Adv Exp Med Biol - Cell Biology and Translational Medicine (2019) 7: 135–149
https://doi.org/10.1007/5584_2019_420
© Springer Nature Switzerland AG 2019
Published online: 3 August 2019

# The Impact of the Low Frequency of the Electromagnetic Field on Human

Kawthar A. Diab

**Abstract**

Recently, there has been attention and controversial debate topic about the effect of low-frequency electromagnetic fields (EMFs) on human beings. The catalyst for public awareness initiated from the first epidemiological study in 1979 that reported an association between residential EMFs exposure and the incidence of childhood leukemia. For over 40 years, many epidemiological and laboratory investigations were conducted to identify the possible biological effects of low-frequency EMF. Several studies conducted at frequencies 50/60 Hz, which related to generating of electricity from electrical appliances. Experimental studies on low-frequency EMF have provided conflicting data under specific *"in vivo" and "in vitro"* environments. Some original papers have reported the damaging effect on DNA molecule in EMF-exposed cells. Other studies have suggested no such damage in EMF-exposed cells. Also, the conclusions from other studies were inconclusive. These conflicting findings may attribute to the differences in the apparatus used to generate electromagnetic fields, experimental design, exposure time, genetic endpoints, and biological materials such as cell lines and animal species, strain, and age. As DNA damage is frequently a prerequisite for cancer disease, this review provided an experimental body of evidence on the effect of EMF on genetic material.

**Keywords**

Carcinogenicity · Epidemiological studies · Genotoxicity · Low-frequency electromagnetic field · Mammalian cells

## Abbreviations

| | |
|---|---|
| 2dG | 2-Deoxyguanosine |
| 8-OHdG | 8-Hydroxy-2′-deoxyguanosine |
| ALL | Acute lymphoblastic leukemia |
| BNU | n-butylnitrosourea |
| BP | Benzo(a)pyrene |
| CAs | Chromosomal aberrations |
| CHO | Chinese hamster ovary |
| CREST | Antikinetochore antibody staining |
| DMBA | 7, 12-dimethylbenz[a]anthracene |
| EMFs | Electromagnetic fields |
| ENU | N-ethyl-N nitrosourea |
| G | Gauss |
| Gd | Gadolinium |
| GMF | Gradient magnetic field |
| HF-EMFs | Higher-frequency-electromagnetic fields |
| HLECs | Human lens epithelial cells |
| HMSC | Human mesenchymal stromal cells |
| Hz | Hertz |
| LM-EFs | Low- to mid-frequency EMFs |

K. A. Diab (✉)
Genetics and Cytology Department, Genetic Engineering and Biotechnology Division, National Research Centre (NRC), Cairo, Egypt
e-mail: ka.diab@nrc.sci.eg; kawthar_diab@yahoo.com

| | |
|---|---|
| MN | Micronuclei |
| M054 | Human brain glioma |
| MRI | Magnetic resonance imaging |
| SCE | Sister chromatid exchange |
| SI units | International System of Units |
| T | Tesla |

## 1 Introduction

Recently, much attention has increased in electromagnetic fields (EMFs) due to concerns about the possible adverse effects of low-frequency EMF on humans and animals (WHO 2007). All living organisms surrounded by the Earth's magnetic field and electromagnetic pollution that resulted from man-made EMF sources such as electrical wiring, appliances, and power lines. The possible damaging effect of EMF depends on the density of the field, the wavelength or frequency, and the exposure period (Phillips et al. 2009). Low-frequency EMFs emit non-ionizing radiations that produce long wavelengths and small frequencies (Furse et al. 2009). Most experimental studies performed at a frequency range between 50 and 60 hertz to generate electricity from electrical appliances at homes (WHO 2007). Fifty Hertz matched to a wavelength of 3500 km, which is near to the Earth's radius (Furse et al. 2009; WHO 2007).

Mutation alteration of the genome is considered as the main key in the cancerous process. The chromatin integrity under low-frequency EMF exposure conditions has been assessed in different model systems with inconsistent outcomes (Vijayalaxmi and Prihoda 2009). These contradictory data may be due to the differences in the animal model, type of cell line, experimental design, biomarker assays and equipment used for generation EMF (Jin et al. 2014). Furthermore, many epidemiological studies pointed out the presence link between low-frequency EMF exposure and increased incidence of cancer in children and adults (Marcilio et al. 2011; Sermage-Faure et al. 2013). Other studies reported no such associations (Koeman et al. 2014; Sorahan 2012). The present review presented the following points: (1) The basic background to EMF; (2) The potential effects of EMF on the human health; (3) The published literature and future research.

## 2 Basic Background of EMF

### 2.1 Definition of EMF

Both electric and magnetic fields are invisible regions of energy that are formed by electricity, which is the movement of electrons through the electrical wiring. The electric field strength is measured by the voltage that is the force used to push the electrons through the electrical wires, similar to pushing water through a pipe. While the voltage increases, the electric field strength increases. The magnetic field is generated during the flow of electric current in wires or electrical devices and increases in strength as the current increases. The SI units of electrical potential differences and electric current are measured in volts per meter (V/m) and amperes (A), respectively. The units of magnetic intensity (flux density) are measured in either Tesla (T) or Gauss (G). The strength of a magnetic field decreases rapidly with increasing distance from its source (Furse et al. 2009).

The EMF, invisible energy, is generated from the charged particles and is indefinitely expanded throughout the space. Electromagnetic waves are waves carrying an electric field, a magnetic field, and quanta energy. These waves can travel at the

| Units of magnetic intensity |
|---|
| Tesla (T) = 1000 mT (milli tesla) = $10^6$μT (micro tesla) = $10^9$ nT (nano tesla) |
| Gauss (G) = 1,000 mG (milli gauss) = $10^6$μG (micro gauss) = $10^9$nG (nano guass) |
| Tesla (T) = 10,000 G = 1000 mT |
| Gauss (G) = $10^{-4}$ T = 100 μT |

speed of the light in space and can travel at a slower speed through a medium. These waves have a snake-like figure that makes them as transverse waves. The highest peak of a wave is known as a crest, while the lowest peak of a wave is known as a trough. Electromagnetic waves are measured by their height (amplitude) or by their wavelength, which is the distance between the crest of one wave to the crest of the next wave. One complete wave, from trough to trough, or from crest to crest is called a cycle. The number of complete cycles that occur per second is called the wave's frequency. The hertz (Hz) is the standard of wave's frequency (Furse et al. 2009).

## 2.2 Types of Electromagnetic Field (EMFs)

Basically, EMFs can be classified into two main types: Higher-frequency EMFs and low to mid-frequency EMFs (Table 1, Fig. 1). The electromagnetic waves possess two major effects on the human body namely, thermal effect (heat-dependent damage) and non-thermal effect (chemical) effect (WHO 2007).

### 2.2.1 Higher-Frequency EMFs (HF-EMFs)

HF-EMFs, which include gamma rays, X-rays, and higher ultraviolet, are in the ionizing radiation part of the electromagnetic spectrum and cause DNA damage directly (Furse et al. 2009). The lower ultraviolet part, invisible light and infrared are considered high frequency and are in the non-ionizing radiation part of the electromagnetic spectrum.

### 2.2.2 Low- To Mid-Frequency EMFs (LM-EMFs)

LM-EMFs include static fields (electric or magnetic fields that do not vary with time), magnetic fields from power lines and electrical equipment, visible light, infrared radiation, microwaves, and radio waves. These LM-EMFs are in the non-ionizing radiation part of the electromagnetic

**Table 1** Types of EMFs and their frequencies

| Types of EMFs | Wavelength | Frequency | Designation |
|---|---|---|---|
| **I-Higher frequency EMFs** | | | |
| 1-High frequency | 100–10 m | 3–30 MHz | Radio waves |
| 2-Very high frequency | 10–1 m | 30–300 MHz | Infrared ray |
| 3-Ultra high frequency | 1 m–10 cm | 300 MHz −3 GHz | Visible light |
| 4-Super high frequency | 10–1 cm | 3–30 GHz | Ultraviolet ray |
| 5-Extremely high frequency | 1 cm–1 mm | 30–300 GHz | X-ray |
| 6-Tremendously high frequency | 1 mm–0.1 mm | 300 GHz–3THz | Gamma ray |
| **II-Low to mid frequency EMFs** | | | |
| 1-Extremely low frequency | $10^5$–$10^4$ km | 3–30 Hz | Lightning and natural disturbances in the geomagnetic field |
| 2-Super low frequency | $10^4$–$10^3$ km | 30–300 Hz | Power cables and electronic instruments |
| 3-Ultra low frequency | $10^3$–100 km | 300–3,000 Hz | Military communication through the ground |
| 4-Very low frequency | 100–10 km | 3–30 kHz | Radio navigation service; secure military with submarines; computer monitors and TV sets |
| 5-Radiofrequency | 10–1 km | 30–300 kHz | Radar signals |
| 6-Medium frequency | 1 km−100 m | 300 kHz–3 MHz | Radio broadcasting; navigation radio beacons; maritime ship-to-shore communication |

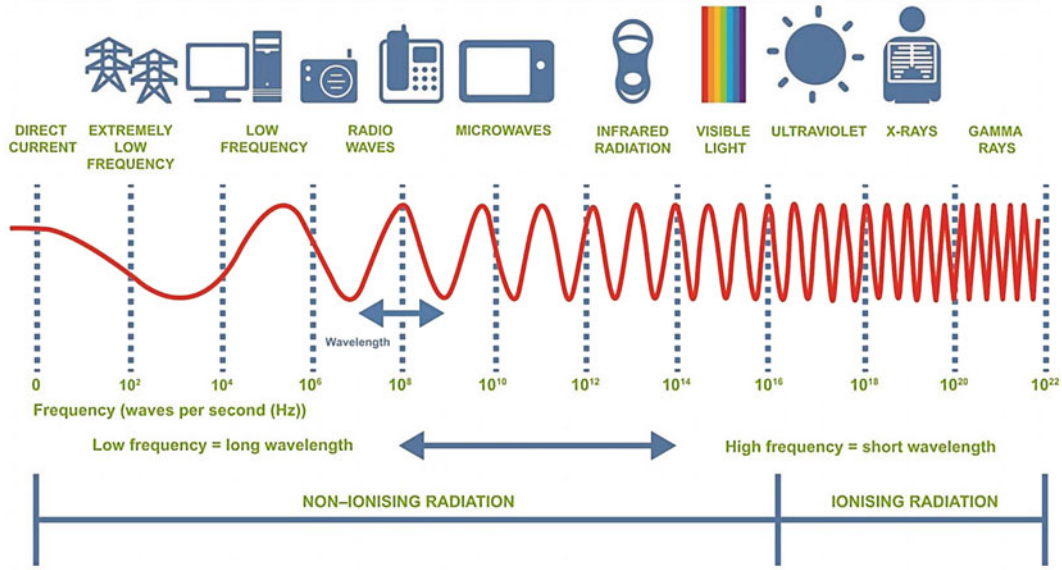



**Fig. 1** Electromagnetic spectrum

spectrum and are not known to damage DNA or cells directly (WHO 2007). LM-EMFs include different frequencies of EMFs that ranged from extremely low-frequency EMFs and radiofrequency EMFs (Table 1). Radiofrequency EMFs have frequencies from 30 kHz to 300 KHz which corresponds to the frequency of electrical singles used to produce and detect radio waves.

## 2.3 Sources of Non-ionizing EMFs

### 2.3.1 Natural Source of EMFs

Before the invention of electricity, human beings were exposed only to the magnetic field of the earth. The electric field is produced by charges in the clouds or by the static electricity of two items abrasion together, or the unexpected electric and magnetic fields caused by lighting. Geomagnetic field or earth's magnetic field originates in earth's core, a region of iron alloys extending to about 3400 km (the earth's radius is 6370 km). This region consists of a solid inner core and liquid outer core (Livermore et al. 2013). The magnetic field of the earth generates from the motion of liquid iron alloy in the outer core. This motion is driven by heat flow from the solid inner core, which its thermal conductivity is about 6000 K (5730 °C; 10,340 °F), to the core-mantle boundary, which is about 3800 K (3530 °C; 6380 °F). The geomagnetic field is organized by the rotation of the earth around the sun and the presence of the solid inner core (Finlay et al. 2010).

Earth's magnetic field that extends from the Earth's interior out into space meets the solar wind, a stream of energetic particle emanating from the sun. Its magnitude at the earth's surface ranges from 25 to 65 μT (0.25–0.65 G) (Finlay et al. 2010). Geomagnetic field deflects the solar wind, whose charged particles would otherwise strip away the ozone layer that protects the living organism from harmful ultraviolet radiation (Randall et al. 2005). The earth's magnetic field causes a compass needle to orient in a North-South direction and is used by birds and fish for navigation (Ng 2003). The electric field is caused by charges in the clouds or by the static electricity of two items abrasion together, or the unexpected electric and magnetic fields caused by lighting (Ng 2003).

### 2.3.2 Human-Made Source of Non-ionizing EMFs

After invention of electricity, humans have been increasingly surrounded by man-made EMFs which included extremely low-frequency and radiofrequency categories of non-ionizing part

of the electromagnetic spectrum. These EMFs can come from a number of sources (Ng 2003).

**Low-frequency EMFs:** The most common sources of ELF-EMFs are included power lines, electrical wiring in buildings, electricity emerged from power socket, and electrical equipments such as shavers, hair dryers, computer monitor, and electric blankets (WHO 2007).

**Radiofrequency EMF:** The most common sources of radiofrequency EMF are microwave ovens, cell phones, tablets, and portable wireless devices (IARC 2013). Other sources for radiofrequency EMF are magnetic resonance imaging (MRI), radio and television waves, radar, satellite stations, cordless telephones, wireless telecommunication devices televisions and computer monitors, wireless local area networks (Wi-Fi), antenna towers (radio and television broadcasting), mobile phone networks and smart meters such as digital electric and gas meters (IARC 2013).

## 3 Effect of Low-Frequency EMFs on Health

A static magnetic field is created during the direct flow of electric current while a time-varying gradient magnetic field (GMF) is created by alternating current supply. Household electronic devices produce a 4 μT EMF which extend from 0.01 to 1 μT inside and outside of house respectively. The strength of low frequency-EMF depends on the electrical current and distance from the conductor. Therefore, low frequency-EMFs are the highest near the power cable and decrease rapidly by distance. Without doubt, our bodies are exposed daily to a huge amount of EMFs in all over the place (outdoors, indoors, and workplaces). EMFs are considered too-weak to influence on human biological systems in the short-term, but in the long-term they have accumulative effects which could lead to different damages in the human genome, causing dangerous diseases such as cancers.

### 3.1 Cancer Epidemiological Researches

Most studies focused on the effects of low-frequency EMFs on human health, mostly focused on cancer (Hug et al. 2010; Pedersen et al. 2014). Since, Wertheimer and Leeper (1979) demonstrated the presence of a relationship between the population who lived near power-lines and risk of childhood leukemia. At the time, several epidemiological studies have been reported an association between residential or occupational exposure to low-frequency EMF and potentially human health. The probable association between exposure to low-frequency EMF and human cancer risk has extensively studied in the past decades. Leukemia, breast, and brain cancers have received more attention than other types of cancers (Calvente et al. 2010; Kaszuba-Zwoinska et al. 2015).

**Brain Cancer**

Brain cancer has become a topic of interest after Lin et al. (1985) reported a possible relationship between workers in electrical factories and increased brain cancer risk. According to information available from IARC (2002) and WHO (2007), the effect of low-frequency EMF on the incidence of cancer was inadequate. Some studies reported a positive correlation between occupational exposure to low-frequency EMF and brain cancer. For example, a small increase of 10–20% in the incidence of brain cancer was recorded among broad workers of electrical occupations (Ahlbom et al. 2001). Furthermore, Kheifets et al. (2008) observed occupation low-frequency EMF induced a small significant increase of 10% in the brain tumor (gliomas). On the other hand, other studies supported no correlation between occupational exposure low-frequency EMF and central nervous tumors such as brain cancer, glioma, and meningioma (Carlberg et al. 2018; Koeman et al. 2014; Marcilio et al. 2011).

**Hemo-Lymphoproliferative Malignancies**

Leukemia cancer is characterized by the abnormal proliferation of lymphocytes. Human beings who have dysfunction or deregulation of lymphocytes are susceptible to grow a blood or bone marrow cancer (Calvente et al. 2010). Leukemia has gained great attention since childhood acute lymphoblastic leukemia has been found to be consistently associated with low-frequency EMF exposure (Schuz 2011). In England and Wales, during the period 1962–1995, Draper et al. (2005) studied the relationship between childhood leukemia risk and distance of birth from the high-voltage power lines. The authors found that leukemia was increased within 600 m of the powerlines compared to children residing away from 600 m.

In large population-based-control study, children whose fathers were occupationally exposed to low-frequency EMF (50/60 Hz) either preconceptionally or during pregnancy did induce an increase in leukemia or non-Hodgkin's lymphoma. Regarding maternal exposure, the number of causes was so small to conclude firm findings (Hug et al. 2010). A study for the period 2002–2007 in France recorded elevated childhood leukemia within 50 m, confined to the higher-voltage power lines and to younger children but not extending outside 50 m (Sermage-Faure et al. 2013). It is noteworthy, the positive correlation between EMF and childhood leukemia might be due to selection bias and exposure misclassification. A study in Denmark found no overall pattern of increased risk childhood leukemia living 200–599 m of overhead powerline (132–400 kV) (Pedersen et al. 2014).

These findings in children have raised question about the existence of a similar relationship for adult leukemia. For example, Kheifets et al. (2006) found positive association between occupational exposure to low-frequency EMF and adult leukemia particularly chronic lymphocytic leukemia and acute myeloid leukemia for the people living around power lines. Furthermore, Marcilio et al. (2011) pointed out the presence of positive correlation between adult leukemia and exposure to low-frequency EMF. Negative correlation between adult leukemia and EMF was recorded in several reports (Koeman et al. 2014; Willett et al. 2003). In United Kingdom, a study found that no increased rate of leukemia among electricity and transmission workers. However, it was observed and increased trend for workers (Sorahan 2012).

**Breast Cancer**

Interest in breast cancer based on a hypothesized inhibition of nighttime melatonin level due to nighttime low-frequency EMF exposure, which in turn might increase breast cancer occurrence (Ahlbom et al. 2001). It well known that low-frequency EMF at night disrupts normal sleep (Juutilainen and Kumlin 2006). Melatonin is a hormone secreted by the pineal gland in response to darkness. It is act as a powerful, endogenously antioxidant which responsible for scavenger of free radical species (Juutilainen and Kumlin 2006). Low-frequency EMF decreased the melatonin level during sleep leading to oxidative damage through disturbance between the pro-oxidants and antioxidants (Irmak et al. 2002)

The possible association between exposure to low-frequency of EMFs (50–60 Hz) and breast cancer risk has generated significant controversy. Several studies have reported an increase breast cancer risk in women and men working in electrical occupational that involve presumed high level of EMFs (Feychting and Forssen 2006; McElroy et al. 2007; Zhu et al. 2016). Other studies did not support the hypothesis of an association between occupational exposures to EMFs in the electric utility industry and the risk for breast cancer (Johansen et al. 2007; Koeman et al. 2014).

**Interpretation of Contradictory Epidemiological Outcomes**

Epidemiological studies have not able to prove a clear relationship between cancer risk and the effect of low-frequency EMF. Suppose a hypothetical study exhibited an association between an increased occurrence of cancer and occupational exposure to EMF to workers in electronic

factories. Presence of a significant positive correlation between the occurrence of cancer and the exposure to EMF does not necessarily mean that EMF is the chief cause of cancer. As the factories workers were not only exposed to EMF, but also they were exposed to other factors such as chemical solvents, smoking, and alcohol. All these factors have affected together on the incidence of cancer. Therefore, the positive association may result in statistical effects or may be due to some problem in the study design (WHO 2007).

Discover the causes of the disease require that the researchers take into account many factors such as clear dose-response relationship, a credible biological justification, evidence provided by experimental animal studies, and consistency between results. These factors have been not present in the epidemiological studies of the effect of low- frequency EMF and cancer risk. Accordingly, scientists have hesitated to conclude that low-frequency EMF has induced the occurrence of cancer (WHO 2007).

## 3.2 Animal Carcinogenicity Studies

Cancer epidemiological studies are contradictory; thus, it difficult to conclude the effect of EMF on the occurrence of cancer. Therefore, the scientists turn toward laboratory animal to determine whether EMF can initiate, promote or co-promote cancer in experimental animals.

There is no evidence that EMF cause tumors with the possible exception of lymphomas arising after chronic exposure to very strong EMF (60 Hz, 25 mT) exposing CFW mice for EMF at high-strength fields (60 kHz, 25 mT) for prolonged period induced the development of malignant lymphoma (Fam and Mikhail 1996). Overall, no persuasive findings of animal carcinogenesis have been supported the hypothesis that exposure to low-frequency EMF affects the development of cancer (Boorman et al. 2000; Sommer and Lerchl 2004). The rodents especially mice has been used broadly as animal model for leukaemogenesis. Murine lymphoproliferative disorders are closely similar to that found in human beings. Exposure of rodents to carcinogenic agents was exhibited an association between human carcinogens, and cancer risk (Lagroye et al. 2011).

McCormick et al. (1999) observed a small significant increase in mortality in B6C3F mice that were continuously exposed to pure transient-free 60 Hz low-frequency EMF at 10G (Gauss). The authors found that low-frequency EMF did not induce leukemia, breast cancer, and brain cancer in B6C3F mice (both sexes).

Mandeville et al. (2000) examined the promoter effect of low-frequency EMF using Fisher 344 rats. N-ethyl-N nitrosourea (ENU) was injected prenatally for induction neurogenic tumours in Fisher 344 rats. The offspring were exposed to different EMF intensity ranged from 2 to 2000 mT, 20 h/day, 7 days/weeks for 60 weeks. The results pointed out that EMF did not induce glioma, meningioma and schwannoma indicated that EMF has no promoter effect.

Boorman et al. (2000) exposed a group of F344/N rats to continuous low-frequency 60 Hz EMF (pure, linearly polairized, transient -free) at flux intensity of 2 mG, 2G, and 10G. The authors also exposed another group to intermittent (1 h on/1 h off) EMF (60 Hz, 10 G). The findings showed that no statistical change in mortality percentage, body weight, and rate of benign and malignant tumors in all groups. The occurrence of leukemia, breast cancer, and brain cancer did not statistically increase in the two groups. However, chronic exposure to EMF (20 mG and 2G) has a little effect on cancer development in the male rat. EMF did not exert an effect on oncogenic activity.

The AKR/J mouse model for thymic lymphoblastic lymphoma was used in two following investigations:low-frequency EMF (sinusoidal 50 Hz, 1 and 100 mT), 24 h/day, 7 days/week for 38 weeks (Sommer and Lerchl 2004); low-frequency EMF (sinusoidal 50 Hz, 1000 mT), 7 days/week (Sommer and Lerchl 2006). The findings suggested no evidence that low-frequency EMF induce survival time, hematological parameters, and body weight and lymphoma development. The authors concluded that

exposure to sinusoidal 50 Hz EMF did not induce haematopoietic malignancy event at the high intensity 1000 mT.

Bernard et al. (2008) used WKAH/Hkm male rat for induction B acute lymphoblastic leukemia (ALL) by n-butylnitrosourea (BNU). From the onset of BNU treatment, the rats exposed to low-frequency EMF (50 Hz, 100uT, sinusoidal) for 53 weeks. The positive control was irradiated with gamma ray (4.8G) prior to BUN treatment. No remarkable difference was recorded in parameters of induced leukemia between the positive control group and BUN-treated. However, a considerable decrease in erythroleukaemia and increase in immature leukemia and the most immature ALL was found in rats treated by gamma rays. Exposing the rats to EMF did not induce a significant increase in the percentage of leukemia and type of leukemia between the group treated with BNU and groups treated with EMF and BNU.

Some investigations supported the hypothesis that chronic exposure low-frequency EMF is an important risk factor for tumor development. For example, Mevissen et al. (1993) used DMBA (7, 12-dimethylbenz[a]anthracene) for induction breast cancer in female rats. Female rats were exposed to low-frequency EMF (50 Hz, 50 mT, 24/day) for three successive months with or without DMBA. The results showed that EMF acts as promoter and enhance the development of mammary tumors in DMBA model.

Qi et al. (2015) exposed pregnant C57BL/6NCrj mice to low-frequency EMF (50 Hz, 500mG, 12h/day) and exposed their offspring B6C3F1mice to EMF for 15.5 months. The results showed that significant reduction in the body weight of the EMF-exposed groups compared to the control group. Chronic myelogenous leukemia (7%) was observed in bone marrow of female exposed mice.

Soffritti et al. (2016) studied the carcinogenic effect of synergistic exposure to low-frequency EMF (50 Hz) and gamma radiation in Sprague-Dawley rats. The rats were exposed to EMF (20 and 1000μT) from prenatal life until natural death and gamma radiation (0.1Gy) at single exposure at 6 weeks of age. The results showed that EMF increased heart schwannoma malignant, breast cancer, and lymphomas/leukemias. These data supported the hypothesis that EMF induced cancer in animal model.

It is rationally hypothesized that EMF acts as initiator or co-initiator (promoter) of carcinogenic tumors. Since EMF can alter the DNA configuration which could stimulate the initiation of carcinogenetic processes or can accelerate the development or spreading of already present cancer (Mevissen et al. 1993).

### 3.3 Effect of EMF on Genetic Material

There is a bulk of data concerning the assessment of low-frequency EMFs on the genetic material in humans and animals. However, their genotoxicity remains controversial in *"in vivo"* and *"in vitro"* models (Phillips et al. 2009). The controversial results are due to the different exposure conditions such as field intensity and field's regularity. Genetic damage of EMF may occur through direct or indirect mechanisms. Direct genetic toxicity may occur by injury to chromosome or damage to DNA repair mechanisms. Indirect genetic damage may arise by various processes such as the generation of free radicals or impairment of radical scavenging mechanisms. The conflicting data have been used different genotoxic endpoints such as sister chromatid exchange (SCE), micronuclei (MN), chromosomal aberrations (CAs), comet assay and DNA adducts at exposure EMF intensities ranging from 1 μT to 10 mT (Ivancsits et al. 2002; Phillips et al. 2009).

According to International Agency for Research on Cancer (IARC), low-frequency EMFs are classified as "possibly carcinogenic" to human (IARC 2002). The main causes for the increase of human cancers are still inadequately understood. However, there are at least two pathways to understand the causation of cancer (Fig. 2). These pathways are not mutually and included: (1) Genotoxic Pathway; (2) Epigenetic Pathway (Vijayalaxmi and Obe 2005).

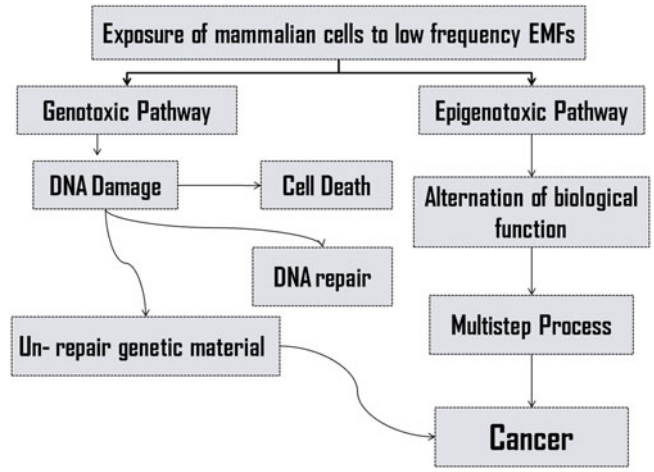



**Fig. 2** Genotoxic and Epigenotoxic (non-genotoxic) pathways of carcinogenesis process

**A Genetic Pathway**

The exogenous gents (physical, chemical) can induce genetic damage in mammalian cells. The damaged cells could go through death or undergo to repair process. The unrepaired cells induced single and double strand breaks in the DNA molecule causing the formation of mutation, micronucleus, sister chromatid exchanges, and chromosomal aberrations. Some of these genetic endpoints can lead to the development of cancer (Phillips et al. 2009; Vijayalaxmi and Obe 2005).

**An Epigenetic Pathway**

The exogenous agents cannot induce genotoxic effect or cancer by themselves. However, they can contribute to development of carcinogenesis/tumorigenicity by increasing the genotoxic effect of other agents, interfering with the DNA repair process, permitting a cell with DNA lesion to survive and stimulating the cell division causing alteration in normal biological activities of the cell (Phillips et al. 2009; Vijayalaxmi and Obe 2005).

### 3.3.1 Genotoxic Effect of EMF

Winker et al. (2005) used human diploid fibroblast (ES-1, male, 6 years ago) which initiated from a skin biopsy of a healthy donor. The cells were exposed to intermittent exposure low-frequency EMF (50 Hz, sinusoidal, 1mT, 5 min field-on/10 min field off, for 2–24 h). Variation of exposure of human fibroblasts to EMF from 2 to 24 h revealed a time-dependent increase in the frequency of micronucleus and chromosomal aberrations. The occurrence of micronuclei became significant after 10 h of intermittent exposure and reached a constant level of micronuclei (three times above the control value) after 15 h of exposure. These findings supported the hypothesis that EMF exerts clastogenic activity.

Udroiu et al. (2006) exposed newborn mice and their parents to low-frequency EMF (50 Hz, 650μT) during the intrauterine life (21 days). DNA damage was detected by using micronucleus assay with antikinetochore antibody staining (CREST staining). The data pointed out that low-frequency EMF produced a significant increase in CREST-negative micronuclei (chromosome fragment) and a highly significant increase in CREST-positive micronuclei (whole chromosome) in newborn mice. However, no remarkable increase in micronuclei incidence was observed in their parents exposed to EMF. These data suggested that EMF possess aneugenic properties which may be related to the possible carcinogenesis.

Rageh et al. (2012) exposed newborn rats (10 days after delivery) to low-frequency EMF (50 Hz, 0.5mT, 24 h/day) for successive 30 days. The authors found that a remarkable increase in Olive tail moment in rat brain cells, as well as four-fold increase in the incidence of micronucleus in rat bone marrow cells.

Balamuralikrishnan et al. (2012) found that a remarkable increase in the occurrence of chromosomal aberrations and micronucleus formation in blood lymphocytes of workers occupationally exposed to low-frequency EMF in electric transformer and distribution station. Exposing African green monkey kidney epithelium cells (Vero) to 100 Hz EMF caused a blockage of the cells in S-phase. Also, EMF induced DNA damage as indicated by a remarkable increase of the tail lengths, the quality of DNA in the tail and Olive tail moments (Mihai et al. 2014). As well, 50 Hz EMF at high intensities (2, 3Tm) induced DNA damage in mouse spermatocytes-derived GC-2 cell line detected by alkaline comet assay (Duan et al. 2015).

On the other hand, many studies are rejected the hypothesis that low-frequency EMF may cause genomic instability. For example, Erdal et al. (2007) exposed Wistar male rats to acute (4h for day) and chronic (4h/day for 45days) to days horizontal low-frequency (50Hz, 1mT). The results showed that acute and chronic exposure EMF did not induce a significant increase in the occurrence of chromosomal aberration in rat bone marrow cells.

Furthermore, occupational exposure to low-frequency EMF did not induce chromosomal aberrations, sister chromatid exchange, and micronucleus formation among the workers (Scaringi et al. 2007). For example, Burdak-Rothkamm et al. (2009) exposed human skin fibroblast (VH25) to intermittent low-frequency EMF (50 Hz). The cells were exposed to switching fields (5 min on, 10 min off) for 15 h, with field intensity of 50, 100, 500 and 1000 μT. Neither the alkaline comet DNA assay nor the γH2AX assay could detect significant damage at the DNA-breakage level in VH25 cells. No remarkable increases in chromosome-type aberrations, sister chromatid exchange, and cytokinesis-block assays were observed in VH25 cells. No significant damage at the DNA-breakage level in VH25 cells was detected using alkaline comet DNA assay nor the γH2AX assay.

Zhu et al. (2016) exposed human lens epithelial cells (LECs) to low-frequency EMF (50 Hz, 0.4 mT) for short term (2 h, 6 h), and long term (12 h, 24 h, 48 h). The results demonstrated no DNA damage in alkaline comet assay for short and long term in human LECs. Recently, Ross et al. (2018) found that exposed human mesenchymal stromal cells (HMSC) to extremely low-frequency EMF (5 Hz, 0.4 mT for 20 min/day, three-time/week, for 2 weeks) did not induce cytotoxicity and chromosomal breakage.

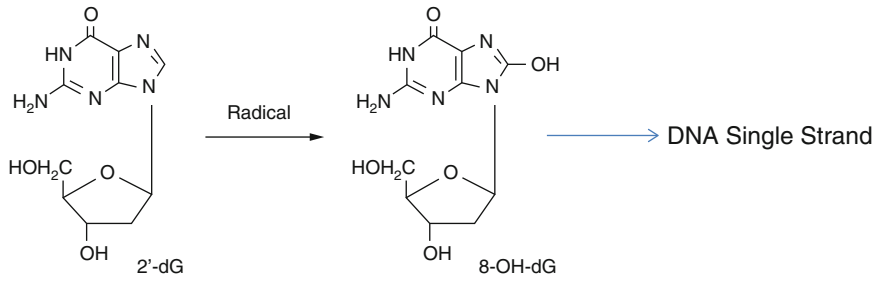
It is rational to hypothesize that genotoxic effects of EMF mediated through indirect mechanisms such as producing of free radical species or disruption of DNA repair pathway. Free radical can interact to DNA molecule (2-Deoxyguanosine, 2dG) forming primarily 8-hydroxy-2′-deoxyguanosine (8-OHdG) adduct that caused single-strand breaks. These strand breaks are usually removed by a specific repair pathway. However, genomic instability could become a site of mutation and the main step to the carcinogenesis process if the DNA damage were extensive sufficient to overcome the repair capacity of the cells (Cavalcanti et al. 2012).

### 3.3.2 Epigenetic Effect of EMF

Exposing human brain glioma (M054) to low-frequency EMF (100 Hz, 50 or 400 mT) did not induce DNA damage in alkaline comet assay. When the cells were exposed to X-ray (5 Gy) followed by low-frequency EMF (50 or 400 mT), the positive findings were detected using comet assay as indicated by a significant increase in tail moment compared with that for X-rays alone (Miyakoshi et al. 2000).

Nakahara et al. (2002) found that exposing Chinese hamster ovary (CHO) to static EMF alone (up to 10 T) has no genotoxic effect on the cell viability, cell cycle distribution, and formation of micronuclei. By contrast, the CHO cells exposed to EMF followed by X–irradiation (4 G) caused a significant increase in micronuclei formation. Surprisingly, the cells exposed to X-irradiation (1–2 Gy) and EMF did not induce the frequency of micronucleus.

Low-frequency EMF (60 Hz, 0.8 mT) did not cause genetic damage in human lymphocytes. However, co-exposure to benzo(a)pyrene (BP) and EMF provoked a remarkable increase in the frequencies of micronucleus and sister




chromatid exchanges compared to the cells treated with BP alone (Cho and Chung 2003).

Cho et al. (2014) reported that low-frequency EMF (60 Hz, 0.8 mT) boosted the cytotoxic and genotoxic activities of gadolinium (Gd). Coincident exposure to EMF and Gd increased micronucleus, single strand DNA breakage, Olive tail moment, apoptotic cells, and formation of free radical in human lymphocytes compared to gadolinium alone.

Other studies have rejected the hypothesis that co-exposure to EMF and other mutagenic agents may increase genetic damage. For example, Stronati et al. (2004) exposed human blood lymphocytes of five donors for 2 h to 50 Hz low-frequency EMF (1 mT) which generated by the Helmholtz coil system. Negative results were recorded in alkaline single cell electrophoresis assay, micronucleus assay and, chromosomal aberrations in human blood lymphocytes. As well, the synergistic effect between X-ray and EMF has no influence on DNA damage which is one hallmark of malignant cell transformation.

Gadhia et al. (2010) examined genetic damage in blood lymphocytes of electric train engine drivers who occupationally exposed to relatively high EMF intensity. The authors reported that no significant increase in the occurrence of chromosomal aberration and sister chromatid exchange. The co-mutagenic effect showed that exposing blood lymphocytes of electric train engine drivers to mitomycin C (6 ng/ml) have no genotoxic effect on the incidence of chromosomal damage and sister chromatid exchanges. It is rational to hypothesize that, EMF in the presence of initiator (e.g X-ray radiation) act as promoter to stimulate the DNA damage of genetically altered cells, rather than acting as initiator resulting in the proper lesion in DNA molecule (Timmel et al. 1998).

## 4 Assessment of the Published Literature and Further Research

The majority of original reports that indicated an absence of genotoxic or carcinogenic effect have explained the EMF exposure conditions and experimental protocols in detail. Therefore, the findings could be confirmed by other independent researchers. The findings are not in conflict with the other recognized characteristics of EMF. In other words, the interpretations for the presence of the genotoxic or carcinogenic effect of EMF were not substantiated by experimental data. Considering the "weight of scientific evidence" for scientific studies as suggested by IARC (2002), the preponderance of findings available in the literature review exhibits that EMF exposure by itself is not genotoxic or carcinogenic in mammalian cells. However, research must continue to resolve the controversial data published in the literature.

Many studies have reviewed the occurrence of non-reproducible positive results particularly *"in vitro"* assays (Vijayalaxmi and Obe 2005; Vijayalaxmi and Prihoda 2009). The following potential causes for conflicting findings can be reviewed according to Vijayalaxmi and Obe 2005:

1. The changes in environmental conditions in "*in vitro*" studies resulted in oxidative stress and false positive results. For example, high osmotic conditions, and low pH of media may

induce gene mutation, sister chromatid exchange, chromosomal aberrations, and morphological cell transformation.
2. There have been about 10% incidences of random and non-reproducible positive results in micronucleus assay in *"in vivo"* studies.
3. Data analysis obtained from many different bioassays, without appropriate statistical analysis reflecting the various observations tested could have misrecognized as a "significant effect" as a result of random chance occurrence (statistical deviations).
4. The findings from a well harmonized and multicenter collaborative investigation with adequate statistical analysis can be required the factors that cause these controversial data. The studies of EMF exposure can be conducted in a single laboratory with validated equipment for generation EMF. Many bioassay endpoints (e.g comet assay) and multiple cell lines from different origin (e.g human, mouse) should be examined. It may also be valuable to examine cells with different genetic backgrounds (heterozygous and homozygous mutation).

## 5 Conclusion

According to above investigations that showed a number of shortcomings and contradictions in findings of these studies, no firm conclusion can be drawn about the effect of EMF on genetic material. However, we cannot simply ignore the supported studies for the hypothesis that EMF induced genetic damage and cancer. Therefore, we need future better controlled investigations using the right and accurate biomarker assays and sufficient number of the individuals, adequate statistical analysis of data.

## References

Ahlbom IC, Cardis E, Green A et al (2001) Review of the epidemiologic literature on EMF and health. Environ Health Perspect 109(Suppl 6):911–933. https://doi.org/10.1289/ehp.109-1240626

Balamuralikrishnan B, Balachandar V, Kumar SS et al (2012) Evaluation of chromosomal alteration in electrical workers occupationally exposed to low frequency of electro magnetic field (EMFs) in Coimbatore population, India. Asian Pac J Cancer Prev 13:2961–2966. https://doi.org/10.7314/APJCP.2012.13.6.2961

Bernard N, Alberdi AJ, Tanguy ML et al (2008) Assessing the potential leukemogenic effects of 50 Hz magnetic fields and their harmonics using an animal leukemia model. J Radiat Res 49:565–577. https://doi.org/10.1269/jrr.08019

Boorman GA, Rafferty CN, Ward JM, Sills RC (2000) Leukemia and lymphoma incidence in rodents exposed to low-frequency magnetic fields. Radiat Res 153:627–636. https://doi.org/10.1667/0033-7587(2000)153[0627:LALIIR]2.0.CO;2

Burdak-Rothkamm S, Rothkamm K, Folkard M et al (2009) DNA and chromosomal damage in response to intermittent extremely low-frequency magnetic fields. Mutat Res 672:82–89. https://doi.org/10.1016/j.mrgentox.2008.10.016

Calvente I, Fernandez MF, Villalba J, Olea N, Nunez MI (2010) Exposure to electromagnetic fields (non-ionizing radiation) and its relationship with childhood leukemia: a systematic review. Sci Total Environ 408:3062–3069. https://doi.org/10.1016/j.scitotenv.2010.03.039

Carlberg M, Koppel T, Ahonen M, Hardell L (2018) Case-control study on occupational exposure to extremely low-frequency electromagnetic fields and the association with meningioma. Biomed Res Int 2018:5912394., 6 pages. https://doi.org/10.1155/2018/5912394

Cavalcanti BC, Ferreira JR, Cabral IO et al (2012) Genetic toxicology evaluation of essential oil of Alpinia zerumbet and its chemoprotective effects against $H_2O_2$-induced DNA damage in cultured human leukocytes. Food Chem Toxicol 50:4051–4061. https://doi.org/10.1016/j.fct.2012.03.038

Cho YH, Chung HW (2003) The effect of extremely low frequency electromagnetic fields (ELF-EMF) on the frequency of micronuclei and sister chromatid exchange in human lymphocytes induced by benzo(a) pyrene. Toxicol Lett 143:37–44. https://doi.org/10.1016/S0378-4274(03)00111-5

Cho S, Lee Y, Lee S et al (2014) Enhanced cytotoxic and genotoxic effects of gadolinium following ELF-EMF irradiation in human lymphocytes. Drug Chem Toxicol 37:440–447. https://doi.org/10.3109/01480545.2013.879662

Draper G, Vincent T, Kroll ME, Swanson J (2005) Childhood cancer in relation to distance from high voltage power lines in England and Wales: a case-control study. BMJ (Clin Res Ed) 330:1290. https://doi.org/10.1136/bmj.330.7503.1290

Duan W, Liu C, Zhang L et al (2015) Comparison of the genotoxic effects induced by 50 Hz extremely low-frequency electromagnetic fields and 1800 MHz

radiofrequency electromagnetic fields in GC-2 cells. Radiat Res 183:305–314. https://doi.org/10.1667/RR13851.1

Erdal N, Gurgul S, Celik A (2007) Cytogenetic effects of extremely low frequency magnetic field on Wistar rat bone marrow. Mutat Res 630:69–77. https://doi.org/10.1016/j.mrgentox.2007.03.001

Fam WZ, Mikhail EL (1996) Lymphoma induced in mice chronically exposed to very strong low-frequency electromagnetic field. Cancer Lett 105:257–269. https://doi.org/10.1016/0304-3835(96)04324-8

Feychting M, Forssen U (2006) Electromagnetic fields and female breast cancer. Cancer Causes Control 17:553–558

Finlay CC et al (2010) International geomagnetic reference field: the eleventh generation. Geophy J Int 183:1216–1230. https://doi.org/10.1111/j.1365-246X.2010.04804.x

Furse C, Christensen DA, Durney CH (2009) Basic introduction to bioelectromagnetics, 2nd edn. CRC Press/Taylor and Francis group, Boca Raton. https://doi.org/10.1201/9781420055436

Gadhia P, Chakraborty S, Pithawala M (2010) Cytogenetic studies on railway engine drivers exposed to extremely low frequency electromagnetic fields (ELF-EMF). Int J Hum Genet 10:263–269. https://doi.org/10.1080/09723757.2010.11886116

Hug K, Grize L, Seidler A, Kaatsch P, Schuz J (2010) Parental occupational exposure to extremely low frequency magnetic fields and childhood cancer: a German case-control study. Am J Epidemiol 171:27–35. https://doi.org/10.1093/aje/kwp339

IARC (2002) Non-ionizing radiation, part 1: static and extremely low-frequency (ELF) electric and magnetic fields. International Agency for Research on Cancer (IARC) monographs on the evaluation of carcinogenic risks to humans. vol 80. IARC Press, Lyon, pp 273–338

IARC (2013) Non-ionizing radiation, part 2: radiofrequency electromagnetic fields. International Agency for Research on Cancer (IARC) working group on the evaluation of carcinogenic risks to humans. IARC Monogr Eval Carcinog Risks Hum 102:1–460. PMC4780878

Irmak MK, Fadillioglu E, Gulec M et al (2002) Effects of electromagnetic radiation from a cellular telephone on the oxidant and antioxidant levels in rabbits. Cell Biochem Funct 20:279–283. https://doi.org/10.1002/cbf.976

Ivancsits S, Diem E, Pilger A et al (2002) Induction of DNA strand breaks by intermittent exposure to extremely-low-frequency electromagnetic fields in human diploid fibroblasts. Mutat Res 519:1–13. https://doi.org/10.1016/S1383-5718(02)00109-2

Jin YB, Choi SH, Lee JS et al (2014) Absence of DNA damage after 60-Hz electromagnetic field exposure combined with ionizing radiation, hydrogen peroxide, or c-Myc overexpression. Radiat Environ Biophys 53:93–101. https://doi.org/10.1007/s00411-013-0506-5

Johansen C, Raaschou Nielsen O et al (2007) Risk for leukaemia and brain and breast cancer among Danish utility workers: a second follow-up. Occup Environ Med 64:782–784. https://doi.org/10.1136/oem.2006.029116

Juutilainen J, Kumlin T (2006) Occupational magnetic field exposure and melatonin: interaction with light-at-night. Bioelectromagnetics 27:423–426. https://doi.org/10.1002/bem.20231

Kaszuba-Zwoinska J, Gremba J, Galdzinska-Calik B et al (2015) Electromagnetic field induced biological effects in humans. Przegl Lek 72:636–641

Kheifets L, Afifi AA, Shimkhada R (2006) Public health impact of extremely low-frequency electromagnetic fields. Environ Health Perspect 114:1532–1537. https://doi.org/10.1289/ehp.8977

Kheifets L, Monroe J, Vergara X, Mezei G, Afifi AA (2008) Occupational electromagnetic fields and leukemia and brain cancer: an update to two meta-analyses. J Occup Environ Med 50:677–688. https://doi.org/10.1097/JOM.0b013e3181757a27

Koeman T, van den Brandt PA, Slottje P et al (2014) Occupational extremely low-frequency magnetic field exposure and selected cancer outcomes in a prospective Dutch cohort. Cancer Causes Control 25:203–214. https://doi.org/10.1007/s10552-013-0322-x

Lagroye I, Percherancier Y, Juutilainen J et al (2011) ELF magnetic fields: animal studies, mechanisms of action. Prog Biophys Mol Biol 107:369–373. https://doi.org/10.1016/j.pbiomolbio.2011.09.003

Lin RS, Dischinger PC, Conde J, Farrell KP (1985) Occupational exposure to electromagnetic fields and the occurrence of brain tumors. An analysis of possible associations. J Occup Med 27:413–419. https://doi.org/10.1023/A:1007487503382

Livermore PW, Hollerbach R, Jackson A (2013) Electromagnetically driven westward drift and inner-core superrotation in Earth's core. Proc Natl Acad Sci U S A 110:15914–15918. https://doi.org/10.1073/pnas.1307825110

Mandeville R, Franco E, Sidrac-Ghali S et al (2000) Evaluation of the potential promoting effect of 60 Hz magnetic fields on N-ethyl-N-nitrosourea induced neurogenic tumors in female F344 rats. Bioelectromagnetics 21:84–93. https://doi.org/10.1002/(SICI)1521-186X(200002)21:2<84::AID-BEM2>3.0.CO;2-B

Marcilio I, Gouveia N, Pereira Filho ML, Kheifets L (2011) Adult mortality from leukemia, brain cancer, amyotrophic lateral sclerosis and magnetic fields from power lines: a case-control study in Brazil. Rev Bras Epidemiol 14:580–588. https://doi.org/10.1590/S1415-790X2011000400005

McCormick DL, Boorman GA, Findlay JC et al (1999) Chronic toxicity/oncogenicity evaluation of 60 Hz (power frequency) magnetic fields in B6C3F1 mice. Toxicol Pathol 27:279–285. https://doi.org/10.1177/019262339902700302

McElroy JA et al (2007) Occupational exposure to electromagnetic field and breast cancer risk in a large, population-based, case-control study in the United States. J Occup Environ Med 49:266–274. https://doi.org/10.1097/JOM.0b013e318032259b

Mevissen M et al (1993) Effects of magnetic fields on mammary tumor development induced by 7,12-dimethylbenz(a)anthracene in rats. Bioelectromagnetics 14:131–143. https://doi.org/10.1002/bem.2250140206

Mihai CT, Rotinberg P, Brinza F, Vochita G (2014) Extremely low-frequency electromagnetic fields cause DNA strand breaks in normal cells. J Environ Health Sci Eng 12:15. https://doi.org/10.1186/2052-336X-12-15

Miyakoshi J, Yoshida M, Shibuya K, Hiraoka M (2000) Exposure to strong magnetic fields at power frequency potentiates X-ray-induced DNA strand breaks. J Radiat Res 41:293–302. https://doi.org/10.1269/jrr.41.293

Nakahara T, Yaguchi H, Yoshida M, Miyakoshi J (2002) Effects of exposure of CHO-K1 cells to a 10-T static magnetic field. Radiology 224:817–822. https://doi.org/10.1148/radiol.2243011300

Ng K-H (2003) Electromagnetic field and our health: non-ionizing radiations–sources, biological effects, emissions and exposures, Proceedings of the International Conference on Non-Ionizing Radiation (ICNIR) at Universiti Tenaga Nasion (UNITEN), Malaysia, pp 1–16

Pedersen C et al (2014) Distance from residence to power line and risk of childhood leukemia: a population-based case-control study in Denmark. Cancer Causes Control 25:171–177. https://doi.org/10.1007/s10552-013-0319-5

Phillips JL, Singh NP, Lai H (2009) Electromagnetic fields and DNA damage. Pathophysiology 16:79–88. https://doi.org/10.1016/j.pathophys.2008.11.005

Qi G, Zuo X, Zhou L et al (2015) Effects of extremely low-frequency electromagnetic fields (ELF-EMF) exposure on B6C3F1 mice. Environ Health Prev Med 20:287–293. https://doi.org/10.1007/s12199-015-0463-5

Rageh MM, El-Gebaly RH, El-Bialy NS (2012) Assessment of genotoxic and cytotoxic hazards in brain and bone marrow cells of newborn rats exposed to extremely low-frequency magnetic field. J Biomed Biotechnol 2012:716023. https://doi.org/10.1155/2012/716023

Randall C, Harvey V, Manney G et al (2005) Stratospheric effects of energetic particle precipitation in 2003–2004. Geophys Res Lett 32:L05802. https://doi.org/10.1029/2004GL022003

Ross CL et al (2018) Evaluation of cytotoxic and genotoxic effects of extremely low-frequency electromagnetic field on mesenchymal stromal cells. Glob Adv Health Med 7:2164956118777472. https://doi.org/10.1177/2164956118777472

Scaringi M, Temperani P et al (2007) Evaluation of the genotoxicity of the extremely low frequency-magnetic fields (ELF-MF) in workers exposed for professional reasons. G Ital Med Lav Ergon 29:420–421

Schuz J (2011) Exposure to extremely low-frequency magnetic fields and the risk of childhood cancer: update of the epidemiological evidence. Prog Biophys Mol Biol 107:339–342. https://doi.org/10.1016/j.pbiomolbio.2011.09.008

Sermage-Faure C, Demoury C, Rudant J et al (2013) Childhood leukaemia close to high-voltage power lines – the Geocap study, 2002-2007. Br J Cancer 108:1899–1906. https://doi.org/10.1038/bjc.2013.128

Soffritti M et al (2016) Life-span exposure to sinusoidal-50 Hz magnetic field and acute low-dose gamma radiation induce carcinogenic effects in Sprague-Dawley rats. Int J Radiat Biol 92:202–214. https://doi.org/10.3109/09553002.2016.1144942

Sommer AM, Lerchl A (2004) The risk of lymphoma in AKR/J mice does not rise with chronic exposure to 50 Hz magnetic fields (1 microT and 100 microT). Radiat Res 162:194–200. https://doi.org/10.1667/RR3219

Sommer AM, Lerchl A (2006) 50 Hz magnetic fields of 1 mT do not promote lymphoma development in AKR/J mice. Radiat Res 165:343–349. https://doi.org/10.1667/RR3513.1

Sorahan T (2012) Cancer incidence in UK electricity generation and transmission workers, 1973-2008. Occup Med (Lond) 62:496–505. https://doi.org/10.1093/occmed/kqs152

Stronati L, Testa A, Villani P et al (2004) Absence of genotoxicity in human blood cells exposed to 50 Hz magnetic fields as assessed by comet assay, chromosome aberration, micronucleus, and sister chromatid exchange analyses. Bioelectromagnetics 25:41–48. https://doi.org/10.1002/bem.10141

Timmel C, Till U, Brocklehurst B et al (1998) Effects of weak magnetic fields on free radical recombination reactions. Mol Phys 95:71–89. https://doi.org/10.1080/00268979809483134

Udroiu I, Cristaldi M, Ieradi LA et al (2006) Clastogenicity and aneuploidy in newborn and adult mice exposed to 50 Hz magnetic fields. Int J Radiat Biol 82:561–567. https://doi.org/10.1080/09553000600876660

Vijayalaxmi, Obe G (2005) Controversial cytogenetic observations in mammalian somatic cells exposed to extremely low frequency electromagnetic radiation: a review and future research recommendations. Bioelectromagnetics 26:412–430. https://doi.org/10.1002/bem.20111

Vijayalaxmi, Prihoda TJ (2009) Genetic damage in mammalian somatic cells exposed to extremely low frequency electro-magnetic fields: a meta-analysis of data from 87 publications (1990-2007). Int J Radiat Biol 85:196–213. https://doi.org/10.1080/09553000902748575

Wertheimer N, Leeper E (1979) Electrical wiring configurations and childhood cancer. Am J Epidemiol 109:273–284. https://doi.org/10.1093/oxfordjournals.aje.a112681

WHO (2007) Extremely low frequency fields, Environmental health criteria monograph no. 238. World Health Organization (WHO), Geneva, p 121

Willett EV, McKinney PA, Fear NT et al (2003) Occupational exposure to electromagnetic fields and acute leukaemia: analysis of a case-control study. Occup Environ Med 60:577–583. https://doi.org/10.1136/oem.60.8.577

Winker R, Ivancsits S, Pilger A, Adlkofer F, Rüdiger HW (2005) Chromosomal damage in human diploid fibroblasts by intermittent exposure to extremely low-frequency electromagnetic fields. Mutat Res 585(1–2):43–49. https://doi.org/10.1016/j.mrgentox.2005.04.013

Zhu K, Lv Y, Cheng Q, Hua J, Zeng Q (2016) Extremely low frequency magnetic fields do not induce DNA damage in human lens epithelial cells In vitro. Anat Rec (Hoboken) 299:688–697. https://doi.org/10.1002/ar.23312