research article

Estimating exposure to extremely low frequency magnetic fields near high-voltage power lines and assessment of possible increased cancer risk among Slovenian children and adolescents

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Radiol Oncol 2023; 57(1): 59-69.

Received 25 October 2022
Accepted 10 November 2022

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Disclosure: No potential conflicts of interest were disclosed.

Background. Some previous research showed that average daily exposure to extremely low frequency (ELF) magnetic fields (MF) of more than 0.3 or 0.4 μT could potentially increase risk of childhood leukaemia.

Materials and methods. To allow calculations of ELF MF around high voltage (HV) power lines (PL) for the whole Slovenia, a new three-dimensional method including precision terrain elevation data was developed to calculate the long-term average ELF MF. Data on population of Slovenian children and adolescents and on cancer patients with leukaemia's aged 0–19 years, brain tumours at age 0–29, and cancer in general at age 0–14 for a 12-year period 2005–2016 was obtained from the Slovenian Cancer Registry.

Results. According to the large-scale calculation for the whole country, only 0.5% of children and adolescents under the age of 19 in Slovenia lived in an area near HV PL with ELF MF density greater than 0.1 μT. The risk of cancer for children and adolescents living in areas with higher ELF MF was not significantly different from the risk of their peers.

Conclusions. The new method enables relatively fast calculation of the value of low-frequency magnetic fields for arbitrary loads of the power distribution network, as the value of each source for arbitrary load is calculated by scaling the value for nominal load, which also enables significantly faster adjustment of calculated estimates in the power distribution network.

Key words: exposure assessment; childhood cancer; extremely low frequency magnetic fields; modelling; cancer; high voltage power lines

Introduction

Ionizing radiation is a known risk factor for the development of leukaemia and thyroid cancer, while the carcinogenicity of non-ionizing radiation has so far not been scientifically proven. Non-ionizing radiation includes the extremely low-frequency (ELF) magnetic fields (MF) that originate from electric current flowing through artificial sources, among which the most widely present in the living and working environments are the high-voltage (HV) power lines (PL) and transformer substations.

The exposure to ELF MP is the highest in the immediate vicinity of the source and decreases very rapidly with distance. For sources in the vicinity of residences, the Slovenian legislation prescribes a ten times lower permissible ELF MF values (10 μT) than the European Recommendation (100 μT).

During the last few decades, several pooled analyses have been published that combined all available data with various exposure indices.[1-4] These pooled analyses consistently found statistically significant increased relative risk estimates for childhood leukaemia in the case of prolonged daily high exposure to ELF MF (above 0.3 or 0.4 μT) compared with low exposure (below 0.1 μT).[5-8] In 2001, the International Agency for Research on Cancer (IARC) examined the available body of scientific literature on ELF MF and from the subset of studies concerning childhood leukaemia concluded that ELF MF should be classified in group 2B as possibly carcinogenic to humans based on "limited evidence of carcinogenicity in humans" and "inadequate evidence of carcinogenicity in experimental animals".[9] Associations between other cancers and ELF MF were not observed or were statistically insignificant, while it is emphasized the biological mechanisms on how would ELF MF induce cancer growth remain unknown despite broad research also in this area.[9-14]

The fear of an increased risk of cancer that could occur after long-term exposure to ELF MF is also expressed by general public[15], which additionally drives the research in this area.

ELF MF that originate mainly from the use of electricity have been studied as a risk factor for childhood leukaemia since 1979.[16] The available studies ever since used different approaches on estimating the long-term exposure to ELF MF. The simplest possible way of assessing exposure is to calculate distance to a facility which is likely to be a source of the field.[17] One of the common methods to estimate the ELF MF exposure is socalled wire code which uses the distance to and the configuration of HV PL wiring to estimate the long-term exposure to ELF MF.[16] Wire code method does not require any consent of the participants (compared to measurements at homes) and therefore the selection of the case and control groups is not biased by their willingness to participate.[18-21] However, because of the overlap in field levels between categories, wire code was not a good predictor of ELF MF levels, accounting for less than 21% of the variance in magnetic-field measurements.[22] Another method has used estimated historical fields where the ELF MF exposure was defined by a combination of measurements and calculations at homes.[23] The inclusion criteria for participants was the distance of the dwelling from the HV PL. The calculations took into account all important technical parameters of HV PL.

The aim of the study was to determine the ELF MF due to all HV PL in Slovenia. We developed a new method for more reliable real-life exposure assessment, since previous research revealed this as a major source of bias. Further, we investigated whether children and adolescents exposed to ELF MF due to living near HV PL in Slovenia have a higher risk of leukaemia. Additionally, to address concerns of the Slovenian public, we analysed the possible association of ELF MF exposure and the incidence of brain tumours and of all childhood cancers together.

Materials and methods

High voltage power lines registry in Slovenia

There are about 670 km of 400 kV PL, 330 km of 220 kV PL, 2600 km of 110 kV PL and 25 km of 110 kV underground cables in Slovenia. The technical data necessary to calculate and determine the spatial distribution of the ELF MF in the vicinity of HV PL were obtained from national power grid company ELES and from 5 power distribution companies covering Slovenia. The following data about each PL tower were collected: the coordinates, altitude, height and type. The tower type defines the type of the PL geometry (Barrel, Danube...) as well as the exact geometry of the tower cross arms. To take the sag of each span into account, the data about the exact catenary of each span was also obtained. For most of the HV PL the catenary for each span was available in the form of 3D lines, generated by national power grid company from the results of the measurements with LIDAR system. For a few HV PL where the 3D lines were not available, the values of the sag of each span or cable tension in each span were used to calculate the 3D lines. For 110 kV underground cables their exact course was available in a form of points along the cable course, but detailed information about the geometry and depth of the cables was not available.

Based on these technical data, each PL was further split into sections with identical tower types and identical or very similar geometries (position and length of tower cross arm). If the PL was double circuit (in Slovenia only single or double circuit PL are in use), the load data were checked for each system of the PL. If the loads were mostly the same, then both systems were deemed as one section, otherwise each system was deemed as separate segment. In total the HV distribution system was split into 17 segments for 400 kV, 13 segments for 220 kV and 411 segments for 110 kV.

The load data provided by national power grid company ELES consisted of the data about the working and reactive energy transferred by each HV PL in 15-minute intervals in the period from 1. 1. 2006 to 31. 12. 2017. From these data the values of electric currents were calculated for every 15 minutes, as well as several geometric mean values: daily, weekly (7 day), monthly (30 day) and total mean value.

There is no unified approach among the studies regarding which mean value to use as the surrogate for long term exposure. Some studies have estimated the variations over time from available data, for example, on electricity consumption.[24,25] Several studies used the yearly mean load value for the year of the diagnosis with some adding also the year of birth.[23,26-29] In this study, the total mean value covers the two-year period from 1. 1. 2006 to 31. 12. 2017.

Calculating ELF MF

The ELF MF level at one location is the result of the contributions of all nearby HV PL. As the ELF MF is a vector quantity, the total value depends not only on the amplitude of each contribution, but also on their direction and the angles between them. Typically, when calculating the ELF MF, a numerical model is created that contains all sources and thus the calculation determines the total ELF MF level for the selected loads of HV PV. With the available programs and computational capacity, such a calculation is not feasible for large areas. In addition, usual approach requires recalculation of the whole model for each load conditions (for example at nominal loads, actual maximum loads, average day or annual loads, conditions in case of one HV PL failure...) or if there are changes in technical characteristics like construction of new or reconstruction of existing HV PL.

To allow largescale ELF MF calculations, a new method was developed and validated, which enables the calculation of the total ELF MF based on the values of the ELF MF of individual sources. The methodology was divided into two steps: the first step was to calculate the ELF MF of one HV PL and the second was to calculate the total ELF MF due to all HV PL for desired loads.

Methodology to calculate the ELF MF of single HV PL

New method to calculate the ELF MF of one HV PL was based on the principle that the distribution of the ELF MF in the vicinity of the PL is not affected by the nearby objects or terrain, and on the fact that as long as the geometry of the PL and its load are the same, the value of the ELF MF in a selected point depends only on the distance between the selected point and the HV PL and on the difference of the altitude of the selected point and the HV PL. Each HV PL was split into sections with identical or quite similar geometries. From the data in the registry, a 3D line was generated for each segment, representing the course of the lowest cable of the HV PL. Additionally, for each HV PL segment the ELF MF distribution in a vertical cross section was calculated with a Narda EFC-400 EP program package at the nominal load. The program package calculated the ELF MF by splitting all conductors into short parts and summing their contributions. The value of the ELF MF of one short part of conductor was calculated by the Biot-Savart law:

$$d\vec{\boldsymbol{B}}(\boldsymbol{t}) = \frac{\mu_o}{\boldsymbol{4\pi}}\frac{\boldsymbol{d}\vec{\boldsymbol{l}} \times \vec{\boldsymbol{r}}}{\boldsymbol{r^3}}\boldsymbol{I}(\boldsymbol{t})$$

where is magnetic flux density contribution from a short part of the conductor at the point given by positon vector and *I* is electric current in the cable.

The calculation took into account exact geometry of the towers in this segment and extended to the distance where the value of the ELF MF fell below 0.05 μT. The result was stored in a GRID matrix with the step of 1 m and positioned so that the center of the matrix aligned with the 3D line of the segment.

The 3D line representing the course of the PL and the matrix with the values of the ELF MF in a vertical cross section were used as the input to a customdeveloped program that calculated the value of the ELF MF along the whole segment length. The program first split the segment into spans. For each span, the program generated a 1m grid of points that covered the area of the whole length of span in one dimension and the same distance as covered by the matrix of the values of ELF MF in a vertical cross section. At both ends of the span (at location of the HV PL towers), additional points were added by rotating the last line of points as presented by blue and black dots in Figure 1. We can see that blue and black dots do overlap in a certain area around the tower. For each point in the 1m grid, first the height difference was calcu-

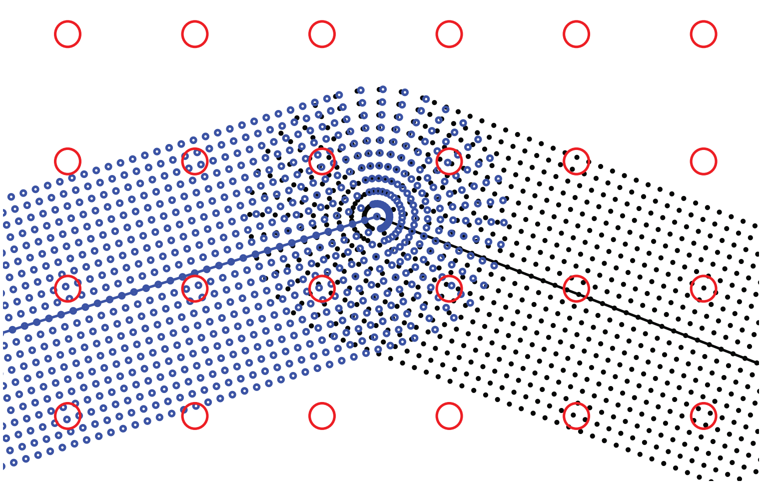

FIGURE 1. Points in 1m grid for two spans of a power line are shown with blue and black dots in which the program determined the values of the extremely low-frequency (ELF) magnetic fields (MF). Red circles represent the final 10 mgrid for which the final results were generated.

lated between the absolute height of the 3D line representing the course of the PL and the point 1 m above the ground. The absolute height of the point 1 m above the ground was determined from the digital elevation model of Slovenia with the resolution of 1 m constructed based on the LIDAR data. Second, the distance of each point in the 1 m grid from the HV PL was calculated. Both values were rounded to the nearest integer and used to pick the corresponding value from the matrix with the calculated values of the ELF MF in a vertical cross section. By this process the proper value of the ELF MF was assigned to each point in the 1 m grid. Finally, a 10 m orthogonal grid was generated (red circles in Figure 1) to which the highest value of nearby points in a 2 m radius was assigned. The output of the program for each segment was a 10m grid of points with the values of the ELF MF.

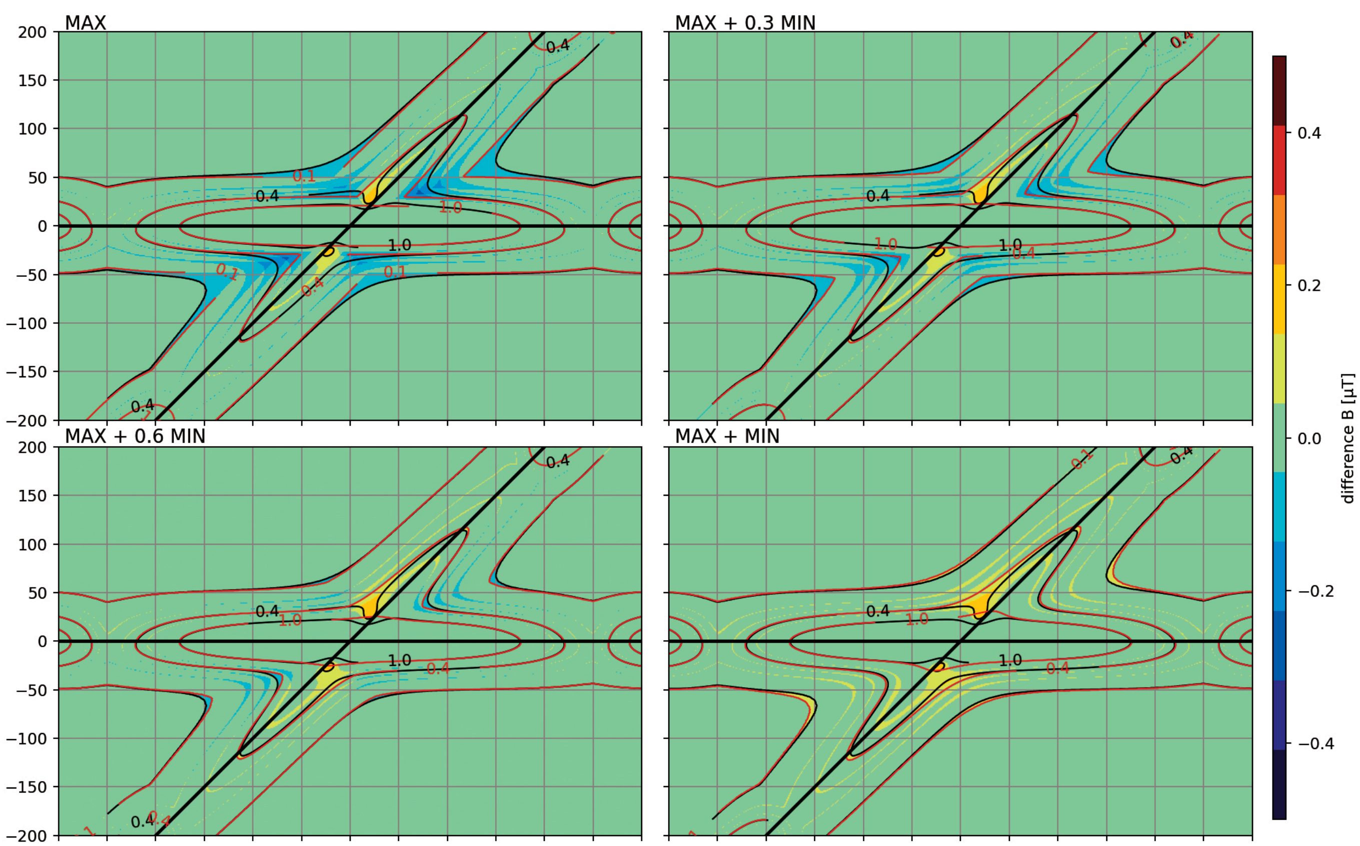

FIGURE 2. Comparison of results obtained by all four algorithms to determine total value of extremely low-frequency (ELF) magnetic fields (MF) for a case of crossing of two 2×110 kV power lines of type barrel under the nominal load of 650 A. The color scale shows the deviation of the estimated value of ELF MF values determined by all four new algorithms from the actual value of ELF MF determined by the usual numerical modeling procedure. The black contours represent the limits of 0.1, 0.4 and 1.0 μT for the actual values, and the red contours for the estimated values.

Finally, if HV PL was split in more than one segment, all 10 m grids of one HV PL were merged together. For those coordinates where values were available in two (or theoretically more) grids, the highest value was used for the final result.

Methodology to calculate the total ELF MF of multiple HV PL

When multiple HV PL either cross or run in parallel, the total value of the ELF MF is a result of the contributions of all nearby HV PL. As ELF MF is a vector quantity, the resulting value is typically significantly lower than a sum of all contributions. Therefore, four different algorithms to determine the total value of the ELF MF in each considered point were analysed and compared:

- the MAX algorithm took the higher value of the two contributions as the total value;
- the MAX + MIN algorithm took the sum of the higher and the lower values as the total value;
- the MAX + 0.3 MIN and MAX + 0.6 MIN calculated the total value by adding to the higher value the lower value multiplied by a specific weight factor of 0.3 and 0.6, respectively.

As, the actual total value of the ELF MF can never exceed the sum of the two values considered, the MAX + MIN algorithm is the most conservative, the MAX algorithm is the least conservative, and the other two are inbetween.

In order to evaluate all four algorithms, various realworld scenarios were analysed where cumulative effects of several HV PL occur, e.g. crossing of two HV PL, or parallel courses of two and three HV PL. Figure 2 presents the analysis of one such case –the intersection of two 110 kV double-circuit HV PL. The colour scale shows the deviation of the estimated ELF MF determined by all four new algorithms from the actual ELF MF determined by usual numerical modelling procedure. Green colour means that there is practically no deviation, red colour marks areas where the algorithm overestimated the values, and blue colour shows areas where the algorithm underestimated the values. Among four proposed algorithms, the MAX algorithm underestimated the values of the ELF MF the most (as the blue areas are the largest) and overestimated them the least (as the red areas are the smallest). The MAX + MIN algorithm never underestimated the values of the ELF MF, and overestimated them the most among the four proposed algorithms. Information regarding the deviation of the estimated value from the actual value is also provided in Figure 2 by black and red contours. The black contours represent the field lines of 0.1, 0.4 and 1.0 μT for the actual value obtained by usual modelling procedure, and the red contours for the estimated value using a novel method. For the MAX + MIN algorithm red contours never lie inside black contours, which means that the MAX + MIN algorithm overestimated the values of the ELF MF. Using the MAX algorithm, red contours often or even predominantly lie within black contours. The analysis showed that the most realistic results for the conditions considered was given by the MAX + 0.6 MIN algorithm, which was thus chosen as the optimal algorithm. Subsequent feasibility analysis showed that calculations could be performed according to all four algorithms, which allowed later sensitivity analysis, i.e. whether the choice of algorithm affects the result of analyses.

A novel program with all four analysed algorithms was developed to determine total value of the ELF MF. The program also featured the functionality to scale the values of each HV PL with a certain factor before calculating the total value of the ELF MF. This functionality enables relatively easy and fast calculation of the total ELF MF not only for the nominal load of HV PL, but for any load conditions or operating conditions of the whole power distribution network. For the later analysis, the total geometric mean value of the load was used that covers the whole period from 1. 1. 2006 to 31. 12. 2017.

Cancer data

We conducted retrospective geographical epidemiological study in population of Slovenian children and adolescents aged 0–19 years diagnosed in a 12-year period 2005–2016.

Address of residence served as a proxy indicator of ELF MF exposure. From Central Population Registry data on permanent address, which was georeferenced to X and Y coordinates, was obtained for all Slovenian children and adolescents in the studied population. Modelled values for ELF MF density near HV PL were used to classify all population of children and adolescents into five categories of ELF MF exposure: $B < 0.1$ μT; 0.1 μT $\leq B < 0.2$ μT; 0.2 μT $\leq B < 0.3$ μT; 0.3 μT $\leq B < 0.4$ μT and 0.4 μT $\leq B$. Georeferenced addresses were allocated to the closest point on the 10m grid by using the k-nearest neighbours (kNN) method on the Quad Tree to avoid calculation of Euclidian distances between each grid point and each address location (building Quad Tree algorithm has running time $O(n \cdot \log(n))$).[30]

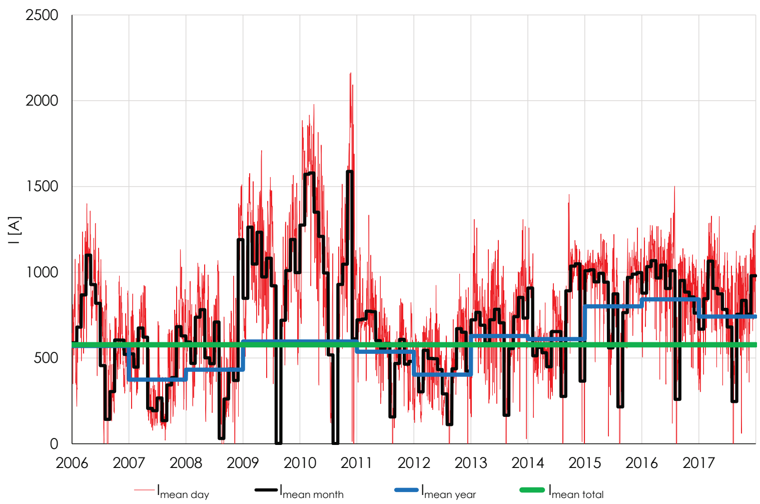

FIGURE 3. The daily, monthly, yearly and total (1. 1. 2006 – 31. 12. 2017) mean values of the load of a 400 kV power line with the highest mean values in Slovenia.

From the Slovenian Cancer Registry incidence (number of all newly diagnosed cancer cases in one calendar year) data on cancer patients were obtained and linked to population data based on Slovenian personal identification number. Patients with leukemias were identified based on codes C91–C95 according to the 10th revision of the International Statistical Classification of Diseases and Related Health Problems (ICD-10). In addition, we analysed all cancer cases occurring in childhood (age at diagnosis 0–14 years) and cases with malignant tumour of the central and autonomic nervous system (or brain tumour in short) with codes C70–C72 diagnosed up to 29 years of age.

Relative risk of cancer was assessed using a standardized incidence ratio (SIR), which is a method for indirect age standardization and is calculated as a ratio between observed and expected incidence for each studied group, i.e. cancer incidence in each of the five categories of ELF MF exposure. Expected incidence is calculated from age distribution in studied group and age-specific incidence rates in the overall population.[31] A SIR value of 1 indicates that observed incidence in the studied group is the same as expected incidence, less than 1 indicates a lower than expected incidence, and over 1 indicates a higher than expected incidence.

Data management and analysis of population and cancer data was performed in R software (version 4.0.2) and R packages dplyr (version 1.0.2) and SearchTrees (version 0.5.2).

Results

ELF MF around HV PL

To measure the ELF MF at the participants homes it is necessary to obtain their consent. This can be potential source of selection bias.[29] It is suggested [32] that although it is an imperfect measure of magnetic field exposure, wire code is the only method applicable to nonparticipating subjects. But if technical data about the HV PL near the residence of participants are available, it is possible to determine the exposure at the desired time interval based on the numerical calculations. Such combined estimation of ELF MF exposure has been used in several studies.[8,27-29] As numerical calculation of ELF MF is very demanding for larger areas, the studies usually limit the area of interest to a pre-selected distance to the HV PL, usually in the range of a few hundreds of meters.

The value of the ELF MF in a selected point near PL depends on the geometry of the PL, the load of the PL, the distance from the HV PL, and the elevation difference between the PL and the selected point. It is not affected by the terrain and nearby objects. This principle was used by Miravet-Garret[33], where the distance and difference of the altitude of the HV PL and of the selected point was determined from the detailed technical data of the HV PL and the ground profile, and then the value of the ELF MF at the selected point was calculated by a simplified analytical formula.

The mean values of the load of HV PL in Slovenia have an increasing tendency, meaning that on average the energy transfer through HV PL is increasing. For 110 kV PL the average value of geometric means of the loads of all PL was 84 A in 2006 and 87 A in 2017, for 220 kV PL it was 185 A in 2006 and 213 A in 2017, and for 400 kV PL it was 282 A in 2006 and 360 A in 2017. The increase is significantly higher for 400 KV PL compared to either 220 or 110 kV PL. However, the mean loads are not high. Among all 400 kV PL, the highest total mean value of the load for one PL for the whole period from 1. 1. 2006 to 31. 12. 2017 was 742 A and it increased to 842 A for the highest yearly mean value (in year 2016). In Figure 3 the daily, monthly and yearly mean values for this HV PL are presented.

Yearly mean loads do not differ significantly from the total mean loads (1. 1. 2006 – 31. 12. 2017). The highest yearly value was achieved in 2016 (842 A), whereas the lowest was achieved in 2007 (374 A). The fluctuations in monthly mean loads are larger, the highest monthly load was achieved in November 2010 (1588 A) and the lowest in August

2010 (1 A). For weekly mean loads, the highest values were achieved at the end of November 2010 (1987 A).

The ELF MF around HV PL was calculated for the entire territory of Slovenia on the 10m grid. On Figure 4 the value of the ELF MF of several HV PL around one transformer stations are presented for nominal load (top) and the total mean geometric load covering the period from 1. 1. 2006 to 31. 12. 2017. The value of the ELF MF was determined by the new algorithm (from chapter Methodology to calculate the total ELF MF of multiple sources). For the total mean geometric load, the value of the ELF MF was higher than 0.1 μT on almost 2 million points. This represents the area of about 191 km^2, which means that on about 1% of the territory of Slovenia the value of the ELF MF is 0.1 μT or higher, while on more than 99% of the territory of Slovenia the value of the ELF MF is below 0.1 μT. For 0.4 μT the areas are significantly smaller, as this value is exceeded only on 0.36% of Slovenian territory.

The results were validated by comparing calculated values of ELF MF with measurements in the vicinity of two 400 kV PL and two 220 kV PL. The same load conditions (nominal load) were used for comparison. For the 400 kV PL with the highest mean load, the comparison is given in Table 2.

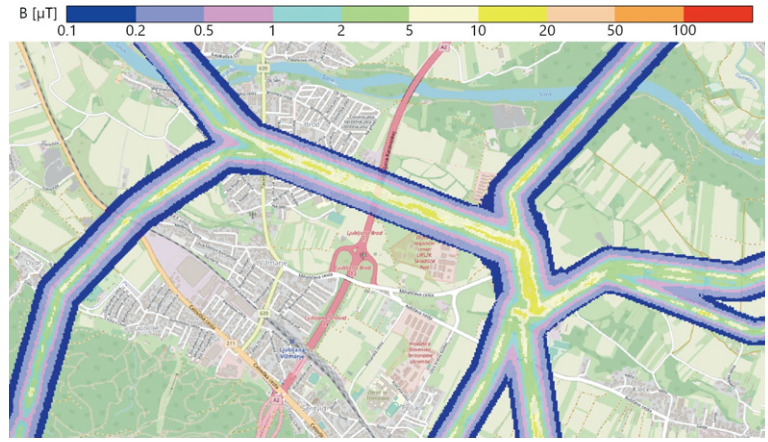

FIGURE 4. Example of the total value of the extremely low-frequency (ELF) magnetic fields (MF) of several high voltage power lines around distribution transformer stations for nominal load in the area of the capital city of Ljubljana (approximately 5 x 2.7 km).

Childhood cancers and ELF MF exposure

Cancer in children and adolescents is a rare disease, as it represents less than 1% of all cancers in Slovenia as well as in Europe.[34,35] In recent years, around 70 cancers are diagnosed annually in Slovenia during childhood and adolescence (from birth to the age of 19), 20% more among boys than among girls.[34] Age-standardized incidence rate has been increasing by an average of slightly more than 1% annually since 1961 in Slovenia and also increased by about 1% per annum in Europe in the past three decades.[34,36] The causes for the increasing incidence are unknown; although it is largely attributed to improved diagnostic and registration procedures, the possibility of increased exposure to different harmful factors, especially intrauterine, cannot be excluded.[36]

The most common groups of malignant cancers in the age group of 0–19 years are leukaemias, lymphomas and tumours of the central nervous system (in short brain tumours). According to the average for the period 1961–2019, leukaemias represented a quarter of all newly diagnosed cancers, followed by brain tumours with around 15%, Hodgkin's lymphoma with 10% and non-Hodgkin's lymphoma with 8%.[34] Apart from exposure to benzene and ionizing radiation, the risk factors for leukaemias are not well known.[37,38] The so-called hygiene hypothesis is also possible, where, due to the improvement of infection prevention in the modern era, leukaemia may develop in geneti-

TABLE 1. The distances from the 400 kV power line with the highest mean load, at which the value of the extremely low frequency magnetic field falls below 0.1, 0.2, 0.3 and 0.4 μT, respectively

Distance	B = 0.1 μT	B = 0.2 μT	B = 0.3 μT	B = 0.4 μT
Nominal load	340 m	238 m	193 m	167 m
Highest daily mean load (2164 A, 23. 11. 2010)	303 m	212 m	172 m	149 m
Highest weekly mean load (1987A, 22. – 28.11.2010)	290 m	203 m	165 m	143 m
Highest monthly mean load (1588 A, 11. 2010)	258 m	181 m	147 m	127 m
Highest yearly mean load (842A, 2016)	187 m	131 m	107 m	92 m
Total mean load (742 A, 1. 1. 2006 – 31. 12. 2017)	175 m	123 m	99 m	87 m

TABLE 2. Comparison of the calculated and measured value of the extremely low frequency magnetic field for 400 kV power line with the highest mean load

Location	1	2	3	4	5
Calculated value [μT]	7.4	3.8	3.0	9.1	3.4
Measured value [μT]	7.3	3.4	4.1	12.3	2.7

cally predisposed individuals due to an incorrect response to infection by the immune system of a child who did not come into contact with non-dangerous infectious agents in early childhood at the right time (early enough).[39] Some (but not all) studies have shown that the risk may be increased (only) for childhood leukaemias with longterm daily exposure to ELF MF densities greater than 0.3 or 0.4 μT, depending on the study.

The key advantage of our study was that with inclusion of the population data from the Slovenian Cancer Registry, we avoided performing a case-control study and, at the same time, selection and participation bias.[8] Research indicates that the fraction of children exposed to higher values of ELF MF (>0.4 μT) is likely to be less than 2% of the population.[40,41] For Slovenia, it was estimated in the past that no more than 1% of children were exposed to long term ELF MF greater than 0.4 μT.[42] In presented study, using an innovative model for evaluating ELF MF on a small spatial network and georeferencing residences and sources of the electricity network in Slovenia, we precisely determined the exposure to ELF MF in children aged up to 14 years in the period 2005–2016 in Slovenia, who live nearby HV PL. We found that as many as 99.5% of all children did not live in the areas with the mean value of ELF MF 0.1 μT or higher. And only 0.09% of all children were exposed for at least one year to the area of potentially carcinogenic ELF MF density, that is greater than 0.4 μT, in the vicinity of HV PL. This population results and results for age groups 0–19 and 0–29 are presented in Table 3 (the results are equal to the first decimal point). These results emphasize the importance of performing exact calculations on real-life population-based data in order to obtain realistic picture of the situation in a specific country.

In Table 3 we also present results according to five categories of ELF MF exposure for observed and expected number of cancer cases, and standardized incidence ratio for all cancers combined, leukaemia and brain tumours. All of the 516 cancer cases in children aged 0–14 years in 2005–2016 were classified in the lowest category of exposure (ELF MF below 0.1 μT) near HV PL. Relative risk cannot be calculated for other categories of ELF MF exposure, since there were no cases.

Among 195 diagnosed cases of leukaemia in children and adolescents aged 0–19 years in 2005–2016 only one adolescent was classified in the category of ELF MF density between 0.1 and 0.2 μT – a person lived in the vicinity of 110 kV PL. This single case of leukaemia represents big variability and thus "shifted" all residents from this group from a relative risk of zero to a relative risk of more than one. Although the value for relative risk in this group appears high (2.4), the confidence interval is far too wide for statistical significance (since it is based on only one case). No leukaemia case was classified in categories with higher ELF MF exposures (i.e., above 0.2 μT).

Among 196 patients aged 0–29 years diagnosed with brain tumour only one adolescent was classified in the category of ELF MF exposure between 0.2 and 0.3 μT, giving standardized incidence ratio 4.4 with wide 95% confidence interval (0.1-24.6). Also, this person lived in the vicinity of 110 kV PL at the time of diagnosis. No brain tumour case was classified in other categories of ELF MF exposure.

We conclude that none of the cases of leukaemia in the studied population can be attributed to exposure to ELF MF – the relative risk of leukaemia in children and adolescents living near HV PL does not differ from the average risk in the general population. Additionally, we could not assess a possible risk trend over exposure categories, because there were also no cases of leukaemias in other categories.

Our findings are in line with other similar studies, but we cannot directly compare the results with other studies due to the different (in our opinion better, more accurate assessment methodology based on actual exposure and availability of exact coordinates for all dwellings on Slovenian population.[41,43] Using place of residence as a surrogate indicator of ELF MF exposure is more reliable in children than in adults, as they spend most of the day in the vicinity of home and the surrounding area. In addition, they migrate less.

Discussion

For the ELF MF exposure assessment, we developed an innovative, accurate model on a fine spatial grid, which is more reliable than exposure approximations used by previous studies (e.g. Euclidean distance from guides, questionnaires,

TABLE 3. The proportion of Slovenian population of children and adolescents in 2005–2016, observed and expected number of cancer cases, and standardized incidence ratio with 95% confidence interval for all cancers combined (age 0–14 years), leukemia (age 0–19 years) and brain tumors (age 0–29 years) are presented according to five categories of ELF MF exposure

	< 0.1 mT	0.1–0.2 mT	0.2–0.3 mT	0.3–0.4 mT	≥ 0.4 mT
Population* (proportion)	99.5 %	0.2 %	0.1 %	0.1 %	0.1 %
All cancers (age 0–14 years)					
Observed number of cases	516	0	0	0	0
Expected number of cases	513.6	1.1	0.6	0.3	0.5
Standardized incidence ratio (95% confidence interval)	1.0 (0.9–1.1)	no cases	no cases	no cases	no cases
Leukemia (age 0–19 years)					
Observed number of cases	194	1	0	0	0
Expected number of cases	194.1	0.4	0.2	0.1	0.2
Standardized incidence ratio (95% confidence interval)	1.0 (0.9–1.2)	2.4 (0.1–13.3)	no cases	no cases	no cases
Brain tumors (age 0–29 years)					
Observed number of cases	195	0	1	0	0
Expected number of cases	195.1	0.4	0.2	0.1	0.2
Standardized incidence ratio (95% confidence interval)	1.0 (0.9–1.2)	no cases	4.4 (0.1-24.6)	no cases	no cases

* Population's proportions for age groups 0–14, 0–19 and 0–29 are equal to the first decimal point.

etc.). With this new method the calculations of ELF MF values generated by all HV PL were performed for the entire territory of Slovenia with the grid of 10 m for average loads of HV PL in the period from 2006 to 2017. The value of ELF MF was higher than 0.1 µT in a little less than 2 million points, which corresponds to an area of about 200 km^2, or one percent of the whole territory of Slovenia. The new method enables relatively fast calculation of the value of ELF MF for arbitrary loads of the power distribution network, as the value of each source for arbitrary load is calculated by scaling the value for nominal load, and at the end the total value is determined by new methodology. The advantage of this approach is also significantly faster adjustment of calculated estimates in the power distribution network, such as a new power line or the reconstruction of an existing power line, as new calculation is required only for a new or modified source. The new methodology was validated on smaller areas by comparing the total values of ELF MF, determined according to the new methodology, with the values obtained with the traditional approach of numerical modelling and with the results of measurements. Both comparisons showed the expected agreement of the results.

Among Slovenian children and adolescents, only 0.5% live in the areas with the mean value of ELF MF 0.1 µT or higher. And only 0.09% of all children were exposed for at least one year in the area of potentially carcinogenic ELF MF density in the vicinity of power lines, which is greater than 0.4 µT. Although the incidence of childhood cancer, which is a rare disease, is gradually increasing in Slovenia, based on our population study, we cannot attribute any case of childhood cancer up to 14 years of age, any leukaemia diagnosed up to 19 years, or any tumour of the central nervous system up to 29 years in the twelve years under study (2005–2016) to the exposure to ELF MF near HV PL.

Finally, although here the new method for estimation of exposures to ELF MF was used for assessment of possible increased cancer risk in children and adolescents, it is also applicable for the broader purpose of exposure assessment, including the planning of proper placement of HV PL and transformer substations into the environment, and of new housing near the existing HV PL.

Acknowledgments

This work was funded by the Slovenian Research Agency (ARRS) and the Slovenian Ministry of Health through the targeted research project "Health risk assessment for exposures of children to lowfrequency electric and magnetic fields in Slovenia" (grant number V3-1718) and by the Slovenian Research Agency and the Ministry of Education, Science and Sport through the research programme "Slovenian research programme for comprehensive cancer control SLORApro" (grant number P3-0429). The funding sources had no role in study design, the collection, analysis or interpretation of data, the writing of the report, or the decision to submit the article for publication.

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