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Insights in the biology of extremely low-frequency magnetic fields exposure on human health

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Abstract

The extremely low-frequency magnetic fields (ELF-EMF) are generated by electrical devices and power systems (1 to 300 Hz). In recent decades, exposure to ELF-EMF has emerged potential concerns on public health. Here, we discuss recent progress in the understanding of ELF-EMF biology with a focus on mechanisms of ELF-EMF-mediated disease and summarize the results of more recent experimental and epidemiological studies of ELF-EMF exposure effects on cancer, neurological, cardiovascular, and reproductive disorders. Current views on genomic instability effects, as well as scientific evidence about ELF-EMF therapy, are put forth. According to our literature review, exposure to ELF-EMF has an adverse biological effect depending on the current intensity, strength of the magnetic field, and duration of exposure. Accumulated epidemiologic evidence indicates a correlation between

exposure to ELF-EMF and childhood cancer incidence, Alzheimer's disease (AD), and miscarriage. However, adult cancer does not show augmented risk caused by the ELF-EMF. Also, no consistent evidence exists in cardiovascular disease mortality due to ELF-EMF exposure. There is a lack of comprehensive mechanisms for explaining the biological effect of ELF-EMF. Eventually, more studies are needed to clarify the mechanisms of these magnetic fields.

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References

1. Tenforde T (1992) Biological interactions and potential health effects of extremely-low-frequency magnetic fields from power lines and other common sources. Annu Rev Public Health 13(1):173–196

2. Touitou Y, Selmaoui B (2012) The effects of extremely low-frequency magnetic fields on melatonin and cortisol, two marker rhythms of the circadian system. Dialogues Clin Neurosci 14(4):381

3. Lee S-K, Park S, Kim Y-W (2016) The Effects of extremely low-frequency magnetic fields on reproductive function in rodents, insights from animal reproduction. IntechOpen, London

4. Marcilio I, Habermann M, Gouveia N (2009) Campos magnéticos de frequência extremamente baixa e efeitos na saúde: revisão da literatura. Rev Bras Epidemiol

12:105–123

5. Ng K-H (2003) Non-ionizing radiations–sources, biological effects, emissions and exposures. In: Proceedings of the international conference on non-ionizing radiation at UNITEN

6. Feychting M, Ahlbom A, Kheifets L (2005) EMF and health. Annu Rev Public Health 26:165–189

7. D'Angelo C, Costantini E, Kamal M, Reale M (2015) Experimental model for ELF-EMF exposure: concern for human health. Saudi J Biol Sci 22(1):75–84

8. Wertheimer N, Leeper E (1979) Electrical wiring configurations and childhood cancer. Am J Epidemiol 109(3):273–284

9. Cancer IAFRO (2013) Non-ionizing radiation, part 2: radiofrequency electromagnetic fields. IARC Monogr Eval Carcinog Risks Hum 102:1–421

10. Schmiedel S, Blettner M (2010) The association between extremely low-frequency electromagnetic fields and childhood leukaemia in epidemiology: enough is enough? Br J Cancer 103:931

11. Schüz 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(3):339–342

12. 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. https://doi.org/10.1155/2018/5912394

13. Jalilian H, Teshnizi SH, Röösli M, Neghab M (2018) Occupational exposure to extremely low frequency magnetic fields and risk of Alzheimer disease: a systematic review and meta-analysis. Neurotoxicology 69:242–252

14. Turner MC, Benke G, Bowman JD, Figuerola J, Fleming S, Hours M, Kincl L, Krewski D, McLean D, Parent ME, Richardson L, Sadetzki S, Schlaefer K, Schlehofer B, Schuz J, Siemiatycki J, Tongeren MV, Cardis E (2017) Interactions between occupational exposure to extremely low frequency magnetic fields and chemicals for brain tumour risk in the INTEROCC study. Occup Environ Med 74(11):802–809. https://doi.org/10.1136/oemed-2016-104080

15. Carlberg M, Koppel T, Ahonen M, Hardell L (2017) Case-control study on occupational exposure to extremely low-frequency electromagnetic fields and glioma risk. Am J Ind Med 60(5):494–503. https://doi.org/10.1002/ajim.22707

16. Turner MC, Benke G, Bowman JD, Figuerola J, Fleming S, Hours M, Kincl L, Krewski D, McLean D, Parent ME, Richardson L, Sadetzki S, Schlaefer K, Schlehofer B, Schüz J, Siemiatycki J, van Tongeren M, Cardis E (2014) Occupational exposure to extremely low-frequency magnetic fields and brain tumor risks in the INTEROCC study. Cancer Epidemiol Biomark Prev 23(9):1863–1872. https://doi.org/10.1158/1055-9965.epi-14-0102

17. Oraby T, Sivaganesan S, Bowman JD, Kincl L, Richardson L, McBride M, Siemiatycki J, Cardis E, Krewski D (2018) Berkson error adjustment and other exposure surrogates in occupational case-control studies, with application to the Canadian INTEROCC study. J Eposure Sci Environ Epidemiol 28(3):251–258. https://doi.org/10.1038/jes.2017.2

18. Li P, McLaughlin J, Infante-Rivard C (2009) Maternal occupational exposure to extremely low frequency magnetic fields and the risk of brain cancer in the offspring. Cancer Causes Control CCC 20(6):945–955. https://doi.org/10.1007/s10552-009-9311-5

19. Huss A, Spoerri A, Egger M, Kromhout H, Vermeulen R (2018) Occupational extremely low frequency magnetic fields (ELF-MF) exposure and hematolymphopoietic cancers—Swiss National Cohort analysis and updated meta-analysis. Environ Res 164:467–474. https://doi.org/10.1016/j.envres.2018.03.022

20. Talibov M, Olsson A, Bailey H, Erdmann F, Metayer C, Magnani C, Petridou E, Auvinen A, Spector L, Clavel J, Roman E, Dockerty J, Nikkila A, Lohi O, Kang A, Psaltopoulou T, Miligi L, Vila J, Cardis E, Schuz J (2019) Parental occupational exposure to low-frequency magnetic fields and risk of leukaemia in the offspring: findings from the Childhood Leukaemia International Consortium (CLIC). Occup Environ Med 76(10):746–753. https://doi.org/10.1136/oemed-2019-105706

21. Su L, Fei Y, Wei X, Guo J, Jiang X, Lu L, Chen G (2016) Associations of parental occupational exposure to extremely low-frequency magnetic fields with childhood leukemia risk. Leuk Lymphoma 57(12):2855–2862. https://doi.org/10.3109/10428194.2016.1165812

22. Koeman T, van den Brandt PA, Slottje P, Schouten LJ, Goldbohm RA, Kromhout H, Vermeulen R (2014) Occupational extremely low-frequency magnetic field exposure and selected cancer outcomes in a prospective Dutch cohort. Cancer Causes Control CCC 25(2):203–214. https://doi.org/10.1007/s10552-013-0322-x

23. Li W, Ray RM, Thomas DB, Yost M, Davis S, Breslow N, Gao DL, Fitzgibbons ED, Camp JE, Wong E, Wernli KJ, Checkoway H (2013) Occupational exposure to magnetic fields and breast cancer among women textile workers in Shanghai. China Am J Epidemiol 178(7):1038–1045. https://doi.org/10.1093/aje/kwt161

24. Zhou H, Chen G, Chen C, Yu Y, Xu Z (2012) Association between extremely low-frequency electromagnetic fields occupations and amyotrophic lateral sclerosis: a meta-analysis. PLoS ONE 7(11):e48354. https://doi.org/10.1371/journal.pone.0048354

25. Parlett LE, Bowman JD, van Wijngaarden E (2011) Evaluation of occupational exposure to magnetic fields and motor neuron disease mortality in a population-based cohort. J Occup Environ Med 53(12):1447–1451. https://doi.org/10.1097/JOM.0b013e318237a1d0

26. Huss A, Spoerri A, Egger M, Kromhout H, Vermeulen R (2015) Occupational exposure to magnetic fields and electric shocks and risk of ALS: the Swiss National Cohort. Amyotroph Lateral Scler Frontotemporal Degener 16(1–2):80–85. https://doi.org/10.3109/21678421.2014.954588

27. Koeman T, Slottje P, Schouten LJ, Peters S, Huss A, Veldink JH, Kromhout H, van den Brandt PA, Vermeulen R (2017) Occupational exposure and amyotrophic lateral sclerosis in a prospective cohort. Occup Environ Med 74(8):578–585. https://doi.org/10.1136/oemed-2016-103780

28. Peters S, Visser AE, D'Ovidio F, Beghi E, Chiò A, Logroscino G, Hardiman O, Kromhout H, Huss A, Veldink J, Vermeulen R, van den Berg LH (2019) Associations of electric shock and extremely low-frequency magnetic field exposure with the risk of amyotrophic lateral sclerosis. Am J Epidemiol 188(4):796–805. https://doi.org/10.1093/aje/kwy287

29. Pedersen C, Poulsen AH, Rod NH, Frei P, Hansen J, Grell K, Raaschou-Nielsen O, Schuz J, Johansen C (2017) Occupational exposure to extremely low-frequency magnetic fields and risk for central nervous system disease: an update of a Danish cohort study among utility workers. Int Arch Occup Environ Health 90(7):619–628. https://doi.org/10.1007/s00420-017-1224-0

30. Vergara X, Kheifets L, Greenland S, Oksuzyan S, Cho YS, Mezei G (2013) Occupational exposure to extremely low-frequency magnetic fields and neurodegenerative disease: a meta-analysis. J Occup Environ Med 55(2):135–146. https://doi.org/10.1097/JOM.0b013e31827f37f8

31. van der Mark M, Vermeulen R, Nijssen PC, Mulleners WM, Sas AM, van Laar T, Kromhout H, Huss A (2015) Extremely low-frequency magnetic field exposure, electrical shocks and risk of Parkinson's disease. Int Arch Occup Environ Health 88(2):227–234. https://doi.org/10.1007/s00420-014-0949-2

32. Brouwer M, Koeman T, van den Brandt PA, Kromhout H, Schouten LJ, Peters S, Huss A, Vermeulen R (2015) Occupational exposures and Parkinson's disease mortality in a prospective Dutch cohort. Occup Environ Med 72(6):448–455. https://doi.org/10.1136/oemed-2014-102209

33. Koeman T, Slottje P, Kromhout H, Schouten LJ, Goldbohm RA, van den Brandt PA, Vermeulen R (2013) Occupational exposure to extremely low-frequency magnetic fields and cardiovascular disease mortality in a prospective cohort study. Occup Environ Med 70(6):402–407

34. Migault L, Garlantezec R, Piel C, Marchand-Martin L, Orazio S, Cheminat M, Zaros C, Carles C, Cardis E, Ancel PY, Charles MA, de Seze R, Baldi I, Bouvier G (2020) Maternal cumulative exposure to extremely low frequency electromagnetic fields, prematurity

and small for gestational age: a pooled analysis of two birth cohorts. Occup Environ Med 77(1):22–31. https://doi.org/10.1136/oemed-2019-105785

35. Migault L, Piel C, Carles C, Delva F, Lacourt A, Cardis E, Zaros C, de Seze R, Baldi I, Bouvier G (2018) Maternal cumulative exposure to extremely low frequency electromagnetic fields and pregnancy outcomes in the Elfe cohort. Environ Int 112:165–173. https://doi.org/10.1016/j.envint.2017.12.025

36. Bowman JD, Touchstone JA, Yost MG (2007) A population-based job exposure matrix for power-frequency magnetic fields. J Occup Environ Hyg 4(9):715–728. https://doi.org/10.1080/15459620701528001

37. Jauchem JR (1997) Exposure to extremely-low-frequency electromagnetic fields and radiofrequency radiation: cardiovascular effects in humans. Int Arch Occup Environ Health 70(1):9–21

38. Gye MC, Park CJ (2012) Effect of electromagnetic field exposure on the reproductive system. Clin Exp Reprod Med 39(1):1–9

39. Cichoń N, Czarny P, Bijak M, Miller E, Śliwiński T, Szemraj J, Saluk-Bijak J (2017) Benign effect of extremely low-frequency electromagnetic field on brain plasticity assessed by nitric oxide metabolism during poststroke rehabilitation. Oxidat Med Cell Longev. https://doi.org/10.1155/2017/2181942

40. Mansourian M, Firoozabadi M, Hassan ZM (2020) The role of 217-Hz ELF magnetic fields emitted from GSM mobile phones on electrochemotherapy mechanisms. Electromagn Biol Med. https://doi.org/10.1080/15368378.2020.1762635

41. Lai H (2019) Exposure to static and extremely-low frequency electromagnetic fields and cellular free radicals. Electromagn Biol Med 38(4):231–248. https://doi.org/10.1080/15368378.2019.1656645

42. Carpenter DO (2019) Extremely low frequency electromagnetic fields and cancer: how source of funding affects results. Environ Res 178:108688. https://doi.org/10.1016/j.envres.2019.108688

43. Pedersen C, Raaschou-Nielsen O, Rod NH, Frei P, Poulsen AH, Johansen C, Schüz J (2014) Distance from residence to power line and risk of childhood leukemia: a population-based case–control study in Denmark. Cancer Causes Control 25(2):171–177

44. Sermage-Faure C, Demoury C, Rudant J, Goujon-Bellec S, Guyot-Goubin A, Deschamps F, Hemon D, Clavel J (2013) Childhood leukaemia close to high-voltage power lines–the Geocap study, 2002–2007. Br J Cancer 108(9):1899

45. Campos-Sanchez E, Vicente-Duenas C, Rodriguez-Hernandez G, Capstick M, Kuster N, Dasenbrock C, Sanchez-Garcia I, Cobaleda C (2019) Novel ETV6-RUNX1 mouse model to study the role of ELF-MF in childhood B-acute lymphoblastic leukemia: a pilot study. Bioelectromagnetics 40(5):343–353. https://doi.org/10.1002/bem.22193

46. Pearce MS, Hammal DM, Dorak MT, McNally RJ, Parker L (2007) Paternal occupational exposure to electro-magnetic fields as a risk factor for cancer in children and young adults: a case-control study from the North of England. Pediatr Blood Cancer 49(3):280–286. https://doi.org/10.1002/pbc.21021

47. Reid A, Glass DC, Bailey HD, Milne E, de Klerk NH, Downie P, Fritschi L (2011) Risk of childhood acute lymphoblastic leukaemia following parental occupational exposure to

extremely low frequency electromagnetic fields. Br J Cancer 105(9):1409–1413. https://doi.org/10.1038/bjc.2011.365

48. Mezei G, Gadallah M, Kheifets L (2008) Residential magnetic field exposure and childhood brain cancer: a meta-analysis. Epidemiology 19:424–430

49. Kheifets L, Ahlbom A, Crespi C, Feychting M, Johansen C, Monroe J, Murphy M, Oksuzyan S, Preston-Martin S, Roman E (2010) A pooled analysis of extremely low-frequency magnetic fields and childhood brain tumors. Am J Epidemiol 172(7):752–761

50. Turner MC, Benke G, Bowman JD, Figuerola J, Fleming S, Hours M, Kincl L, Krewski D, McLean D, Parent M-E (2014) Occupational exposure to extremely low-frequency magnetic fields and brain tumor risks in the INTEROCC study. Cancer Epidemiol Prev Biomark 23(9):1863–1872

51. Zhao G, Lin X, Zhou M, Zhao J (2014) Relationship between exposure to extremely low-frequency electromagnetic fields and breast cancer risk: a meta-analysis. Eur J Gynaecol Oncol 35(3):264–269

52. Sorahan T (2012) Cancer incidence in UK electricity generation and transmission workers, 1973–2008. Occup Med 62(7):496–505

53. Elliott P, Shaddick G, Douglass M, de Hoogh K, Briggs DJ, Toledano MB (2013) Adult cancers near high-voltage overhead power lines. Epidemiology 24:184–190

54. Koeman T, Van Den Brandt PA, Slottje P, Schouten LJ, Goldbohm RA, Kromhout H, Vermeulen R (2014) Occupational extremely low-frequency magnetic field exposure

and selected cancer outcomes in a prospective Dutch cohort. Cancer Causes Control 25(2):203–214

55. Soffritti M, Giuliani L (2019) The carcinogenic potential of non-ionizing radiations: the cases of S-50 Hz MF and 1.8 GHz GSM radiofrequency radiation. Basic Clin Pharmacol Toxicol 125(Suppl 3):58–69. https://doi.org/10.1111/bcpt.13215

56. Schüz J, Dasenbrock C, Ravazzani P, Röösli M, Schär P, Bounds PL, Erdmann F, Borkhardt A, Cobaleda C, Fedrowitz M (2016) Extremely low-frequency magnetic fields and risk of childhood leukemia: a risk assessment by the ARIMMORA consortium. Bioelectromagnetics 37(3):183–189

57. Herrala M, Kumari K, Koivisto H, Luukkonen J, Tanila H, Naarala J, Juutilainen J (2018) Genotoxicity of intermediate frequency magnetic fields in vitro and in vivo. Environ Res 167:759–769

58. Jelenković A, Janać B, Pešić V, Jovanović D, Vasiljević I, Prolić Z (2006) Effects of extremely low-frequency magnetic field in the brain of rats. Brain Res Bull 68(5):355–360

59. Huang C-Y, Chang C-W, Chen C-R, Chuang C-Y, Chiang C-S, Shu W-Y, Fan T-C, Hsu IC (2014) Extremely low-frequency electromagnetic fields cause G1 phase arrest through the activation of the ATM-Chk2-p21 pathway. PLoS ONE 9(8):e104732

60. Song K, Im SH, Yoon YJ, Kim HM, Lee HJ, Park GS (2018) A 60 Hz uniform electromagnetic field promotes human cell proliferation by decreasing intracellular reactive oxygen species levels. PLoS ONE 13(7):e0199753

61. Kapri-Pardes E, Hanoch T, Maik-Rachline G, Murbach M, Bounds PL, Kuster N, Seger R (2017) Activation of signaling cascades by weak extremely low frequency electromagnetic fields. Cell Physiol Biochem 43(4):1533–1546

62. Lee HC, Hong MN, Jung SH, Kim BC, Suh YJ, Ko YG, Lee YS, Lee BY, Cho YG, Myung SH (2015) Effect of extremely low frequency magnetic fields on cell proliferation and gene expression. Bioelectromagnetics 36(7):506–516

63. Yoshizawa H, Tsuchiya T, Mizoe H, Ozeki H, Kanao S, Yomori H, Sakane C, Hasebe S, Motomura T, Yamakawa T (2002) No effect of extremely low-frequency magnetic field observed on cell growth or initial response of cell proliferation in human cancer cell lines. Bioelectromagnetics 23(5):355–368

64. Delle Monache S, Alessandro R, Iorio R, Gualtieri G, Colonna R (2008) Extremely low frequency electromagnetic fields (ELF-EMFs) induce in vitro angiogenesis process in human endothelial cells. Bioelectromagnetics 29(8):640–648

65. Patruno A, Tabrez S, Pesce M, Shakil S, Kamal MA, Reale M (2015) Effects of extremely low frequency electromagnetic field (ELF-EMF) on catalase, cytochrome P450 and nitric oxide synthase in erythro-leukemic cells. Life Sci 121:117–123

66. Sobel E, Davanipour Z (1996) Electromagnetic field exposure may cause increased production of amyloid beta and eventually lead to Alzheimer's disease. Neurology 47(6):1594–1600

67. Davanipour Z, Tseng C-C, Lee P-J, Sobel E (2007) A case-control study of occupational magnetic field exposure and Alzheimer's disease: results from the California Alzheimer's Disease Diagnosis and Treatment Centers. BMC Neurol 7(1):13

68. Huss A, Spoerri A, Egger M, Röösli M, Study SNC (2008) Residence near power lines and mortality from neurodegenerative diseases: longitudinal study of the Swiss population. Am J Epidemiol 169(2):167–175

69. Huss A, Koeman T, Kromhout H, Vermeulen R (2015) Extremely Low frequency magnetic field exposure and Parkinson's disease—a systematic review and meta-analysis of the data. Int J Environ Res Public Health 12(7):7348–7356

70. Reale M, D'Angelo C, Costantini E, Tata AM, Regen F, Hellmann-Regen J (2016) Effect of environmental extremely low-frequency electromagnetic fields exposure on inflammatory mediators and serotonin metabolism in a human neuroblastoma cell Line. CNS Neurol Disord 15(10):1203–1215. https://doi.org/10.2174/1871527315666160920113407

71. Consales C, Cirotti C, Filomeni G, Panatta M, Butera A, Merla C, Lopresto V, Pinto R, Marino C, Benassi B (2018) Fifty-hertz magnetic field affects the epigenetic modulation of the miR-34b/c in neuronal cells. Mol Neurobiol 55(7):5698–5714. https://doi.org/10.1007/s12035-017-0791-0

72. Kolbabová T, Malkemper EP, Bartoš L, Vanderstraeten J, Turčáni M, Burda H (2015) Effect of exposure to extremely low frequency magnetic fields on melatonin levels in calves is seasonally dependent. Sci Rep 5:14206

73. Del Giudice E, Facchinetti F, Nofrate V, Boccaccio P, Minelli T, Dam M, Leon A, Moschini G (2007) Fifty Hertz electromagnetic field exposure stimulates secretion of β-amyloid peptide in cultured human neuroglioma. Neurosci Lett 418(1):9–12

74. Maes A, Anthonissen R, Wambacq S, Simons K, Verschaeve L (2016) The cytome assay as a tool to investigate the possible association between exposure to extremely low

frequency magnetic fields and an increased risk for Alzheimer's Disease. J Alzheimer's Dis JAD 50(3):741–749. https://doi.org/10.3233/jad-150669

75. Consales C, Panatta M, Butera A, Filomeni G, Merla C, Carri MT, Marino C, Benassi B (2019) 50-Hz magnetic field impairs the expression of iron-related genes in the in vitro SOD1(G93A) model of amyotrophic lateral sclerosis. Int J Radiat Biol 95(3):368–377. https://doi.org/10.1080/09553002.2019.1552378

76. McNamee DA, Legros AG, Krewski DR, Wisenberg G, Prato FS, Thomas AW (2009) A literature review: the cardiovascular effects of exposure to extremely low frequency electromagnetic fields. Int Arch Occup Environ Health 82(8):919–933. https://doi.org/10.1007/s00420-009-0404-y

77. Sastre A, Cook MR, Graham C (1998) Nocturnal exposure to intermittent 60 Hz magnetic fields alters human cardiac rhythm. Bioelectromagnetics 19(2):98–106

78. Johansen C, Feychting M, Møller M, Arnsbo P, Ahlbom A, Olsen JH (2002) Risk of severe cardiac arrhythmia in male utility workers: a nationwide Danish cohort study. Am J Epidemiol 156(9):857–861

79. Håkansson N, Gustavsson P, Sastre A, Floderus B (2003) Occupational exposure to extremely low frequency magnetic fields and mortality from cardiovascular disease. Am J Epidemiol 158(6):534–542

80. McNamee DA, Corbacio M, Weller JK, Brown S, Prato FS, Thomas AW, Legros AG (2010) The cardiovascular response to an acute 1800-μT, 60-Hz magnetic field exposure in humans. Int Arch Occup Environ Health 83(4):441–454

81. Azab AE, Ebrahim SA (2017) Exposure to electromagnetic fields induces oxidative stress and pathophysiological changes in the cardiovascular system. J Appl Biotechnol Bioeng 4(4):540

82. Goodman R, Blank M (2002) Insights into electromagnetic interaction mechanisms. J Cell Physiol 192(1):16–22. https://doi.org/10.1002/jcp.10098

83. Wei J, Sun J, Xu H, Shi L, Sun L, Zhang J (2015) Effects of extremely low frequency electromagnetic fields on intracellular calcium transients in cardiomyocytes. Electromagn Biol Med 34(1):77–84

84. Martínez-Sámano J, Torres-Durán PV, Juárez-Oropeza MA, Elías-Viñas D, Verdugo-Díaz L (2010) Effects of acute electromagnetic field exposure and movement restraint on antioxidant system in liver, heart, kidney and plasma of Wistar rats: a preliminary report. Int J Radiat Biol 86(12):1088–1094

85. Canseven AG, Coskun S, Seyhan N (2008) Effects of various extremely low frequency magnetic fields on the free radical processes, natural antioxidant system and respiratory burst system activities in the heart and liver tissues. Indian J Biochem Biophys 45:326

86. Lee GM, Neutra RR, Hristova L, Yost M, Hiatt RA (2002) A nested case-control study of residential and personal magnetic field measures and miscarriages. Epidemiology 13(1):21–31

87. Hardell L, Sage C (2008) Biological effects from electromagnetic field exposure and public exposure standards. Biomed Pharmacother 62(2):104–109

88. Wang Q, Cao Z, Qu Y, Peng X, Guo S, Chen L (2013) Residential exposure to 50 Hz magnetic fields and the association with miscarriage risk: a 2-year prospective cohort study. PLoS ONE 8(12):e82113

89. Shamsi Mahmoudabadi F, Ziaei S, Firoozabadi M, Kazemnejad A (2013) Exposure to extremely low frequency electromagnetic fields during pregnancy and the risk of spontaneous abortion: a case-control study. J Res Health Sci 13(2):131–134

90. Wertheimer N, Leeper E (1986) Possible effects of electric blankets and heated waterbeds on fetal development. Bioelectromagnetics 7(1):13–22

91. Mahram M, Ghazavi M (2013) The effect of extremely low frequency electromagnetic fields on pregnancy and fetal growth, and development. Arch Iran Med 16(4):221

92. Iorio R, Scrimaglio R, Rantucci E, Monache SD, Di Gaetano A, Finetti N, Francavilla F, Santucci R, Tettamanti E, Colonna R (2007) A preliminary study of oscillating electromagnetic field effects on human spermatozoon motility. Bioelectromagnetics 28(1):72–75

93. Avendano C, Mata A, Sarmiento CAS, Doncel GF (2012) Use of laptop computers connected to internet through Wi-Fi decreases human sperm motility and increases sperm DNA fragmentation. Fertil Steril 97(1):39–45

94. Auger N, Park AL, Yacouba S, Goneau M, Zayed J (2012) Stillbirth and residential proximity to extremely low frequency power transmission lines: a retrospective cohort study. Occup Environ Med 69(2):147–149

95. Sun W, Tan Q, Pan Y, Fu Y, Sun H, Chiang H (2010) Effects of 50-Hz magnetic field exposure on hormone secretion and apoptosis-related gene expression in human first

trimester villous trophoblasts in vitro. Bioelectromagnetics 31(7):566–572

96. Aydin M, Cevik A, Kandemir F, Yuksel M, Apaydin A (2009) Evaluation of hormonal change, biochemical parameters, and histopathological status of uterus in rats exposed to 50-Hz electromagnetic field. Toxicol Ind Health 25(3):153–158

97. Aksen F, Akdag MZ, Ketani A, Yokus B, Kaya A, Dasdag S (2006) Effect of 50-Hz 1-mT magnetic field on the uterus and ovaries of rats (Electronmicroscopy evaluation). Med Sci Monitor 12(6):215–220

98. Liu Y, Liu W-B, Liu K-J, Ao L, Zhong JL, Cao J, Liu J-Y (2015) Effect of 50 Hz extremely low-frequency electromagnetic fields on the DNA methylation and DNA methyltransferases in mouse spermatocyte-derived cell line GC-2. Biomed Res Int. https://doi.org/10.1155/2015/237183

99. Al-Akhras M-A (2008) Influence of 50 Hz magnetic field on sex hormones and body, uterine, and ovarian weights of adult female rats. Electromagn Biol Med 27(2):155–163

100. Elbetieha A, AL-Akhras MDA, Darmani H (2002) Long-term exposure of male and female mice to 50 Hz magnetic field: Effects on fertility. Bioelectromagnetics 23(2):168–172

101. Al-Akhras MDA, Darmani H, Elbetieha A (2006) Influence of 50 Hz magnetic field on sex hormones and other fertility parameters of adult male rats. Bioelectromagnetics 27(2):127–131

102. Li Y, Liu X, Liu K, Miao W, Zhou C, Li Y, Wu H (2014) Extremely low-frequency magnetic fields induce developmental toxicity and apoptosis in zebrafish (Danio

rerio) embryos. Biol Trace Elem Res 162(1–3):324–332

103. Koziorowska A, Waszkiewicz EM, Romerowicz-Misielak M, Zglejc-Waszak K, Franczak A (2018) Extremely low-frequency electromagnetic field (EMF) generates alterations in the synthesis and secretion of oestradiol-17β (E2) in uterine tissues: an in vitro study. Theriogenology 110:86–95

104. Liu Y, Liu W-b, Liu K-j, Ao L, Cao J, Zhong JL, Liu J-y (2015) Extremely low-frequency electromagnetic fields affect the miRNA-mediated regulation of signaling pathways in the GC-2 cell line. PLoS ONE 10(10):e0139949

105. El-Hussein A, Kasem M, Saad AEH, Hamblin MR, Harith M (2018) An extremely low frequency-weak magnetic field can induce alterations in a biological system: a case study in chick embryo development. Prog Biophys Mol Biol S0079-S6107(18):30202–30205

106. Svedenstål B, Johanson K, Mild KH (1999) DNA damage induced in brain cells of CBA mice exposed to magnetic fields. vivo 13(6):551–552

107. Delimaris J, Tsilimigaki S, Messini-Nicolaki N, Ziros E, Piperakis S (2006) Effects of pulsed electric fields on DNA of human lymphocytes. Cell Biol Toxicol 22(6):409–415

108. Ahuja Y, Vijayashree B, Saran R, Jayashri E, Manoranjani J, Bhargava S (1999) In vitro effects of low-level, low-frequency electromagnetic fields on DNA damage in human leucocytes by comet assay. Indian J Biochem Biophys 36:318

109. Lourencini da Silva R, Albano F, Lopes dos Santos L, Tavares A Jr, Felzenszwalb I (2000) The effect of electromagnetic field exposure on the formation of DNA lesions. Redox Rep 5(5):299–301

110. Schmitz C, Keller E, Freuding T, Silny J, Korr H (2004) 50-Hz magnetic field exposure influences DNA repair and mitochondrial DNA synthesis of distinct cell types in brain and kidney of adult mice. Acta Neuropathol 107(3):257–264

111. Robison JG, Pendleton AR, Monson KO, Murray BK, O'Neill KL (2002) Decreased DNA repair rates and protection from heat induced apoptosis mediated by electromagnetic field exposure. Bioelectromagnetics 23(2):106–112

112. Chow K-C, Tung WL (2000) Magnetic field exposure enhances DNA repair through the induction of DnaK/J synthesis. FEBS Lett 478(1–2):133–136

113. Phillips JL, Singh NP, Lai H (2009) Electromagnetic fields and DNA damage. Pathophysiology 16(2–3):79–88

114. Ivancsits S, Diem E, Pilger A, Rüdiger HW, Jahn O (2002) Induction of DNA strand breaks by intermittent exposure to extremely-low-frequency electromagnetic fields in human diploid fibroblasts. Mutat Res 519(1–2):1–13

115. Ivancsits S, Pilger A, Diem E, Jahn O, Rüdiger HW (2005) Cell type-specific genotoxic effects of intermittent extremely low-frequency electromagnetic fields. Mutat Res 583(2):184–188

116. Winker R, Ivancsits S, Pilger A, Adlkofer F, Rüdiger H (2005) Chromosomal damage in human diploid fibroblasts by intermittent exposure to extremely low-frequency electromagnetic fields. Mutat Res 585(1–2):43–49

117. Yokus B, Cakir DU, Akdag MZ, Sert C, Mete N (2005) Oxidative DNA damage in rats exposed to extremely low frequency electro magnetic fields. Free Radical Res

39(3):317–323

118. Lai H, Singh NP (2004) Magnetic-field-induced DNA strand breaks in brain cells of the rat. Environ Health Perspect 112(6):687–694

119. Lai H, Singh NP (1997) Melatonin and N-tert-butyl-α-phenylnitrone block 60-Hz magnetic field-induced DNA single and double strand breaks in rat brain cells. J Pineal Res 22(3):152–162

120. Jajte J, Zmyślony M, Palus J, Dziubałtowska E, Rajkowska E (2001) Protective effect of melatonin against in vitro iron ions and 7 mT 50 Hz magnetic field-induced DNA damage in rat lymphocytes. Mutat Res 483(1–2):57–64

121. Zendehdel R, Yu IJ, Hajipour-Verdom B, Panjali Z (2019) DNA effects of low level occupational exposure to extremely low frequency electromagnetic fields (50/60 Hz). Toxicol Ind Health 35(6):424–430. https://doi.org/10.1177/0748233719851697

122. Wilson JW, Haines J, Sienkiewicz Z, Dubrova YE (2015) The effects of extremely low frequency magnetic fields on mutation induction in mice. Mutat Res 773:22–26. https://doi.org/10.1016/j.mrfmmm.2015.01.014

123. Prochownik EV (2008) c-Myc: linking transformation and genomic instability. Curr Mol Med 8(6):446–458. https://doi.org/10.2174/156652408785747988

124. Cordaux R, Batzer MA (2009) The impact of retrotransposons on human genome evolution. Nat Rev Genet 10(10):691

125. Kidwell MG, Lisch DR (2001) Perspective: transposable elements, parasitic DNA, and genome evolution. Evolution 55(1):1–24

126. Del Re B, Marcantonio P, Gavoçi E, Bersani F, Giorgi G (2012) Assessing LINE-1 retrotransposition activity in neuroblastoma cells exposed to extremely low-frequency pulsed magnetic fields. Mutat Res 749(1–2):76–81

127. Strauch B, Patel MK, Navarro JA, Berdichevsky M, Yu H-L, Pilla AA (2007) Pulsed magnetic fields accelerate cutaneous wound healing in rats. Plast Reconstr Surg 120(2):425–430

128. Athanasiou A, Karkambounas S, Batistatou A, Lykoudis E, Katsaraki A, Kartsiouni T, Papalois A, Evangelou A (2007) The effect of pulsed electromagnetic fields on secondary skin wound healing: an experimental study. Bioelectromagnetics 28(5):362–368

129. Grant DN, Cozad MJ, Grant DA, White RA, Grant SA (2015) In vitro electromagnetic stimulation to enhance cell proliferation in extracellular matrix constructs with and without metallic nanoparticles. J Biomed Mater Res B Appl Biomater 103(8):1532–1540

130. Ottani V, De Pasquale V, Govoni P, Franchi M, Ruggeri A, Zaniol P (1988) Effects of pulsed extremely-low-frequency magnetic fields on skin wounds in the rat. Bioelectromagnetics 9(1):53–62

131. Pesce M, Patruno A, Speranza L, Reale M (2013) Extremely low frequency electromagnetic field and wound healing: implication of cytokines as biological mediators. Eur Cytokine Netw 24(1):1–10

132. Patruno A, Amerio P, Pesce M, Vianale G, Di Luzio S, Tulli A, Franceschelli S, Grilli A, Muraro R, Reale M (2010) Extremely low frequency electromagnetic fields modulate expression of inducible nitric oxide synthase, endothelial nitric oxide synthase and cyclooxygenase-2 in the human keratinocyte cell line HaCat: potential therapeutic effects in wound healing. Br J Dermatol 162(2):258–266

133. Li F, Lei T, Xie K, Wu X, Tang C, Jiang M, Liu J, Luo E, Shen G (2016) Effects of extremely low frequency pulsed magnetic fields on diabetic nephropathy in streptozotocin-treated rats. Biomed Eng Online 15(1):8

134. Akbarnejad Z, Esmaeilpour K, Shabani M, Asadi-Shekaari M, Saeedi Goraghani M, Ahmadi-Zeidabadi M (2018) Spatial memory recovery in Alzheimer's rat model by electromagnetic field exposure. Int J Neurosci 128(8):691–696

135. Callaghan MJ, Chang EI, Seiser N, Aarabi S, Ghali S, Kinnucan ER, Simon BJ, Gurtner GC (2008) Pulsed electromagnetic fields accelerate normal and diabetic wound healing by increasing endogenous FGF-2 release. Plast Reconstr Surg 121(1):130–141

136. Tepper OM, Callaghan MJ, Chang EI, Galiano RD, Bhatt KA, Baharestani S, Gan J, Simon B, Hopper RA, Levine JP (2004) Electromagnetic fields increase in vitro and in vivo angiogenesis through endothelial release of FGF-2. FASEB J 18(11):1231–1312

137. Elmas O (2016) Effects of electromagnetic field exposure on the heart: a systematic review. Toxicol Ind Health 32(1):76–82

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Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

Ethical approval

This study was approved by the Tabriz University of Medical Sciences Human Research Ethics Committee in Iran (Ref no: IR.TBZMED.REC.1397.973).

Research involving human participants and/or animals

In this review research paper, we had not any experiments on human and animal samples.

Informed consent

In this study, we did not deal with the research participants, and we did not need for informed consent.

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