results suggest that RF radiation can affect nitric oxide signaling pathways, as other scientists have previously postulated [2]. However, the reference to mitochondrial activity is overstated because only one significant field effect is documented. Another interpretive error concerns the early vitality data. The selective loss of vitality described is invalidated by the fact that all untreated controls (not exposed to bacterial or viral stressors) are also affected. The most relevant finding for the debate on non-thermal interactions is that exposure to 2.45 GHz EMFs can interfere with the cellular survival response. (RH)

1. Sueiro-Benavides RA, Leiro-Vidal JM, Salas-Sánchez AÁ, Rodríguez-Gonzalez JA, Ares-Pena FJ, Martín MEL (2021). Radiofrequency at 2.45GHz increases toxicity, pro-inflammatory and pre-apoptotic activity caused by black carbon in the RAW 264.7 macrophage cell line. *Science of the Total Environment,* 765, 142681. https://doi.org/10.1016/j.scitotenv.2020.142681

2. Pall ML (2018). Wi-Fi is an important threat to human health. *Environmental Research,* 164, 405–16. https://doi.org/10.1016/j.envres.2018.01.035

Combined effects of 5G and UVB light

Evaluation of mitochondrial stress following ultraviolet radiation and 5G radiofrequency field exposure in human skin cells

Patrignoni L, Hurtier A, Orlacchio R, Joushomme A, Poulletier de Gannes F, Lévêque P et al. (2024). Evaluation of mitochondrial stress following ultraviolet radiation and 5G radiofrequency field exposure in human skin cells. *Bioelectromagnetics,* 45(3), 110–129. https://doi.org/10.1002/bem.22495

The skin is the largest and most visible organ in the human body. Its primary function is to form a protective barrier against external stimuli. In addition to radiofrequency electromagnetic

fields (HF-EMFs), environmental factors such as ultraviolet radiation (UVR) affect the skin as well. Small amounts of UV radiation have been shown to have positive health benefits and play an essential role in vitamin D synthesis. However, excessive UV exposure is clearly associated with negative effects, such as DNA mutations. The same French research group that conducted the Hurtier 2025 study [1] conducted this study (see the review in this issue of ElektrosmogReport). The researchers investigated the effects of a 24-hour, 5G-modulated 3.5 GHz signal on skin cells at three different specific absorption rate (SAR) values. To accomplish this, they used human fibroblasts and keratinocytes, some of which had previously been exposed to UVB radiation and some of which had not.

Study design and implementation:

The UVB radiation at 312 nm was generated artificially. First, the researchers measured the UVB dose that triggered approximately 50% of the maximum effect. This dose was then used for all experiments. This approach allowed the researchers to determine whether 5G exposure could influence the effect of UVB radiation on skin cells, that is, whether it could enhance or reduce the effect. This study used a true 5G-modulated frequency of 3.5 GHz. The 5G EMF exposure setup consisted of a modified cell culture incubator similar to the one used in the aforementioned study [1]. Cells irradiated with UVB were exposed to 5G immediately after UVB irradiation for 24 hours at SARs of 0.25, 1, or 4 W/kg.

A MitoSOX Red probe was used to measure mitochondrial stress in human fibroblasts and keratinocytes. Changes in mitochondrial membrane potential and apoptosis were monitored using the MitoStatus TMRE dye. Positive controls were used in each experimental series to validate the results. All measurements were performed under blinded conditions.

Results:

This study revealed a statistically significant decrease (15%) in mitochondrial ROS levels in fibroblasts exposed to 5G at 1 W/kg. However, RF-EMF exposure at 0.25 or 4 W/kg did not alter ROS production. No difference was observed between sham and RF-EMF exposure in keratinocytes, regardless of the SAR value.

Exposure to RF-EMF increased UVB-induced ROS production by 28%, 20%, or 16% at 0.25, 1, and 4 W/kg, respectively, in keratinocytes previously irradiated with UVB radiation and in keratinocytes subjected to sham RF-EMF exposure. The lowest dose (0.25 W/kg) produced the strongest effect. The authors view this as evidence of a hormetic (U-shaped) dose–response relationship, which appears plausible [3].

Conclusions:

This study demonstrates the interaction between UVB radiation and RF-EMF exposure on ROS production in human keratinocytes. However, RF-EMF exposure alone was not found to increase mitochondrial ROS production. Consistent with studies demonstrating the pro-oxidative effects of RF-EMF exposure, ROS production is considered a rapid and transient response that decreases over time due to the activation of antioxidant metabolic pathways. Furthermore, no association was observed with changes in UVB-induced mitochondrial membrane potential or apoptosis. Taken together, these results suggest that the increase in UVB-induced ROS production caused by RF-EMF exposure is insufficient to adversely affect mitochondrial membrane potential, apoptosis, or necrosis. The authors summarize their findings and provide an overview of related studies. They conclude that only a few heterogeneous studies have investigated the effects of RF-EMF on skin models in vitro or in vivo. This heterogeneity is evident in the experimental conditions (e.g. cell type, RF-EMF frequency, presence or absence of RF-EMF signal modulation, and exposure duration) and biological outcomes in terms of ROS production. These differences currently prevent a clear conclusion. Further studies using 3D or in vivo skin models are needed to reach a definitive conclusion.

Editor's note:

This is an interesting and well-conducted study, even if the results are puzzling and as yet unexplained. Since humans are regularly exposed to UVB radiation from the sun, it makes sense to consider the combined effects of this radiation and that from wireless communication technologies. The researchers state that they intend to examine more realistic models than isolated cells in the future, such as multilayer or 3D skin models. This is important because in vivo studies generally reveal more severe adverse effects than cell culture studies [2, 3]. (AT)

1 Hurtier A, Patrignoni L, Canovi A, Orlacchio R, Tjiou H, Gannes FP et al. (2025). Effects of simultaneous in-vitro exposure to 5G-modulated 3.5 GHz and GSM-modulated 1.8 GHz radio-frequency electromagnetic fields on neuronal network electrical activity and cellular stress in skin fibroblast cells. *Bioelectromagnetics,* 46(7), e70026. https://doi.org/10.1002/bem.70026

2 Souchelnytskyi S (2025). Human cells response to electromagnetic waves of radio and microwave frequencies. *The Ukrainian Biochemical Journal,* 97(6), 5–22. https://doi.org/10.15407/ubj97.06.005

3 Weller SG, McCredden JE, Leach V, Chu C, Lam AK (2025). A scoping review and evidence map of radiofrequency field exposure and genotoxicity: Assessing in vivo, in vitro, and epidemiological data. *Frontiers in Public Health,* 13, 1613353. https://doi.org/10.3389/fpubh.2025.1613353

Base stations and green roofs

Radiofrequency electromagnetic field effects on green roof ecosystems: An unexplored topic

Czerwiński M, Recuero Virto L, Vian A, Thielens A (2026). Radiofrequency electromagnetic field effects on green roof ecosystems: An unexplored topic. *Environmental Reviews,* 34, 1–14. http://dx.doi.org/10.1139/er-2026-0053

This new interdisciplinary review summarizes the existing literature on green roof ecosystems and the effects of electromagnetic fields on plants and insects. It also provides power density measurements on roof surfaces. The growth in popularity of green roofs is closely tied to the global expansion of wireless communication technologies.

Study design and implementation:

In Phase 1, the authors conducted a narrative synthesis of empirical radiofrequency electromagnetic field (RF-EMF) measurements taken on urban rooftops, covering the frequency range from 0.7 to 3.8 GHz. The synthesis was based on a comprehensive literature review, from which the authors selected 20 articles. In Phase 2, the researchers conducted a thematic synthesis of published findings on the biological and ecological effects of RF-EMFs on plants and insects. Following the literature review, they included 34 studies.

Results:

The review of the literature shows that RF-EMF levels on rooftops are significantly higher than at ground level. Some studies report that RF-EMF levels on rooftops are up to 150 times higher than at ground level, while others cite differences of 30 to 100 times higher. The two most recent studies found an average difference of 16 times higher. These levels vary depending on the height of the building (and the base station), the urban environment, the wireless communication technologies used (1G to 5G), and the frequency bands employed. Overall, the cited studies demonstrate that RF-EMF exposure on rooftops near base station antennas is highly variable and often exceeds several tens of milliwatts per square meter. Levels exceeding 10,000 mW/m² only occur at very close range, directly in front of base station antennas. For a standard 900 MHz antenna, this distance ranges from 1 to 4 m, depending on the radiated power and antenna gain. These results suggest that thermal effects on green roof plants and animals are likely minor and rare. However, flying insects can come into close proximity to transmitting antennas and receive thermally relevant doses. Due to the limited number of high-quality studies examining invertebrates under RF-EMF exposure, several review articles conclude that definitive conclusions on this topic are difficult to draw. Two recent review articles acknowledge the shortcomings of some studies and discrepancies between RF-EMF exposure in laboratories and the environment. These articles assert with greater certainty that RF-EMF exposure in insects is associated with harmful, non-thermal biological effects. It has long been known that RF-EMF is a genuine environmental stimulus for plants. However, little is known about the quantitative relationship between plant responses and RF-EMF exposure. The accumulated evidence is insufficient to define the nature of the relationship between the magnitude of the plant response and the level of EMF power density.

Conclusions:

Ecosystems on green roofs near base station antennas may be exposed to RF-EMF levels significantly higher than those at ground level. Since plants are fundamental to these ecosystems, how they respond to RF-EMF exposure is especially relevant. These responses can be broadly divided into two categories. The first category includes stress effects, such as increased production of reactive oxygen species (ROS) and changes in cytosolic calcium (Ca^{2+}) signaling. The second category includes direct morphological effects, such as decreased photosynthetic pigments and shorter roots or stems. Chronic ROS and Ca^{2+} stress signals lead to phenotypic adaptations that are well documented in the literature on plant stress. These adaptations are accompanied by slower growth and promote vegetative reproduction at the expense of seed production. Since bees pollinate some plant species on green roofs, these behavioral effects provide an additional pathway through which RF-EMFs can influence green roof ecosystem functioning, regardless of their direct effects on plants.

The authors present compelling arguments and propose concrete ways to use urban green roofs as models to study the ecological impacts of RF-EMFs from mobile phone base stations. This suggests that research projects of this nature are already planned or underway.

Editor's note:

It is encouraging to see scientists from diverse backgrounds – two botanists who are experienced in the effects of electromagnetic fields on plants and a biophysicist who specializes in modeling electromagnetic radiation absorption (in insects) – collaborating and advocating for a research area that has received little attention to date. The authors convincingly argue that urban rooftops are relevant and well-suited models for investigating the effects of RF-EMFs. Hopefully, the authors will conduct (semi-)field studies in urban rooftop environments. One minor drawback is that, although RF radiation levels on urban rooftops are generally higher than at ground level, several recent studies and reviews have found stronger EMF effects at lower doses (e.g. 5 V/m) than at much higher doses (e.g. 40 V/m) [1, 2]. Therefore, future experiments should use a wide range of EMF power densities or field strengths. (AT)

1 Brzozek C, Mate R, Bhatt CR, Loughran S, Wood AW, Karipidis K (2024). Investigating the impact of anthropogenic radiofrequency electromagnetic fields on animals and plants in the environment: Analysis from a systematic map. *International Journal of Environmental Studies,* 81(5), 2343-2358. https://doi.org/10.1080/00207233.2024.2375861

2 Bundesamt für Strahlenschutz (BfS) (2026). Einfluss hochfrequenter elektromagnetischer Felder auf Pflanzengesundheit und Wachstum: Vorhaben 3622EMF404. Ressortforschungsberichte zum Strahlenschutz-261/26. https://doris.bfs.de/jspui/handle/urn:nbn:de:0221-2026060160272

Addresses for additional reliable information

Diagnose-Funk e. V. - Environmental and consumer organization for protection from electromagnetic radiation (Germany):
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Email: info@diagnose-funk.de

Microwave News (USA):
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Prof. Igor Belyaev, Biomedical Research Center of the Slovak Academy of Science, Department of Radiobiology:
http://www.biomedcentrum.sav.sk/research-departments/department-of-radiobiology/?lang=en
Shortened Link: kurzlinks.de/belyaev

Blog by Prof. Darius Leszczynski (Finland):
Website: betweenrockandhardplace.wordpress.com

Databases:

www.emfdata.org
www.emf-portal.de
www.orsaa.org