

# DNA effects of low level occupational exposure to extremely low frequency electromagnetic fields (50/60 Hz)

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## Abstract

**Aims:** Exposure to extremely low frequency magnetic fields (ELF-MF) occurs from natural and artificial sources. Although ELF-MF has been classified as a suspected humans carcinogen agent by the International Agency for Research on Cancer, little is known of the effects of ELF-MF at lower exposure levels of the recommended range. In the present study, DNA damage in the peripheral blood cells of power line workers was investigated.

**Materials and Methods:** Occupational exposure to ELF-MF in a power plant was measured using the National Institute for Occupational Safety and Health (NIOSH) manual. Single-strand breaks (SSBs) in DNA were evaluated in 29 male utility workers as the exposed population and 28 male support personnel as the control subjects using the comet assay. Effects of ELF-MF on subjects were evaluated using DNA percent in tails, tail length, olive length, and tail moment.

**Results:** Occupational exposure levels to ELF-MF in the utility workers were less than the threshold limit values (TLV) recommended by the American Conference of Government Industrial Hygienist (ACGIH). The median value of the magnetic field at the working sites was 0.85  $\mu$ T. Induction of DNA damage was observed for the exposed workers compared with the controls. Olive length, tail moment, and tail DNA percent increased significantly ( $p < 0.05$ ) in the utility workers.

**Conclusions:** Exposure to ELF-MF at levels less than the ACGIH exposure limit can produce DNA strand breaks.

## Keywords

ELF-MF, comet assay, DNA damages, occupational exposure

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## Introduction

Exposure to extremely low frequency magnetic fields (ELF-MF) could occur from both natural and man-made sources. Electrical devices and high-voltage electricity lines produce ELF-MF within the frequency range of 50 to 60 Hz (Ansari et al., 2016). In this regard, ELF-MF exposure has become a public concern because of the extreme use of nonionizing radiation (Touitou et al., 2013). The body of the literature dealing with the effects of electromagnetic field exposure in humans, especially in a real working environment, is limited (Albert et al., 2009;

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**Table 1.** General characteristics of the studied utility workers and support personnel.

| Groups                       | N  | Age (year)                | Work experience (year) | Smokers <sup>d</sup> |
|------------------------------|----|---------------------------|------------------------|----------------------|
| Utility workers <sup>a</sup> | 29 | 36.03 ± 3.15 <sup>c</sup> | 9.86 ± 2.99            | 7                    |
| Support personnel            | 28 | 34.46 ± 3.89              | 7.64 ± 3.36            | 8                    |
| p Value <sup>b</sup>         |    | 0.668                     | 0.786                  | 0.067                |

<sup>a</sup>Utility workers and support personnel considered as exposed and control groups, respectively.

<sup>b</sup>Proved that there is no significance difference between groups ( $p > 0.05$ ).

<sup>c</sup>Mean ± SD.

<sup>d</sup>Smoking habit more than 1 year.

Gourzoulidis et al., 2016; Jalilian et al., 2018; Touitou et al., 2012). Nevertheless, there are some reports indicating the epidemiological evidence with regard to the carcinogenic effects of ELF-MF exposure such as leukemia or neoplasm on the central nervous system (Huss et al., 2018; Tofani et al., 1995). Alterations in blood chemistry (Touitou et al., 2012), impairment of body homeostasis (Zhang et al., 2017), and oxidative damages (Ansari et al., 2016) were reported as the adverse effects of ELF-MF. Furthermore, ELF-MF exposure might cause neurodegenerative diseases, cardiovascular diseases, brain cancer, breast cancer, and other types of cancer (Dominici et al., 2011; Liburdy et al., 1993). In contrast, there are reports in the literature claiming that ELF-MF exposure cannot alter the immune system's mechanism (Touitou et al., 2013) or cause chromosomal damages (Tofani et al., 1995) in humans.

The American Conference of Governmental Industrial Hygienists (ACGIH) has provided a threshold limit value–ceiling (TLV-C) of 1.2 and 1 mT (ACGIH, 2015) for ELF-MF within the frequencies of 50 and 60 Hz, respectively. There is limited epidemiological evidence confirming the risk of carcinogenesis among the people who are exposed to a low intensity of ELF-MF. International Agency for Research on Cancer (IARC) has classified ELF-MF in group 2B as “possibly carcinogenic to humans.” Some reports demonstrated that exposure to ELF-MF at the levels higher than occupational exposure limit can produce genotoxicity (IARC, 2002). Dominici et al. established micronuclei and sister chromatid exchange in welding exposure and confirmed that metal exposure in welder groups could lead to genotoxicity (Dominici et al., 2011). However, one of the most important concerns related to ELF-MF exposure is the genetic damage to human populations (Vijayalaxmi and Prihoda, 2009). One of the most sensitive methods for measuring DNA damage is comet assay.

The modified comet assay, which was first introduced by Singh et al., is an electrophoresis gel-based method which can measure DNA breaks via the application of fluorescent microscopy (Singh et al., 1988).

In the present study, the impact of ELF-MF exposure to intensities less than the occupational exposure limit on DNA damage was investigated. Genotoxicity in peripheral blood mononuclear cells (PBMC) was evaluated using the comet assay among the employees of a power plant.

## Material and methods

### Study population

In this cross-sectional study, 29 male utility workers from a power plant (Iran, Tehran) were selected as the exposed participants. The means of age and work experience (related to the power lines) of the exposed groups were  $36.03 \pm 3.15$  and  $9.86 \pm 2.99$  years, respectively. Accordingly, 28 male support personnel with no background of occupational exposure to ELF-MF were selected as the control group. The exposed group was matched with nonexposed workers in terms of sex, age, work experiences, and smoking level (Table 1). The procedures of this study were approved by the Committee on Research Ethics at Shahid Beheshti University of Medical Sciences, SBMU-IRB (IR.SBMU.PHNS.REC.1397.037 approved on 2018), and a written informed consent was obtained from each individual and employer in advance.

### Magnetic field measurement

Protocol #401 of the NIOSH manual (Bowman et al., 1998) was used to assess the ELF-MF in a power plant during a working shift. In this regard, TES-1393 (TEC Electrical Electronic Corp. Taipei, Taiwan) was set for magnetic field exposure measurements. The measurements were made with a hand-held magnetic field survey meter and were done on long walks through the

plant area stopping at each workstation. Next, the magnetic field was measured at a triple axis, and the ranges were adjusted to the frequency of 3–3000 Hz and the intensity of 0.1 to 200 mG. ELF-MF was measured in the working site using the dimension of  $64 \times 240 \text{ m}^2$ . ELF-MF was characterized by the walkway of the plant, while the center of 78 stations was evaluated using the distance of 16 m. The assessed stations included local utility workers stopping to fill forms and checklists. In each station, four repeats of ELF-MF intensity were recorded, and the means were calculated.

### Chemical and reagents

Low-gelling-temperature (LGT) agarose (Sigma; Type VII), agarose,  $\text{Na}_2\text{EDTA}$ , NaOH, and dimethyl sulfoxide (DMSO) were purchased in analytical grade from Merck, Sigma, and Fluka and were used without further purification. FluoroVue™ Nucleic Acid Gel Stain (10,000 $\times$ ) was purchased from Smobio company (Hsinchu, Taiwan) and was used as a safe DNA gel stain.

### Comet assay procedure

The comet assay was performed according to the method presented by Olive and Banáth (Olive and Banáth, 2006). The alkaline procedure was used to determine DNA strand breaks in peripheral blood mononuclear cells (PBMC). Samples of 1 mL heparinized blood were taken from the studied population. Accordingly, slides were prepared adding 40  $\mu\text{L}$  of whole blood and 120  $\mu\text{L}$  of LGT agarose in a clean microtube that was followed by pipetting 120  $\mu\text{L}$  of cell suspension quickly onto the agarose-covered surface of a pre-coated slide. Lysis and electrophoresis were performed under alkaline conditions ( $\text{pH} > 13$ ). The slides were submerged in the fresh lysis buffer (A1 solution containing 1.2M NaCl, 100mM  $\text{Na}_2\text{EDTA}$ , 0.1% sodium lauryl sarcosinate, 0.26M NaOH, and 2% DMSO) for 2 h in a dark and cold place ( $4^\circ\text{C}$ ). Then, the slides were removed and washed by electrophoresis buffer (A2 solution containing 0.03M NaOH, 2mM  $\text{Na}_2\text{EDTA}$  in pH approximately 12.3) twice. Thereafter, the slides were submerged in a fresh A2 solution using an electrophoresis chamber. Subsequently, power supply voltage was set to 0.6 V/cm, and electrophoresis was done for 25 min. Finally, the slides were removed and stained using fluorescent DNA dye.

DNA damage was investigated using a fluorescence microscope (ECLIPS 80 with WG filter, Nikon, Tokyo,

Japan). Images of slides were analyzed via Image J 1.50i-Open Comet software (Rashand, 2017). A minimum of 50 randomly selected cells from each sample were measured for their tail length (TL), % DNA in tail, tail moment (TM), and olive moment (OM). OM is defined as the amount of DNA and the mean distance of migration in the tail ( $\text{OM} = (\text{Tail-mean} - \text{Head-mean}) \times \text{Tail\% DNA}/100$ ). In this regard, mean values were calculated in the statistical analysis (Mozaffarieh et al., 2008; Zendejdel et al., 2017).

The percent DNA in the tail is the most informative parameter for judging comet assay results (Collins, 2014). TM is derived from TL, which is sensitive to the background or threshold setting of the image analysis program, as the end of the tail is defined by a certain excess of fluorescence over background (Gyori et al., 2014). Moreover, % DNA in the tail is linearly related to DNA break frequency, is relatively unaffected by threshold settings, and allows discrimination of damage over the widest possible range (Collins, 2004).

### Statistical analysis

Statistical analysis was performed using SPSS V.16 software. The variation between the exposed and the control group was evaluated using an independent *t*-test and Mann–Whitney *U* test for normal and non-normal distributions, respectively. The Spearman correlation coefficient test was applied to investigate the correlation between DNA damage parameters (TL, TDNA%, TM, and OM) of PBMC and ELF exposure considering a significance level of 0.05. Data normality was determined using the Shapiro–Wilk test.

### Results

There were no statistically significant differences in term of age, work experience, and smoking level among utility workers and support personnel (Table 1).

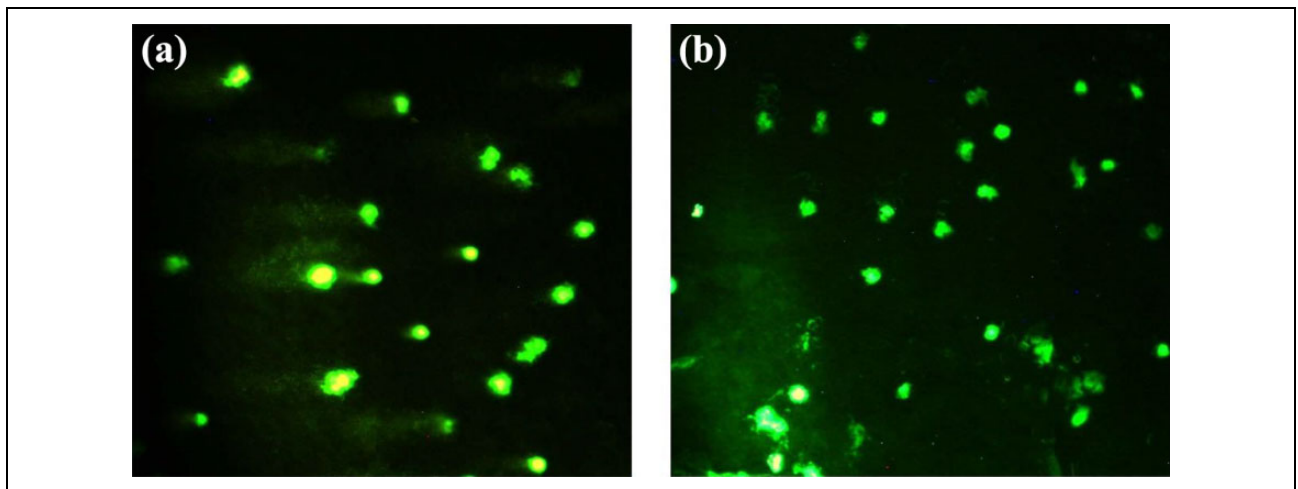
According to the normality test, TL and OM data had a normal distribution, while TDNA% and TM data were non-normally distributed. In this regard, the Independent sample *t*-test and Mann Whitney *U* test were used for testing normal and non-normal distributions, respectively.

ELF-MF measurements were carried out based on the sampling strategy suggested by NIOSH (Bowman et al., 1998). Stations were selected in work sites by at least the distance of 5 m from the sources of elevated magnetic fields such as turbines of power generator, where utility workers spend at least one-third of their working time. ELF-MF exposure was measured

**Table 2.** The ELF-MF measurement in the stations along with the generators in the studied power plant ( $\mu\text{T}$ ).

| Station          | Generators |              |            |            |            |          |
|------------------|------------|--------------|------------|------------|------------|----------|
|                  | 1          | 2            | 3          | 4          | 5          | 6        |
| 1                | 4          | 5.1          | 35         | 5          | 10         | 12       |
| 2                | 4.1        | 5            | 32         | 8.7        | 10         | 11       |
| 3                | 7          | 15           | 29         | 14         | 17         | 8.5      |
| 4                | 11         | 11.8         | 50         | 13         | 13         | 9        |
| 5                | 12.7       | 4.9          | 39         | 6.1        | 13.5       | 5        |
| Median (min–max) | 7 (4–12.7) | 5.1 (4.9–15) | 35 (29–50) | 8.7 (5–14) | 13 (10–17) | 9 (5–12) |

ELF-MF: extremely low frequency magnetic field.

**Figure 1.** The microscopic images (magnitude of  $\times 200$ ) of blood sample prepared according to the comet protocol of this study: (a) exposed and (b) unexposed sample.

around six generators. The results showed that ELF-MF exposure around the third generator was greater than others.

Exposure levels in the measured stations were between 4 and 50  $\mu\text{T}$  with a median of 0.85  $\mu\text{T}$ . ELF-MF was recorded during normal work shifts (Table 2). ELF-MF exposure of support personnel was reported as the background, which was between 0.4 to 25.5  $\mu\text{T}$  (Table 3). ELF-MF data in eight stations of work sites were greater than the upper level of support exposure personnel. The recorded exposure of utility workers was significantly ( $p < 0.001$ ) greater than that of the unexposed population.

TL in the exposed group was significantly ( $p < 0.001$ ) greater than the one in the control group (Figure 1). The mean  $\pm$  SD values of utility workers and controls were  $25.87 \pm 12.76$  and  $12.71 \pm 12.38$ , respectively. OM of exposed subjects (mean  $\pm$  SD:  $25.87 \pm 12.76$ ) was also significantly ( $p < 0.001$ ) greater than that of the control group (Table 4).

**Table 3.** ELF-MF exposure in the workstation of the studied utility workers and support personnel.

| Groups           | ELF-MF in groups ( $\mu\text{T}$ ) |                   |
|------------------|------------------------------------|-------------------|
|                  | Utility workers <sup>a</sup>       | Support personnel |
| Median (min–max) | 11 (4–50)                          | 0.85 (0.4–25.5)   |

ELF-MF: extremely low frequency magnetic field.

<sup>a</sup>Utility workers and support personnel considered as exposed and control groups, respectively.

The results showed that utility workers contained % DNA in tail ( $p = 0.017$ ) and TM ( $p = 0.006$ ) compared to those of the support personnel (Table 5).

The two-tailed Pearson correlation coefficient showed a significant and positive relationship between work experience and both TL ( $r = 0.446$ ,  $p = 0.001$ ) and OM ( $r = 0.434$ ,  $p = 0.001$ ). There was no significant relationship between age and DNA parameter damages.

**Table 4.** TL and OM values in the utility workers and support personnel.

| Groups                       | TL (mean $\pm$ SD) | OM (mean $\pm$ SD) |
|------------------------------|--------------------|--------------------|
| Utility workers <sup>a</sup> | 25.87 $\pm$ 12.76  | 12.25 $\pm$ 6.16   |
| Support personnel            | 12.71 $\pm$ 12.38  | 5.97 $\pm$ 6.47    |
| <i>p</i> Value               | <0.001             | <0.001             |

TL: tail length; OM: olive moment.

<sup>a</sup>Utility workers and support personnel considered as exposed and control groups, respectively.

**Table 5.** Tail DNA percent and TM values in the utility workers and support personnel.

| Groups                       | % DNA in tail<br>Median (min–max) | Tail moment<br>Median (min–max) |
|------------------------------|-----------------------------------|---------------------------------|
| Utility workers <sup>a</sup> | 54.82 (26.19–76.20)               | 14.79 (3.60–49.80)              |
| Support personnel            | 18.82 (0.45–80.20)                | 3.13 (0.01–30.30)               |
| <i>p</i> Value               | 0.017                             | 0.006                           |

TM: tail moment.

<sup>a</sup>Utility workers and support personnel considered as exposed and control groups, respectively.

## Discussion

Since IARC classified ELF-MF as a possible carcinogenic agent (2B) in humans, there are numerous evidences that show the genetic damages caused by ELF-MF exposure to cells, animals, and humans (Dominici et al., 2011; Havas, 2017; Tofani et al., 1995; Verschaeve et al., 2016; Vijayalaxmi and Prihoda, 2009; Zhang et al., 2017). Dominici reported genotoxic damage of ELF-MF during a complete day exposure in welders (Dominici et al., 2011). The aim of the present study was to determine DNA damage caused by ELF-MF discontinuous exposure to low intensity among workers in power plant industries.

In this regard, blood samples of the selected subjects, including high voltage technicians and control group, were taken, and DNA damages were evaluated using the comet assay. Comet assay is one of the versatile, quantitative, and sensitive methods (Collins and Azqueta, 2012) to detect DNA strand breaks and could determine single-strand breaks (SSBs), double-strand breaks, alkali-labile sites, and DNA crosslinks (Gyori et al., 2014). Four of the comet parameters including TL, TM, OM, and % DNA in tail were reported as indicators of the DNA damage among workers (Zendehdel et al., 2017). The statistical analysis of the TL parameter showed a significant

decrease in the control compared to the exposed group. In order to better assess, another parameter, namely % DNA in tail, was used in this experiment (Collins, 2004). The % DNA in tail was also significantly greater than the control. This parameter was recommended by Hellman et al. to be applied in DNA damage measurements (Hellman et al., 1995). The main benefit of using TM is that it represents both damaged DNA and migration in one value. The results of the present study showed a statistically significant difference between the exposed and control groups ( $p = 0.006$ ). Finally, OM showed a significant difference between exposed and control groups ( $p < 0.001$ ).

The recommended TLV-C by ACGIH for ELF-MF 50 Hz is 1 mT (ACGIH, 2015). The limit value of 0.5 mT has been accepted by the European Union for occupational exposure. However, results of the present study showed that the exposure level in all stations was lower than ACGIH and EU standards (Collins, 2014; Havas, 2017; IARC, 2002).

Since all comet parameters represented greater DNA damage in the exposed group, it was concluded that the ELF-MF exposure induced those damages. Investigations show that occupational discontinuous exposure to low levels of ELF-MF has a potential to cause DNA damages. Ruiz-Gomez reviewed 29 studies on DNA strand breaks induced by ELF-MF (Ruiz-Gómez and Martínez-Morillo, 2009). They reported that 50% of the studies confirmed DNA damages. However, it is generally accepted that ELF-MFs are unable to transfer a sufficient amount of energy to cells in order to damage DNA directly. Perhaps, there is DNA damages of ELF-MF through co-exposure to other pollutions (Moretti et al., 2005). Our study confirmed DNA damage of ELF-MF exposure. Although we matched the exposed subjects and control population, we could not control urban air pollution and food consumption of people. Air and food contamination could increase the effects of ELF-MF in utility workers with higher exposure than unexposed people. Further studies are needed in this respect in order to provide more conclusive results.

Tofani et al. reported that exposure to ELF in the presence of static magnetic field caused chromosomal aberrations (Tofani et al., 1995). Touitou et al. studied the chronic exposure to the ELF for 7 to 20 years during which the participants were exposed to more than 0.3  $\mu$ T. Their results showed that the chemistry of blood (such as glucose, sodium, chloride, and phosphorus concentration) changed among healthy men

who were employed as high voltage technicians (Touitou et al., 2012). Nevertheless, hematological parameters and immune system changes were not observed (Touitou et al., 2013). In another study (Svedenstål et al., 1999), degradation of DNA was reported by Svedenstål in brain cells of CBA mice. In their studies, 50-Hz, 0.5-mT magnetic fields were used for exposing mice groups for 2 h, 5 days, and 14 days. Fourteen days exposure to the magnetic field has the potential to cause DNA damage, which was not found in 2-h and 5-day exposures (Havas, 2017). According to the epidemiological studies, there is some evidence suggesting a link between occupational exposure to ELF-MF and the development of breast cancer among males and females, leukemia, and brain cancer (Demers et al., 1991; Havas, 2000; Lai, 2014; Tynes et al., 1992). In line with our study, Havas highly recommends that IARC reclassify the ELF-MF, considering new carcinogenic evidence in her recently published “Letter to the Editor” in 2017 (Havas, 2017). The lack of collaboration on the part of the power plant was a challenge for this study. However, the main limitation of this study was the small sample size.

## Conclusion

Indirect effects of magnetic field could cause injury in exposed workers due to a discontinuous exposure at a low level. It can be concluded that the occupational exposure to ELF-MF (50/60HZ) below the standards induced DNA damages among workers. It is highly recommended that exposure to ELF-MF be reduced in workplaces.

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## References

- ACGIH (2015) *TLVs and BEIs, Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*. USA: ACGIH.
- Albert GC, McNamee JP, Marro L, et al. (2009) Assessment of genetic damage in peripheral blood of human volunteers exposed (whole-body) to a 200  $\mu$ T, 60 Hz magnetic field. *International Journal of Radiation Biology* 85(2): 144–152.
- Ansari AM, Farzampour S, Sadr A, et al. (2016) Effects of short term and long term extremely low frequency magnetic field on depressive disorder in mice: involvement of nitric oxide pathway. *Life Sciences* 146: 52–57.
- Bowman JD, Kelsh MA and Kaune WT (1998) *Manual for Measuring Occupational Electric and Magnetic Field Exposures (#401)*. October 1998 Ed. Washington: US Department of Health and Human Services.
- Collins A and Azqueta A (2012) DNA repair as a biomarker in human biomonitoring studies; further applications of the comet assay. *Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis* 736(1): 122–129.
- Collins AR (2004) The comet assay for DNA damage and repair. *Molecular Biotechnology* 26(3): 249.
- Collins AR (2014) Measuring oxidative damage to DNA and its repair with the comet assay. *Biochimica et Biophysica Acta (BBA)-General Subjects* 1840(2): 794–800.
- Demers PA, Thomas DB, Rosenblatt KA, et al. (1991) Occupational exposure to electromagnetic fields and breast cancer in men. *American Journal of Epidemiology* 134(4): 340–347.
- Dominici L, Villarini M, Fatigoni C, et al. (2011) Genotoxic hazard evaluation in welders occupationally exposed to extremely low-frequency magnetic fields (ELF-MF). *International Journal of Hygiene and Environmental Health* 215(1): 68–75.
- Gourzoulidis G, Tsaprouni P, Skamnakis N, et al. (2016) Occupational exposure to electromagnetic fields—the situation in Greece. *Physica Medica* 32: 276.
- Gyori BM, Venkatachalam G, Thiagarajan P, et al. (2014) OpenComet: an automated tool for comet assay image analysis. *Redox Biology* 2: 457–465.
- Havas M (2000) Biological effects of non-ionizing electromagnetic energy: a critical review of the reports by the US National Research Council and the US National Institute of Environmental Health Sciences as they

- relate to the broad realm of EMF bioeffects. *Environmental Reviews* 8(3): 173–253.
- Havas M (2017) When theory and observation collide: Can non-ionizing radiation cause cancer? *Environmental Pollution* 221: 501–505.
- Hellman B, Vaghef H and Boström B (1995) The concepts of tail moment and tail inertia in the single cell gel electrophoresis assay. *Mutation Research/DNA Repair* 336(2): 123–131.
- Huss A, Spoerri A, Egger M, et al. (2018) Occupational extremely low frequency magnetic fields (ELF-MF) exposure and hematolymphopoietic cancers—Swiss National Cohort analysis and updated meta-analysis. *Environmental Research* 164: 467–474.
- IARC (2002) *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 80. Non-Ionizing Radiation, Part 1: Static and Extremely Low-frequency (ELF) Electric and Magnetic Fields*. Lyon: IARC.
- Jalilian H, Teshnizi SH, Rösli M, et al. (2018) Occupational exposure to extremely low frequency magnetic fields and risk of Alzheimer disease: a systematic review and meta-analysis. *Neurotoxicology* 69: 242–252.
- Lai H (2014) *Extremely-Low Frequency EMF Free Radical Studies*. Available at: <http://www.bioinitiative.org/research-summaries/> (accessed September 2018).
- Liburdy R, Sloma T, Sokolic R, et al. (1993) ELF magnetic fields, breast cancer, and melatonin: 60 Hz fields block melatonin's oncostatic action on ER+ breast cancer cell proliferation. *Journal of Pineal Research* 14(2): 89–97.
- Moretti M, Villarini M, Simonucci S, et al. (2005) Effects of co-exposure to extremely low frequency (ELF) magnetic fields and benzene or benzene metabolites determined in vitro by the alkaline comet assay. *Toxicology Letters* 157(2): 119–128.
- Mozaffarieh M, Schoetzau A, Sauter M, et al. (2008) Comet assay analysis of single-stranded DNA breaks in circulating leukocytes of glaucoma patients. *Molecular Vision* 14: 1584–1588.
- Olive PL and Banáth JP (2006) The comet assay: a method to measure DNA damage in individual cells. *Nature Protocols* 1(1): 23.
- Rashand W (2017) *ImageJ 1.50i*. Bethesda: National Institutes of Health.
- Ruiz-Gómez MJ and Martínez-Morillo M (2009) Electromagnetic fields and the induction of DNA strand breaks. *Electromagnetic Biology and Medicine* 28(2): 201–214.
- Singh NP, McCoy MT, Tice RR, et al. (1988) A simple technique for quantitation of low levels of DNA damage in individual cells. *Experimental Cell Research* 175(1): 184–191.
- Svedenstål B, Johanson K and Mild KH (1999) DNA damage induced in brain cells of CBA mice exposed to magnetic fields. *In Vivo (Athens, Greece)* 13(6): 551–552.
- Tofani S, Ferrara A, Anglesio L, et al. (1995) Evidence for genotoxic effects of resonant ELF magnetic fields. *Bioelectrochemistry and Bioenergetics* 36(1): 9–13.
- Touitou Y, Djeridane Y, Lambrozo J, et al. (2012) Long-term (up to 20 years) effects of 50-Hz magnetic field exposure on blood chemistry parameters in healthy men. *Clinical Biochemistry* 45(6): 425–428.
- Touitou Y, Djeridane Y, Lambrozo J, et al. (2013) Long-term (up to 20 years) effects of 50-Hz magnetic field exposure on immune system and hematological parameters in healthy men. *Clinical Biochemistry* 46(1): 59–63.
- Tynes T, Andersen A and Langmark F (1992) Incidence of cancer in Norwegian workers potentially exposed to electromagnetic fields. *American Journal of Epidemiology* 136(1): 81–88.
- Verschaeve L, Wambacq S, Anthonissen R, et al. (2016) Co-exposure of ELF-magnetic fields and chemical mutagens: an investigation of genotoxicity with the SOS-based VITOTOX test in *Salmonella typhimurium*. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis* 795: 31–35.
- Vijayalaxmi and 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). *International Journal of Radiation Biology* 85(3): 196–213.
- Zendehdel R, Jouni FJ, Hajipour B, et al. (2017) DNA damage in workers exposed to formaldehyde at concentrations below occupational exposure limits. *Toxicological & Environmental Chemistry* 99(9–10): 1–16.
- Zhang D, Zhang Y, Zhu B, et al. (2017) Resveratrol may reverse the effects of long-term occupational exposure to electromagnetic fields on workers of a power plant. *Oncotarget* 8(29): 47497.