Letter to the Editor

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Underground power lines as a confounding factor in observational studies concerning magnetic fields and childhood leukemia

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Introduction

Extremely low-frequency magnetic fields (ELF-MF), those between 1 and 300 Hz, have been associated with childhood leukemia since the late 1970s [2, 7]. The accumulated evidence provided by several epidemiological studies led the World Health Organization (WHO) in 2002 to consider these types of fields as possibly carcinogenic (category 2B). However, there is still discussion in the scientific community about whether power lines should continue to be classified in that category (e.g., [1]), as observational studies have produced fewer clear results in recent decades (e.g., [6]). This increasing concern about the plausibility of this association has implications for regulations on reference levels of public exposure. Those levels have not been modified for decades and remain two or three orders of magnitude above what epidemiology suggests as a risk threshold (≥200–400 nT, see Ref. [8]).

One of the most significant recent contributions to the field is the research by [2]; who conducted separate meta-analyses of studies investigating exposure to magnetic fields and childhood leukemia, utilizing various exposure variables. When the magnetic field was a variable derived from distance-to-line measurements or calculated based on distance, the meta-analyses did not demonstrate a significant relationship between exposure to magnetic fields and childhood leukemia (OR=1.07, p=0.74; OR=1.24, p=0.56, respectively). However, the meta-analysis conducted exclusively with studies that conducted direct measurements of the magnetic field did show a significant association (OR=1.23, p=0.02). This suggests that confounding factors might be present in studies that do not incorporate *in situ* measurements (e.g., [5]), such as other magnetic field sources that lead to actual exposure differing significantly from estimates based solely on distance to high voltage overhead lines.

Underground power lines can constitute a relevant source of magnetic fields, given their proximity to the ground compared to overhead wires. They carry intensities that, in some instances, can be of the same order of magnitude as those of high-voltage overhead lines. The objective of this research is to empirically analyze whether the presence of underground wires results in a significant contribution to the exposure to magnetic fields originating from overhead lines. This analysis aims to offer a plausible explanation for the disparate results observed in the meta-analyses conducted by [2].

Methods

We selected a location that possessed ideal characteristics for the aims of the research, a residential neighborhood named Polígono de Santa Ana in Cartagena, Spain, with a population of over 7,000 residents. The neighborhood is intersected by a 132 kV high-voltage overhead line with three conductors that do not provide power to the area. There are no other high-voltage or low-voltage overhead lines; all electricity supply wires for the neighborhood are situated underground.

The sampling was conducted at 36 points within the neighborhood: 15 on the north side of the line, 15 on the south side, and 6 directly beneath the line. The distances were 0, 25, 50, 100, 200, and 400 m, measured from the ground projection of each side of the line.

Three perpendicular streets to the main avenue, through which the line passes, were selected. This approach ensured that measurements were consistently taken along the same line for each perpendicular, preserving a 90° angle with the span of the line. This strategy maintained a constant measurement line on the same wire projection,

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thereby avoiding variations inherent to the catenary. Data collection was carried out over six consecutive business days in October 2022, within a short time frame from 11.30 a.m. to 1.30 p.m. To prevent systematic bias, the order of the 36 sampling points was randomly determined.

The Spectran NF-5030, a certified professional device, was employed as the measuring instrument. This device covers a measurement range from 1 nT to 500 μT with a maximum error margin of 3 %. Measurements were taken every 5 s [3], one meter above the ground [4], for 6 min at each point [4]. Consequently, 72 measurements were taken at the 36 sampling points, resulting in a total of 2,592 observations. The collected data was subsequently transferred to a personal computer using the LCS program provided by the manufacturer.

For the statistical analysis, the distribution of the nested data was considered. Given the non-normal distribution of the data, the median of the distribution and a bootstrapping procedure were employed to calculate standard errors. The Stata 13.0 software was used for this purpose, with 1,000 repetitions for resampling and calculation of the Normal 95 % confidence interval for standard errors.

The collected data was then compared with an ideal model featuring three balanced conductors and no current passing through the neutral conductor. The magnetic field equations were defined as follows (1):

$$\boldsymbol{B}(t) \cong \boldsymbol{B}_x(t) + \boldsymbol{B}_y(t) = \sum_{i=1}^{3}\left(-\frac{\mu_0}{2\pi}\frac{y_i I_i(t)}{(x_i^2 + y_i^2)}\boldsymbol{u}_x + \frac{\mu_0}{2\pi}\frac{x_i I_i(t)}{(x_i^2 + y_i^2)}\boldsymbol{u}_y \right) \quad (1)$$

$$B_{rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} \boldsymbol{B}(t)^2 dt}$$

where $\boldsymbol{B}(t)$ represents a time-dependent magnetic field vector, $\boldsymbol{B}_x(t), \boldsymbol{B}_y(t)$ denote its Cartesian components in the X and Y directions (with the Z direction considered as the direction of the electric current), $\boldsymbol{u}_x$ and $\boldsymbol{u}_y$ are unit vectors, μ_0 stands for the magnetic permeability of air, i=1, 2, 3 correspond to the three conductors of the power line, x_i and y_i indicate the Cartesian coordinates of the measurement location with respect to each conductor, $I_i(t)$=$I_0 e^{j\omega t} e^{j\theta_i}$ signifies the AC intensity of each conductor (where ω represents the angular frequency, θ denotes the phase offset angle, j is an imaginary unit, and I_0 is the maximum amplitude of the wave), and B_{rms} refers to the root mean square magnitude of the magnetic field, which constitutes the output of the measurement device.

The equations shown in (1) were formulated using the Maxima programming language. This symbolic calculation software facilitated the simulation of various analysis scenarios with ease. Initially, the necessary current in each conductor to generate the measured field beneath the overhead powerline was computed. Subsequently, utilizing the calculated intensity value, a simulated magnetic field distribution was generated for each sampled area. Finally, based on this simulated magnetic field distribution, the obtained measurement values (median and 95 % confidence interval) were represented to assess the potential disturbances caused by the underground conductors in the neighborhood concerning the magnetic field that would arise solely from the presence of the overhead power line.

Results and discussion

The median values obtained from each of the collected samples and their corresponding confidence intervals are presented in Table 1. Notably, there was substantial heterogeneity in the medians beneath the overhead power line due to inherent variations in charge. The maximum magnetic field measurements were recorded on day 2, reaching 649.00 nT directly beneath the north conductor. There was no discernible pattern of magnetic field reduction with increasing distance. Intriguingly, in several instances, the magnetic field at greater distances exceeded that of shorter distances within the same measurement time slot. This observation serves as compelling evidence of the contribution made by the underground conductors. A comparison was made between the measured magnetic field for each location and the magnetic field that would be expected if only the overhead power line were considered. As indicated in Table 1, the underground contribution to the magnetic field was significant at 30 out of 30 locations (100 %) beyond 0 m from the line. Furthermore, the effect sizes consistently mirrored the measured magnetic field magnitudes. Figure 1 helps to better understand the difference between the estimated magnetic field and the measured magnetic field for the north side and the south side of the three sampled streets.

The implications of our study are as follows: (1) Given the substantial and statistically significant differences (with high effect sizes) between the estimated magnetic field (accounting solely for overhead conductors) and the measured magnetic field (factoring in both overhead and underground conductors), it is crucial to always obtain *in situ* measurements of the magnetic field in empirical research. Neglecting this step could introduce a high risk of bias and cast doubt on the validity of the obtained results; (2) The variation in line charge over a relatively homogeneous period of time (consecutive business days within a short time span) underscores the recommendation to avoid reliance on any proxy measures for magnetic field (such as calculated magnetic field or distance between the child's home and the power lines). Instead, the study advocates for direct magnetic field measurements, ideally encompassing multiple measurements taken across diverse hours, days, and even seasons of the year.

It is important to acknowledge several limitations in our study, including the relatively modest number of sample points (36). Future research could replicate this study by employing a fully randomized sampling approach for the

Table 1: Median of the measured magnetic field (nT) along with its 95 % Normal confidence interval, using standard errors computed through bootstrapping. It also shows the effect sizes representing the disparity between the estimated magnetic field considering solely the overhead power line and the actual magnetic field measured at each location.

	B (nT)	Distance, m					
		0	25	50	100	200	400
Day 1	R	174.38	93.86[a]	35.77[a]	22.68[a]	27.81[a]	22.18[a]
	95 %	(171.42;	(82.72;	(32.78;	(20.82;	(25.66;	(20.58;
	IC	177.35)	105.01)	38.77)	24.54)	29.96)	23.78)
	E	174.38	36.23	11.82	3.29	0.86	0.22
	D	0	57.63	23.95	19.39	26.95	21.96
Day 2	R	649.00	228.94[a]	122.53[a]	22.75[a]	101.46[a]	21.70[a]
	95 %	(647.39;	(224.10;	(114.76;	(22.24;	(94.94;	(20.60;
	IC	650.61)	233.79)	130.31)	23.26)	107.98)	22.81)
	E	649.00	92.82	28.74	7.86	2.04	0.52
	D	0	136.12	93.79	14.89	99.42	21.83
Day 3	R	285.92	95.96[a]	65.49[a]	63.28[a]	132.52[a]	24.78[a]
	95 %	(283.72;	(93.17;	(61.91;	(60.78;	(128.23;	(23.00;
	IC	288.11)	98.76)	69.07)	65.78)	136.80)	26.58)
	E	285.92	40.96	12.66	3.46	0.90	0.23
	D	0	55.00	52.83	59.82	131.62	24.56
Day 4	R	11.48	20.83[a]	14.73[a]	5.64[a]	3.38[a]	89.94[a]
	95 %	(10.91;	(20.25;	(13.48;	(5.25;	(3.17;	(77.81;
	IC	12.05)	21.42)	15.99)	6.04)	3.59)	102.07)
	E	11.48	1.66	0.49	0.13	0.03	0.01
	D	0	19.17	14.24	5.51	3.34	89.93
Day 5	R	55.28	173.51[a]	29.16[a]	8.67[a]	66.08[a]	33.17[a]
	95 %	(53.41;	(163.51;	(26.53;	(7.00;	(62.35;	(31.64;
	IC	57.16)	183.51)	31.78)	10.33)	69.81)	34.70)
	E	55.28	7.99	2.38	0.63	0.16	0.04
	D	0	165.51	26.78	8.03	65.92	33.13
Day 6	R	134.21	39.16[a]	99.76[a]	8.09[a]	4.07[a]	20.80[a]
	95 %	(131.81;	(37.66;	(87.28;	(6.56;	(3.81;	(17.96;
	IC	136.61)	40.66)	112.24)	9.63)	4.32)	23.64)
	E	134.21	36.02	10.45	2.67	0.66	0.16
	D	0	3.14	89.31	5.42	3.41	20.64

R, Real magnetic field measured in each location; E, Estimated magnetic field generated solely by the overhead power line, based on the actual data obtained over the vertical; D, Effect size. [a]$p<0.05$ Difference between actual (considering underground conductors) and estimated magnetic field (considering only the overhead power line). Note: The distances are presented from the lowest to the highest to facilitate interpretation; however, the sequence of measurements was established through random assignment, as detailed in the methodology section.

study area, while considering two synchronous measurements of the magnetic field: one directly beneath the line and another at each point situated far from it. Nevertheless, the randomization of the measurement order for each sampled unit represents a strength of the methodological design, effectively minimizing biases that might arise from slight time discrepancies in the measurement of each point on the same day.

In summary, our research underscores the pivotal role of *in situ* magnetic field measurements in the realm of childhood leukemia epidemiology. These direct measurements inherently incorporate the contribution of underground conductors. These concealed wires significantly contribute to the total magnetic field and, consequently, are vital for constructing an exposure variable when studying risk factors associated with this disease. Our findings, coupled with the findings of the study by [2] identified a significant association between childhood leukemia and ELF-MF only when considering direct magnetic field measurements, should prompt debate on the validity of incorporating alternative types of exposure variables within this research domain.

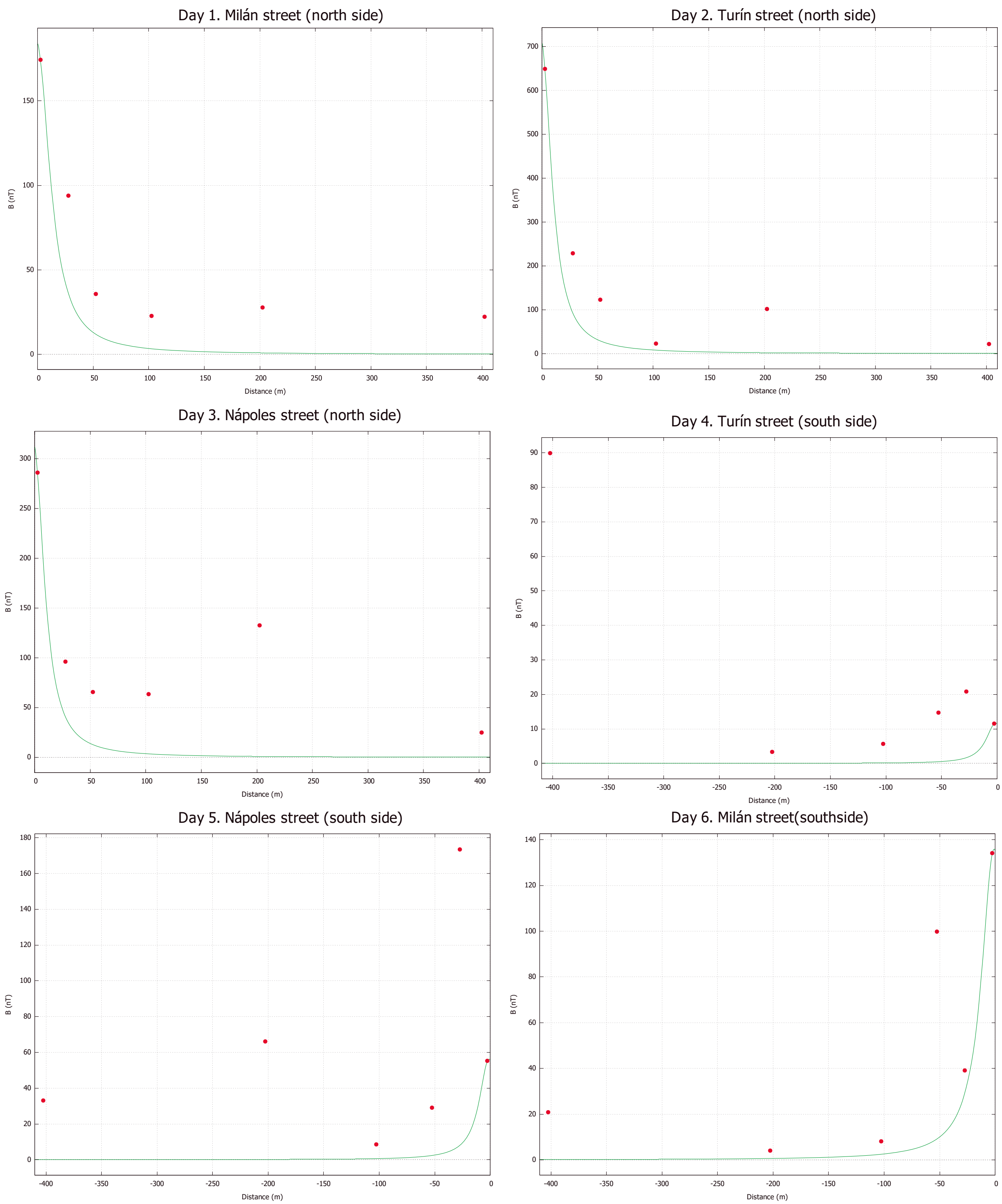

Figure 1: Estimated (green curve) and measured magnetic field (red points) for the north side and the south side of the three sampled streets.

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