Safe Distance for Leukemia Risk Due to Magnetic Fields Caused by High-Voltage Power Lines Using Linear Regression Model

Afsaneh Amiri, Bahram Kamarehie, Mehrdad Gholami[1], Faramarz Azimi

Department of Environmental Health, Faculty of Health and Nutrition, Lorestan University of Medical Sciences, Khorramabad, Iran, [1]Department of Medical Physics, Faculty of Allied Medical Sciences, Lorestan University of Medical Sciences, Khorramabad, Iran

Abstract

Aim: Power transmission lines are considered sources with extremely low-frequency magnetic fields. According to previous studies, these types of electromagnetic fields impose adverse effects on the human health. The present study aimed to assess the health risk associated with magnetic fields generated by high-voltage power lines in Khorramabad urban areas in 2019. **Methods:** In this descriptive-analytical study, the magnetic flux density was measured around high-voltage 63 kV power lines using EMF-TESTER-828 device according to the IEEE Std 644-1994 Standard at 0-, 13-, 26-, and 40-m distances from the high-voltage transmission lines**.** Measurements were performed in the spring and summer from 11:30 to 15:00, when the consumption was at its maximum. The mean magnetic flux density in the spring and summer seasons was measured to be 0.143 ± 0.114 µT and 0.284 ± 0.218 µT, respectively. **Results:** The mean proportional magnetic flux density to the International Commission on Non-Ionizing Radiation Protection 2010 (ICNIRP 2010) standard in the spring and summer was measured to be 0.07% and 0.14%, respectively. The results obtained on the relationship between magnetic flux density and distance fitted the linear regression in the form of equation $y = 0.3741–0.0077x$. Compared to the risk threshold of leukemia (0.2 µT), the mean magnetic flux density in distance <22 m and distance >22 m away from the high-voltage power lines was >0.2 µT and <0.2 µT, respectively. **Conclusion:** Overall, the mean magnetic flux density in this study was found to be lower than the standard level (ICNIRP 2010) enacted for public exposure. The mean magnetic flux density was reduced by increasing the distance and decreasing the lines' passing current intensity. Based on this study, there is a health risk for children (risk of leukemia) in distance <22 m, however, no such health risk threatens the children in distance >22 m.

Keywords: Extremely low-frequency magnetic fields, health risk assessment, high-voltage power lines, magnetic flux density

INTRODUCTION

Ever-increasing use of electricity-dependent technologies increases the electromagnetic fields in our surroundings. Therefore, rising demand for electricity in today's modern life increases the number of high-voltage power lines in urban and rural areas; it can increase the general exposure to extremely low-frequency (ELF) electromagnetic fields, so-called exposure to electromagnetic pollution.[1,2] ELF electromagnetic fields are part of the spectrum of electromagnetic radiation with a frequency of 3–300 Hz. These fields are generated through production, transmission, distribution, and use of electric power. The high-voltage power lines and distribution lines are considered the main sources for generation of ELF electromagnetic fields.[3,4] The evidence on the adverse effects of exposure to ELF electromagnetic fields on human health has drawn much attention over the world. Wertheimer and Leeper showed that leukemia was more likely to occur in children living near high-voltage transmission lines.[5] In 2000, two meta-analysis studies were published; the obtained results showed an increased risk of leukemia in children exposed to magnetic fields greater than 0.3 and 0.4 µT.[6,7] Other studies

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Address for correspondence: Dr. Mehrdad Gholami,
Department of Medical Physics, Faculty of Allied Medical Sciences,
Lorestan University of Medical Sciences, Khorramabad, Iran.
E-mail: gholami.mehrdad@lums.ac.ir

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found that children whose parents had high occupational exposure to ELF electromagnetic fields had an increased risk of leukemia.[8,9] In some other studies, a relationship was also reported between exposure to ELF electromagnetic fields and Alzheimer's disease, suicide, and mental disorders.[10-14] On the contrary, a number of epidemiological studies have not confirmed the relationship between exposure to ELF electromagnetic fields and breast and brain cancers.[15-18] Given the studied focused on exposure to electromagnetic fields and cancer, especially leukemia in children, the International Agency for Research on Cancer classified the ELF electromagnetic fields in the category of possibly carcinogen radiation (Group 2B).[2] The magnitude recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) is 50 Hz for exposure to magnetic fields, 2000 mG for general exposure, and 10,000 mG for occupational exposure.[19,20] Given the studies conducted on biological effects of exposure to ELF magnetic fields on human health, this study aimed to measure the intensity of magnetic fields generated by high-voltage power lines in Khorramabad urban areas and assess the corresponding health risk of these fields.

Materials and Methods

This study was conducted in Khorramabad city located on 48° 22' longitude and 33° 29' latitude with elevation of 1171 m above sea level in 2019. The magnetic flux density was measured around high-voltage 63 kV power lines in Khorramabad urban areas in the spring and summer seasons. According to the sample size estimation formula, 266 samples were estimated and 14 power stations (pylons) were randomly selected. Considering the sample size, 19 measurements were performed for each pylon. Measurements were made at four horizontal distances of 0, 13, 26, and 40 m from the high-voltage pylon. Four measurements were performed at a distance of 0 and five measurements at each of the other distances. TheTriple Axis EMF-TESTER-828 device made in Taiwan was used to measure the magnetic field. Manufacturer is LUTRON.This device has a measurement bandwidth of 3-300 Hz; it can measure in three directions X, Y, and Z. The accuracy of the device was ±(%4+3d) at 20 micro Tesla. its counting uncertainty was 0.6%. In addition, the geographical coordinates of 14 high-voltage power stations were recorded using the Garmin GPS device; the location of sampling points throughout Khorramabad was prepared [Figure 1]. Magnetic field intensities were measured in three directions X, Y, and Z according to the IEEE Std 644-1994 Standard.[21] The device probe was kept 1 m above ground level to avoid the effects of the Earth's magnetic field during measurement. After each measurement, the device was switched off for 1 min and the measurement was performed again at the same point in three directions X, Y, and Z. Of the values measured in three directions for each point, the highest value was recorded, and in addition, the mean value was calculated from division of sum different values at 3.[22,23] In this study, measurements were made over a short period of time on sunny days to minimize the impact of environmental conditions, such as temperature, humidity, and precipitation. In addition, all measurements were performed from 11:30 to 15:00 when the consumption was at its maximum in these seasons.

Statistical analysis

The data were described using descriptive statistics such as mean and standard deviation. The hypotheses and relationships were tested using one-sample *t*-test, three-factor ANOVA, and linear regression. The R core team the university of Auckland, USA was employed for the analyses, and the significance level was set at 0.05 for all the tests.

Results

The data distribution curve (b) was utilized to test the normality of the data distribution. As the distribution was found not to be normal, the log-normal distribution curve was used to describe the data (a).

The data analysis indicated that magnetic flux density results obtained from the high-voltage power lines fitted the log-normal distribution. The regression model was adopted to determine the effects of the independent variables: location, distance, and season, on the dependent variable (magnetic flux density) [Table 1].

Based on the results, the relationship between magnetic flux density and season and distance were significant ($P < 0.001$), but some parameters between Magnetic Flux Density and location were not significa. For instance, the relationship was not significant for stations 9 and 11 ($P > 0.1$) and stations 5 and 12 ($P > 0.05$). A Q-Q plot was employed to check the normality of the residuals (the difference between the measured values

Table 1: Relation between regression model of magnetic flux density and station, distance, and session

Beta coefficient	Estimate	SE	*t*	Pr (>|*t*|)	Signif. codes
Intercept	-1.78536	0.09379	-19.036	2.00E-16	***
LocationA10	0.25163	0.11461	2.195	0.028575	*
LocationA11	-0.08091	0.11461	-0.706	0.480568	
LocationA12	-0.22396	0.11461	-1.954	0.051241	.
LocationA13	0.7262	0.11461	6.336	5.16E-10	***
LocationA14	0.62927	0.11461	5.49	6.31E-08	***
LocationA2	0.42805	0.11461	3.735	0.000209	***
LocationA3	0.26962	0.11461	2.352	0.01903	*
LocationA4	0.33948	0.11461	2.962	0.003199	**
LocationA5	0.20597	0.11461	1.797	0.072913	.
LocationA6	0.53458	0.11461	4.664	3.96E-06	***
LocationA7	0.32578	0.11461	2.842	0.004655	**
LocationA8	0.55564	0.11461	4.848	1.66E-06	***
LocationA9	0.0926	0.11461	0.808	0.419516	
DistanceD13	-0.2786	0.06333	-4.399	1.32E-05	***
DistanceD26	-0.95345	0.06333	-15.054	2.00E-16	***
DistanceD40	-1.7335	0.06333	-27.37	2.00E-16	***
Season summer	0.70415	0.04332	16.255	2.00E-16	***

Significant codes: 0, ***0.001, **0.01, *0.05, 0.0.1, 1. SE: Standard error and the values predicted by the model). To check the suitability of this model for fitting the data, the residual versus fitted value plot was employed. Figures 2 and 3 display the results.

The results of ANOVA for determining the relationship between group variables and magnetic flux density are summarized in Table 2.

Based on the ANOVA results, it was found that all three group variables of station, season, and distance have a significant relationship with the mean magnetic flux density ($P < 0.001$). Tukey's honestly significant difference (pairwise comparison) was performed to compare the mean magnetic flux

Table 2: Analysis variance of linear regression model

Beta coefficient	Df	Sum square	Mean square	*F*	Pr (>*F*)	Significant. codes
Location	13	37.707	2.901	11.02	2.20E-16	***
Distance	1	227.304	227.304	863.58	2.20E-16	***
Season	1	65.945	65.945	250.54	2.20E-16	***

Significant codes: 0, ***0.001, **0.01, *0.05, 0.0.1, 1

Table 3: Pairwise comparison of magnetic flux density different distances (μT) in different stations (m) based on Tukey's honestly significant difference

	Difference	Lower	Upper	*P* adjustment
A13-A1	0.72620276	0.339964854	1.112440664	<0.001
A14-A1	0.62927494	0.243037039	1.015512849	<0.001
A2-A1	0.4280464	0.041808494	0.814284303	0.015
A6-A1	0.53457701	0.14833911	0.92081492	<0.001
A8-A1	0.55564077	0.16940286	0.94187867	<0.001
A12-A10	-0.47559229	-0.861830197	-0.089354388	0.003
A13-A10	0.47456871	0.088330801	0.86080661	0.003
A13-A11	0.8071093	0.420871394	1.193347204	<0.001
A14-A11	0.71018148	0.32394358	1.096419389	<0.001
A2-A11	0.50895294	0.122715034	0.895190844	<0.001
A4-A11	0.4203816	0.034143692	0.806619502	0.019
A6-A11	0.61548356	0.22924565	1.00172146	<0.001
A7-A11	0.40668948	0.020451575	0.792927384	0.028
A8-A11	0.63654731	0.250309401	1.02278521	<0.001
A13-A12	0.950161	0.563923093	1.336398903	<0.001
A14-A12	0.85323318	0.466995278	1.239471088	<0.001
A2-A12	0.65200464	0.265766733	1.038242542	<0.001
A3-A12	0.49357416	0.107336258	0.879812068	0.002
A4-A12	0.5634333	0.177195391	0.949671201	<0.001
A5-A12	0.42992709	0.043689183	0.816164992	0.014
A6-A12	0.75853525	0.372297349	1.144773159	<0.001
A7-A12	0.54974118	0.163503273	0.935979083	<0.001
A8-A12	0.779599	0.3933611	1.165836909	<0.001
A3-A13	-0.45658684	-0.84282474	-0.070348931	0.005
A4-A13	-0.3867277	-0.772965607	-0.000489797	0.049
A5-A13	-0.52023391	-0.906471815	-0.133996006	<0.001
A7-A13	-0.40041982	-0.786657725	-0.014181915	0.034
A9-A13	-0.63360466	-1.019842561	-0.247366752	<0.001
A5-A14	-0.4233061	-0.809544001	-0.037068191	0.017
A9-A14	-0.53667684	-0.922914746	-0.150438937	<0.001
A9-A6	-0.44197891	-0.828216817	-0.055741007	0.009
A9-A8	-0.46304266	-0.849280567	-0.076804758	0.005

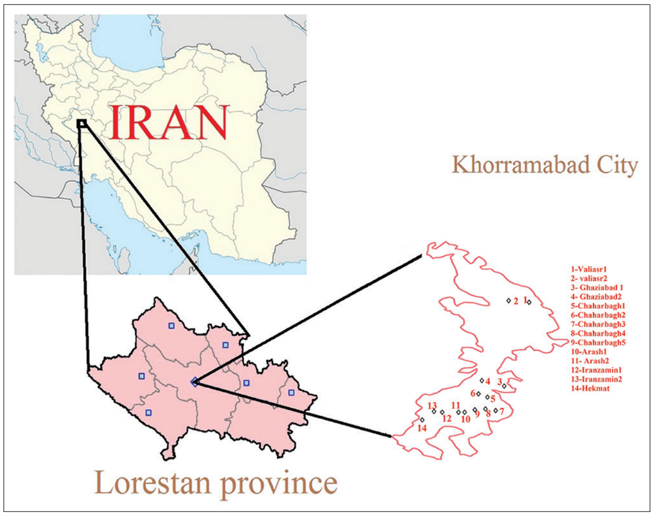

Figure 1: The location case study (Khorramabad, Lorestan)

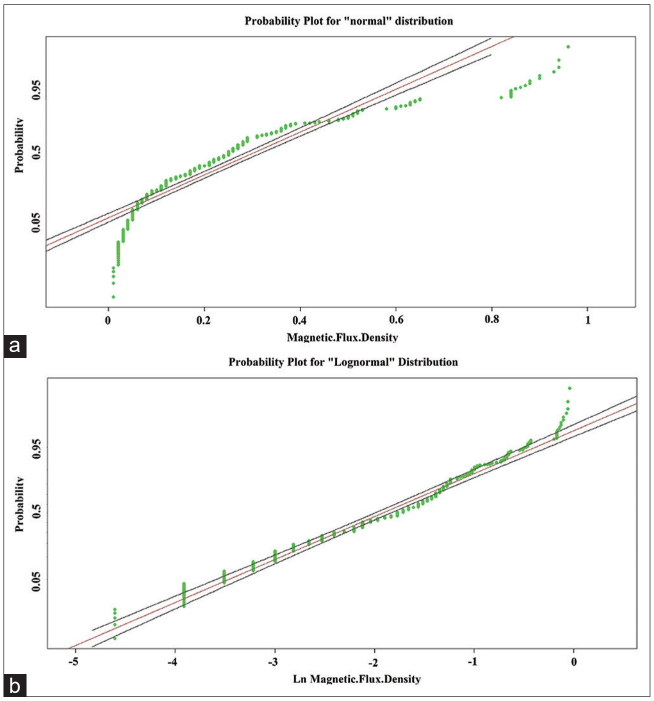

Figure 2: Log-normal and normal distribution of extremely low-frequency magnetic flux. Density from 14 power lines (a and b)

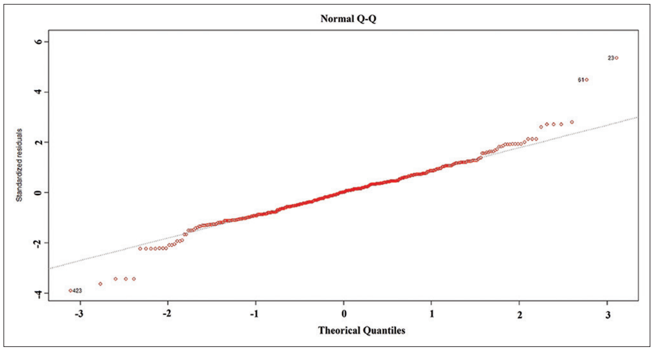

Figure 3: Q-Q plot to determine the normality of the residuals

density (µT) divided by station. Table 3 summarizes the results of Tukey's test for station pairs with a significant difference.

Based on the results, a significant difference was found between some station pairs in terms of mean magnetic flux density ($P < 0.05$). The minimum magnetic flux density belonged to station 12 (0.124 ± 0.112) and station 9 (0.149 ± 0.099), while the maximum magnetic flux density belonged to station 8 (0.324 ± 0.300) and station 14 (0.310 ± 0.249). Table 4 presents the results obtained pairwise comparison of magnetic flux density (µT) in different distances (m) based on Tukey's HSD.

As shown in Table 4, a significant difference was observed between pair distances in terms of the mean magnetic flux density ($P < 0.001$). The minimum magnetic flux density from 40-m distance away from the station was found to 0.069 ± 0.077 µT. However, this value for 0-m distance from the station was 0.383 ± 0.233 µT. The mean magnetic flux density in the spring and summer seasons was measured to be 0.143 ± 0.114 µT and 218 ± 0.284 µT, respectively.

Linear regression was used to check the effect of distance on magnetic flux density [Table 5].

Based on this table, the effect of distance on mean magnetic flux density was significant ($P < 0.001$). The equation of the line is $y = 0.3741–0.0077x$; one can calculate the mean magnetic flux density for different distances. The relationship between the magnetic flux density and distance was assessed via linear regression, and the result was in the form of equation $y = 0.3741–0.0077x$. Finally, by placing values in the equation, it was found that the mean magnetic flux density for distance >22 m away from high-voltage power lines was <0.2 µT, while this value for distance <22 m was >0.2 µT (risk threshold for leukemia in children). To examine the accuracy and validity of the model, the single-sample test was performed. The results obtained from equation at distances of 0, 13, 26, and 40 m were compared with the results of measurements. As the P value was >0.05, there was no significant difference between the results predicted by the model and the measured results; the model had sufficient accuracy and validity. The comparison of mean magnetic flux density in these regions in the spring (0.143 ± 0.114 µT) and summer (218 ± 0.284 µT) with 200 µT (the permissible level for public exposure, determined by the ICNIRP 2010) based on the single-sample t-test indicated that the mean magnetic flux density in these regions is significantly less than the mentioned limit ($P < 0.005$), both in general and divided by distances from high-voltage power lines.

Table 4: Pairwise on Tukey's HSD.comparison of magnetic flux density (µT) in different distances (m) based on Tukey's HSD

	Difference	Lower	Upper	*P* adjustment
D13-D0	-0.2786	-0.44184	-0.11536	7.79E-05
D26-D0	-0.95345	-1.1167	-0.79021	0.00E +00
D40-D0	-1.7335	-1.89674	-1.57025	0.00E +00
D26-D13	-0.67485	-0.82876	-0.52095	0.00E +00
D40-D13	-1.4549	-1.6088	-1.30099	0.00E +00
D40-D26	-0.78004	-0.93395	-0.62614	0.00E +00

Table 5: Linear regression between distance (m) and magnetic flux density (µT)

	Estimate	SE	*t*	Pr (>|*t*|)	Significant. codes
Intercept	0.374142	0.050864	-19.45	<2e-16	***
Distance	-0.0077	0.002005	-22.43	<2e-16	***

Significant codes: 0, ***0.001, **0.01, *0.05, 0.0.1, 1. SE: Standard error

DISCUSSION

Based on the examination of the effects of independent variables on magnetic flux density by using the regression model [Table 1], the relationship between magnetic flux density and season and distance is significant ($P < 0.001$); in other words, there is a linear regression relationship. As for the relationship between magnetic flux density and station, some parameters are not significant. For instance, the relationship is not significant for stations 9 and 11 ($P > 0.1$) and stations 5 and 12 ($P > 0.05$); in other words, there was no linear regression relationship. The Q-Q plot [Figure 3] showed that many points fall on the central line, i.e., the residual normal probability plot follows a somewhat linear pattern; therefore, the normality of the residuals can be confirmed. In the residual versus fitted value plot [Figure 4], since the error distribution around the line is zero, random, and homogeneous, and does not follow any special pattern, this model is appropriate for fitting the data. Since all three variables of station, season, and distance are of the factor (group) type, ANOVA was performed to determine the relationship between group variables and mean magnetic flux density. The results of this analysis [Table 2] showed that a significant difference exists between all three variables of station, season, and distance, and magnetic flux density ($P < 0.001$). Consequently, a significant difference exists between at least two points of each variable of station, season, and distance in terms of mean magnetic flux density ($P < 0.001$). The pairwise comparison of the

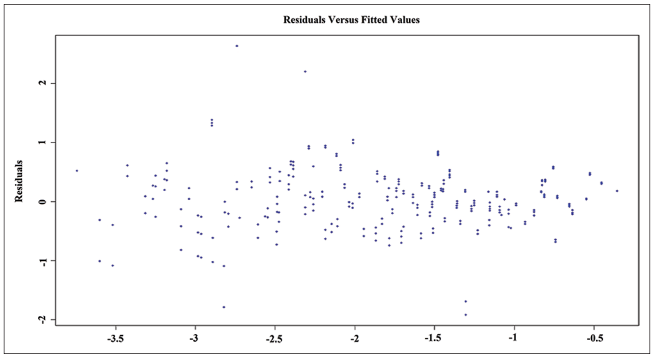

Figure 4: Residual plot versus fitted values to determine data fitness

stations in terms of mean magnetic flux density indicated that station pairs that are close to each other in terms of mean magnetic flux density (i.e., overlap) do not significantly differ ($P > 0.05$). However, station pairs that are not close in terms of mean magnetic flux density (i.e., do not overlap) significantly differ ($P < 0.05$). In this study, the minimum magnetic flux density belonged to station 12 (0.124 ± 0.112) and the maximum magnetic flux density belonged to station 8 (0.324 ± 0.300). Since the voltage of the lines is the same in all these stations, the difference in magnetic flux density is attributed to the difference in consumption load and current intensity. The higher the consumption load and current intensity, the higher the magnetic flux density. A similar result has also been reported in other studies.[24,25] The pairwise comparison of distances from the high-voltage power lines in this study indicated that the mean magnetic flux density is reduced by increasing the distance from these power lines. The same relationship was observed in other studies in other regions.[26,27] In this study, the mean magnetic flux density was recorded as 0.143 ± 0.114 µT in the spring, and 0.284 ± 0.218 µT in the summer, which is, respectively, 0.07% and 0.14% of the standard limit set by the ICNIRP 2010 for public exposure.[19,22] Based on the comparison of the measures in the spring and summer with the standard level for public exposure, the mean magnetic flux density in these regions is markedly lower than the mentioned limit in both the seasons. Compared to the spring, the consumption load is higher in the summer because of the use of electric cooling devices; consequently, the mean magnetic flux density is higher in the summer than in the spring. The mean magnetic flux density in this study in both the seasons was less than the value reported by Lindgren *et al*. in Sweden (0.34 µT), however, these values were higher than the value reported by Paniagua *et al*. in Spain (0.105 µT).[1,28] The examination of the regression relationship between distance and mean magnetic flux density [Table 5] shows that further increased 1 m in the distance from high-voltage power lines increase the mean magnetic flux density by ~0.0077 µT. The equation of the line is as follows: $Y = 0.3741–0.0077x$. Using this equation, one can calculate the magnetic flux density for different distances. In this study, by replacing the values in the equation obtained from the linear regression relationship between distance and magnetic flux density, it was found that the magnetic flux density was <0.2 µT in distances >22 m away from high-voltage power lines, however, the magnetic flux density was calculated to be >0.2 µT (the risk threshold of leukemia in children in many epidemiological studies) in distances <22 m.[1,24,28,29] Based on this test, in these regions, there is a risk of leukemia in children in distances <22 m from high-voltage power lines, however, no such risk threats the children in distances >22 m. The accuracy and validity of the model were also confirmed by a relevant test.

CONCLUSION

In this study, the proportional mean magnetic flux density around high-voltage power lines to the standard limit set by the ICNIRP 2010 in the spring and summer was 0.07% and 0.14%, respectively; these values are lower than the mentioned standard limit. The mean magnetic flux density is reduced by increasing the distance and decreasing the lines' passing current intensity. The results of this study showed that there is a health risk for children (risk of leukemia) in distance <22 m, however, no such health risk threats the children in distance >22 m.

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Conflicts of interest

There are no conflicts of interest.

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