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Authors
Vergara, Ximena P
Kavet, Robert
Crespi, Catherine M
et al.

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Estimating magnetic fields of homes near transmission lines in the California Power Line Study

Ximena P. Vergara [a,*], Robert Kavet [a], Catherine M. Crespi [b], Chris Hooper [c], J. Michael Silva [c], Leeka Kheifets [d]

[a] Electric Power Research Institute, Environment Sector, Palo Alto, CA, USA
[b] UCLA Fielding School of Public Health, Department of Biostatistics, Los Angeles, CA, USA
[c] Enertech Consultants, Campbell, CA, USA
[d] UCLA Fielding School of Public Health, Department of Epidemiology, Los Angeles, CA, USA

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ABSTRACT

The California Power Line Study is a case-control study investigating the relation between residences near transmission lines and risk of childhood leukemia. It includes 5788 childhood leukemia cases and 5788 matched primary controls born between 1986 and 2007. We describe the methodology for estimating magnetic fields at study residences as well as for characterizing sources of uncertainty in these estimates. Birth residences of study subjects were geocoded and their distances to transmission lines were ascertained. 302 residences were deemed sufficiently close to transmission lines to have non-zero magnetic fields attributable to the lines. These residences were visited and detailed data, describing the physical configuration and dimensions of the lines contributing to the magnetic field at the residence, were collected. Phasing, loading, and directional load flow data for years of birth and diagnosis for each subject as well as for the day of site visit were obtained from utilities when available; when yearly average load for a particular year was not available, extrapolated values based on expert knowledge and prediction models were obtained. These data were used to estimate the magnetic fields at the center, closest and farthest point of each residence. We found good correlation between calculated fields and spot measurements of fields taken on site during visits. Our modeling strategies yielded similar calculated field estimates, and they were in high agreement with utility extrapolations. Phasing was known for over 90% of the lines. Important sources of uncertainty included a lack of information on the precise location of residences located within apartment buildings or other complexes. Our findings suggest that we were able to achieve high specificity in exposure assessment, which is essential for examining the association between distance to or magnetic fields from power lines and childhood leukemia risk.

1. Introduction

Draper et al. (2005) reported the risk of childhood leukemia and other cancers in relation to distance from home at birth to overhead transmission lines operating at 275 kilovolt (kV) and 400 kV in England and Wales. Using a distance of ≥ 600 m from a line as a reference, the odds ratio (OR) for childhood leukemia cases (and a set of matched controls) incident from 1962 to 1995 was 1.68 (95% CI; 1.12 to 2.52) for subjects 0 to < 200 m away. However, the OR remained elevated at 1.22 (95% CI; 1.01 to 1.47) for subjects 200 to 600 m away, a distance at which magnetic fields attributable to overhead transmission lines are negligible. More recently, Bunch et al. (2014) updated the Draper et al. study, adding cases and controls up to 2008, extending the reference category to ≥ 1000 m, adding lower voltages and analyzing OR by decade. They report a monotonically decreasing OR from the 1960s through 2000–2008 and suggest that such a decline might be due to changing population characteristics among those living near power lines. Nevertheless, both earlier findings of Draper et al. and later results of Bunch et al. remain unresolved.

Since 1979, several dozen epidemiologic studies have investigated the association of childhood leukemia with estimated residential power-frequency magnetic fields and/or physical surrogates of magnetic fields. In 2001, the International Agency for Research on Cancer (IARC) classified power frequency magnetic fields as a Group 2B carcinogen, or ‘possibly carcinogenic to

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[*] Corresponding author. Fax: +1 650 855 2258.
E-mail address: xvergara@epri.com (X.P. Vergara).

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Table 1
Summary of childhood leukemia studies in populations near high voltage overhead power lines.

Study location	Voltage and distance criteria	Distance estimation	Line configuration and geometry	Load data	Calculation years	Calculation	Calculation software
Feychting and Ahlbom (1993) (Sweden)	220, 400 kV within 300 m of residences across Sweden	Home co-ordinates from the Central Board for Real Estate Data; distance assessed with a "large-scale map" for each home	Utility data on tower height, distances between towers and between phases and ordering of phases	Load data available for most of the period 1958–1985; (contemporaneous measurements compared to calculations for contemporaneous and historical loads)	Year of birth 1960–1985 and date of measurement	Distance between part of house closest to line and midpoint between the outer phases	State Power Board—Vattenfall Utveckling AB software
Olsen et al. (1993), Pedersen et al. (2014) (Denmark)	50–60 kV = 35 m 132-–150 kV = 75 m 220–440 kV = 150 m. Ensure to capture all dwellings w/ $\geq$ 0.1 μT	Typographical maps of utility lines (and associated substations) linked with address; addresses from Danish registries	"Category of line", tower type, including span distance and distance between phases, phase order	Transmission system experts estimated annual average load; assessment included substations, overhead & underground lines	Nine months prior to birth through date of dx 1968–1986 (1993) & date of dx 1987–2003 (2013)	1993: Not specified ("at the dwelling for as long as the family occupied the address") 2013: Birth address	Program from Jutland–Funen Electricity Collaboration
Verkasalo et al. (1993) (Finland)	110, 220, 400 kV within 500 m of lines; criteria for inclusion: B-field $\geq$ 0.01 μT	Map locations of line routes were digitized and linked to a national register of building locations	Not specified ("typical locations of phase conductors")	Estimates from 1977 used for 1970–1976 Load documents: 1977–1983 Annual average load: 1984–1989	Buildings with B-field $\geq$ 0.01 μT for $\geq$ 1 years 1970–89	Shortest distance to center of building	N/A (Imatran Voima Oy power company)
Tynes and Haldorsen (1997) (Norway)	11 kV+ within 101 m	Maps from Royal Norwegian Forces, Central Bureau of Statistics, local municipality authorities, and Cancer Registry staff	Line geometry provided by line owners (attachment heights, phasing, spacing, and load); topography for homes within 50 m estimated during site visit of line owner staff	Calculated annual average load for available utility information (usually day-to-day records); extrapolated historical annual average by utility staff for lines without data	Year closest to date of dx 1965–1989	Closest corner of house to midpoint of line's outer phases	Computer program developed at the University of Oslo
Draper et al. (2005), Swanson (2008), Kroll et al. (2010), Bunch et al. (2014) (UK)	275, 400 kV (few 132 kV) 600 m for all children; added 132 kV and extended to at least 1000 m (2013)	Computerized utility records of line structures linked with Ordnance Surveys and postcodes	Seven standard pylon designs (most double circuit) with default catenary dimensions, unless within 50 m of residence; phasing from 1976, 1979, and 1997 diagrams	Calculated annual average load based on winter peak predictions; for multiple lines, calculated fields for individual lines added in quadrature	Single year based on date of birth, 1962–1995 (2005)	Average of calculations from five evenly spaced points between closest and farthest points from the line; averaged the five values	EM2D by National Grid
Lowenthal et al. (2007) (Tasmania)	88, 110, 220 within 300 m	Utility maps and street atlas with site visits for homes very close to lines	Not specified	Line voltage used as a proxy for electrical current	–	Only distance	N/A (Line voltage proxy)
Sermage-Faure et al. (2013), Bessou et al. (2013) (France)	63–90 kV = 70 m 150 kV = 100 m 225 kV = 120 m 400 kV = 200 m	Geocoded subject addresses ($\geq$ 20 m uncertainty) Utility GIS of towers (2.5–25 m uncertainty)	28 basic categories of tower structures with specific geometries for line height, sag, span length, etc. leading to 216 reference field maps	Annual average load from available utility database for 2002–2007 and "back-estimation" from 2006–07 for lines with no data for 2002–2005 using uniform overall system load growth	Date of dx 2002–2007	Mailbox or driveway entrance	EFC400® profiles for 216 reference maps; "simplified calculation" developed independently of epidemiology study
Kheifets et al. (2013), Vergara et al. (this paper)(California, United States)	100–200 kV = 80 m 200–345 kV = 150 m 500 kV = 200 m (some 60–69 kV)	Utility GIS system; Google Earth aerial photographs; measured distance for homes close to lines	Line geometry collected during site visit; phasing and loading provided by utilities	Calculated and modeled annual average load for available utility database information; extrapolated historical annual average by modeling and utility staff	Date of birth, 1986–2007 & date of dx, 1988–2008 and, date of measurement	Closest and farthest points of home; center of home	EMF Workstation 2013 (3D)

Note: B-field = magnetic field; dx = diagnosis kV = kilovolt humans' (IARC 2002). This determination was based on 'limited' epidemiologic evidence, ‘inadequate' evidence in animal studies, and the lack of a biophysical mechanism that could explain biological effects of magnetic fields at ambient exposure levels.

A surrogate for magnetic field exposure introduced by Wertheimer and Leeper (1979) (W–L) considered the configuration of power line wiring, including both distribution and high voltage overhead transmission lines, and their distances to the residences of cases and controls. This method, called the W–L wire code, was further refined and used in several subsequent studies in the U.S. (Wertheimer and Leeper, 1982; Savitz et al., 1988; Severson et al., 1988; London et al., 1991). Using wire code as an exposure measure had the advantage of minimizing selection bias by not requiring recruitment and enrollment of cases and controls. Measurement of magnetic fields within residences requires subject consent, possibly resulting in differential participation of cases and controls, hence a potential source of selection bias, especially if refusal rates are also associated with exposure (Savitz et al., 1988; London et al., 1991; Hatch et al., 2000; Mezei et al., 2008). Additionally, because power lines tend to maintain the same configuration over many years, wire codes were thought to represent a more stable exposure index than measured magnetic fields. However, wire code and distance have limitations as an accurate predictor of contemporaneously measured residential magnetic fields (Kavet 1995; Kheifets et al., 1997; Rankin et al., 2002; Maslanyj et al., 2009).

Several childhood leukemia studies reported in the 1990s adopted an alternative study design by restricting the study sample to populations residing within several hundred meters of overhead transmission lines (Feychting and Ahlbom, 1993; Verkasalo et al., 1993; Tynes and Haldorsen, 1997). Another countrywide study considered exposure in relation to proximity to high voltage transmission lines (HVTL), as well as to ‘transmission cables and substations' (Olsen et al., 1993). Two exposure studies in North America validated that residents living near (∼0 to 100–150 m) overhead HVTL operating at voltages greater than 200 kV have distinctly greater time-weighted average exposures to power frequency magnetic fields compared to populations who live far from any HVTL (Kavet et al., 1992; Levallois et al., 1995).

Characterizing all HVTLs near a residence with respect to their geometry (i.e., attachment height of conductors, phase spacing, tower location), operating characteristics (temporal characteristics of line load(s), direction(s) of load flow, and phase relationship), and the tower route proximity relative to a residence, would allow one to estimate the magnetic field within that residence at the appropriate point in time (e.g., at birth or at diagnosis), provided data of sufficiently high quality can be obtained.

Table 1 provides a summary of the epidemiology studies that have targeted populations near overhead HVTL, including the California Power Line Study (CAPS) described in this paper.

The CAPS is a case-control study focusing on childhood leukemia, but also including central nervous system (CNS) cancer, for comparison. The study design for assessing leukemia and CNS cancer risks in relation to distance has been thoroughly described in a previous publication (Kheifets et al., 2013). This paper describes the methodology for estimating historic magnetic fields at residences in the immediate vicinity of transmission lines. Papers with similar objectives have been published in connection with a follow-up analysis of magnetic fields, for the Draper et al. study data set (Swanson, 2008) and for a French study that also recently reported childhood leukemia risks in relation to distance from transmission lines (Bessou et al., 2013; Sermage-Faure et al., 2013).

2. Methods

To briefly summarize, leukemia and CNS tumor cases diagnosed at age 0–14 years were ascertained through the California Cancer Registry, and linked to the California Birth Registry, which served as the source of controls (Oksuzyan et al., 2012, 2013). For leukemia, 5788 cases and 5788 primary controls were entered into the study; for CNS tumors, the study comprised 3308 cases and 3308 primary controls. The study was approved by University of California, Los Angeles (UCLA) Office for the Protection of Research Subjects, University of Southern California (USC) Institutional Review Board, and California Committee for the Protection of Human Subjects (CPHS).

Birth and diagnosis addresses were geocoded with the USC Geographic Information System (GIS) open-source geocoder. Parcel or street segment level accuracy was obtained for 88.5% of the geocoded addresses. The four largest electric power companies in California, who serve 85% of the state's customers, provided their GIS databases which were used along with the geocoded addresses to identify birth and diagnosis residences within 2000 m of transmission lines operating at voltages greater than 100 kV, and for two companies as low as 60 kV. A transmission line is defined as a single or individual 3-phase electrical circuit, where individual circuits may be located separately on their own support structures or co-located with other circuits (or multiple circuits) on a common support structure. We used custom software to estimate distances of residence from lines. Distances were verified using Google Earth aerial imagery for some residences. The two distance measures, GIS and Google Earth, were in close agreement, with the Pearson correlation coefficient of 0.998 (Kheifets et al., 2013). About 7% of geocoded residences were in territories served by other smaller companies, and for these aerial imagery was used to determine distances from lines. All determinations were blind to case/control status. The detailed study design, procedures and study population are described in a previous publication (Kheifets et al., 2013).

Following these steps, residences for which the line-attributable fields could exceed background were identified and targeted for site visits as follows: residences within 80 m for 100–200 kV lines; 150 m for 200–345 kV lines; and 200 m for 500 kV lines. Background levels beyond those distances were assumed to be 0.05 μT or less.

Our objective was to create valid models to calculate the magnetic field at each residence on the dates corresponding to the subjects' year of birth, year of diagnosis, and date of measurement. Detailed data describing the physical configuration and dimensions of the circuits contributing to the residential field, as well as the residence's location relative to a circuit's geographic coordinates were collected during in-person site visits (Fig A.1).

2.1. Measurements of line configuration, line dimensions and line-to-residence distances

A measurement system was developed to collect information such as tower coordinates, conductor attachment heights and sag, phase spacing, and location of the subject residence relative to a circuit's coordinates (e.g., center of residence, closest and farthest points). A highly accurate survey grade handheld Global Positioning System (GPS) based measurement system, the Trimble GeoXH (GeoXH), was used with a laser range finder, the LaserCraft Contour XLR (Contour XLR), for the site visits to overcome problems with physical obstacles such as busy streets, restricted access areas or fence, or a transmission tower located across a freeway or on a hillside within an area of private property.

2.2. GPS data quality

To ensure the accuracy of GPS coordinates and transmission line data, and as a quality control check, post-processed GPS coordinates from Pathfinder Office for some residences were entered into Google Earth, allowing coordinates of interest to be overlaid onto aerial photographs for visual confirmation (Google, 2014).

2.3. Residence location

At times, the exact location of the residence was uncertain. These situations included residences in security-gated complexes or apartment buildings. Uncertainties in exact residence location were documented and ranged from lowest to highest uncertainty as follows: (1) location fully known; (2) location of the door known but the center had to be estimated; (3) apartment building known but exact apartment location uncertain; and (4) complex (multiple buildings) known but exact residence location within the complex uncertain, due to lack of access. When direct access to a given location was available, the Trimble GeoXH was used to directly record the GPS location. At locations on private property and/or not directly accessible (e.g. the center of the residence) the GPS coordinates were determined using the Contour XLR in conjunction with the Trimble GeoXH.

For residences located within a gated community, a large apartment complex with no access, or an apartment building, closest and farthest points of the complex or apartment building were measured and center estimated using Google Earth aerial imagery. When the front door or the closest point of the apartment was known, the footprint and the center of the apartment were estimated based upon a typical apartment size for the area.

2.4. Site visit standardized data collection protocol

A standardized data entry form and checklist were developed for residential site visits, performed from 2011–2013 (Fig A.1). In addition to data entry fields photographs were taken of study residences, transmission lines, and any distribution lines potentially influencing magnetic field measurements to help determine parameters such as tower orientation, structure type, conductor spacing, etc.

2.5. Load data, flow direction and phasing

Loading information was typically provided by each electric utility as detailed load readings back to the earliest date available (for 11% of relevant years). Based on this input, yearly average loads were calculated for each circuit. Data with obvious errors (e.g. loading of several thousands of amps) were removed from the yearly average calculations (less than 0.1% of all data).

If loading data were not available for a specific year, then historical extrapolation of the data was performed. Extrapolation was done using predictions from linear mixed models (McCulloch and Searle, 2001) fit to the available yearly average loading data. Separate models were fit for lines of each voltage class (<100 kV, 100–200 kV, >200 kV) for each utility. Models using log-transformed load and untransformed load as the dependent variable gave similar results and log-transformed load was used. All models included a random intercept, which allowed each circuit to have its own typical loading. Three alternative modeling strategies were compared: a no time trend model, which assumed no temporal trend in loadings but rather that loads were stable over time, with residual variation around each circuit's stable level; a common time trend model, which estimated a log-linear temporal trend in loading which was common to all lines within voltage class by utility; and a line-specific time trend model, which allowed each line to follow its own time trend by including a random slope. Comparisons showed that the line-specific time trend model gave implausible estimates in some instances, whereas the other two modeling strategies yielded plausible estimates. Hence predictions using these two strategies were generated.

In addition for two of the companies, utility representatives familiar with system flow patterns provided extrapolated load data for the missing years. These expert estimates were based on the transmission line locations and the type of service areas, historical changes in generation sources, and subsequent year loading values and patterns.

If transmission lines were not owned by the four main California electric utilities, then phasing, loading, or directional load flow data were not available. For these lines, the voltage classification for each circuit was estimated during the site visit or was assessed based upon similar available information from other utilities. To estimate an average load for HVTL for modeling purposes, we used available data from the four main California utilities based on each voltage classification for modeling purposes. These situations comprised less than 5% of the total number of the 302 residences visited.

For residences where phasing and/or direction of load flow was not available from the utility (whether this occurred for the four main California utilities or other smaller utilities), then a bounding evaluation was performed for different phasing/load–flow-direction scenarios to yield upper and lower estimates. Transmission lines with known phasing and direction of load flow were held constant while lines with these unknown parameters were varied to determine the upper and lower limits of the magnetic field calculation range.

Since some residences could have multiple sources of uncertainty, we also computed an uncertainty score as the sum of: 1 point if historical extrapolation of loading was required, 1 point if building (or complex) location was known but location within building (complex) was uncertain, and 1 point if phasing was based on best guess.

2.6. Magnetic field calculation

Modeling of the residential magnetic field included several of the spans and the data for each circuit configuration adjacent to the residence. Computer modeling of each transmission line was performed using data collected from the site visit, which included conductor attachment height, mid-span sag, vertical and horizontal conductor phase spacing, support structure locations, and residential coordinates. The number of spans near each residence included in the computer model varied depending upon the residence location along a given span and the distance to the circuit. Each computer model included a minimally sufficient number of spans to provide an accurate magnetic field calculation at the residence so that inclusion of additional spans would not significantly change the calculated magnetic fields. Loading for the year of birth, year of diagnosis, date and time of the site visit measurements, phasing and direction of load flow were also entered into the computer model. Calculations were performed at the closest edge, center, and farthest edge of the residence, in addition to the location at which magnetic field spot measurements were made during the site visit. When the phasing was unknown, the phasing/load flow which most closely matched the spot measurement at the site visit was used, while other phasing/load flow estimates provided the range of alternative estimates. Magnetic fields were calculated using the EMF Workstation (EPRI, 2013).

In general, the distribution of magnetic field values was highly skewed and hence geometric means and standard deviations (SDs) were used to summarize the data. For the same reason, log transformations were applied to normalize the data before computing Pearson correlation coefficients to compare values. Recognizing that the epidemiologic analyses of calculated fields will rely on classification of residential magnetic fields into exposure bins, we evaluated exposure classification using $\geq 0.4\ \mu T$ as the highest exposure category.

3. Results

Altogether, 302 addresses met our distance–voltage criteria for site visits and had site visit information collected. Nearly 70% of the residences were single-family homes, 28% apartments or condominiums, and the remainder mobile and multi-family homes. Some 842 lines (individual electrical circuits) were located within 200 m of these 302 residences, ranging from 1 to 16 lines per residence. A majority of homes were located near double-circuit lines. The number of lines per residence by voltage class is shown in Fig. 1. Table 2 summarizes data on distance (m) from residence to the nearest HVTL. Given the study design, the majority of lines were 200 kV and above (Table 2). The number of lines below 100 kV was small (3.6%) as only homes of higher voltages were selected for site visits and information on lower voltages was available only from 2 utilities. Forty-one residences were located within 50 m and 106 residences within 50-150 m of 200+kV lines.

3.1. Calculated magnetic fields model evaluation

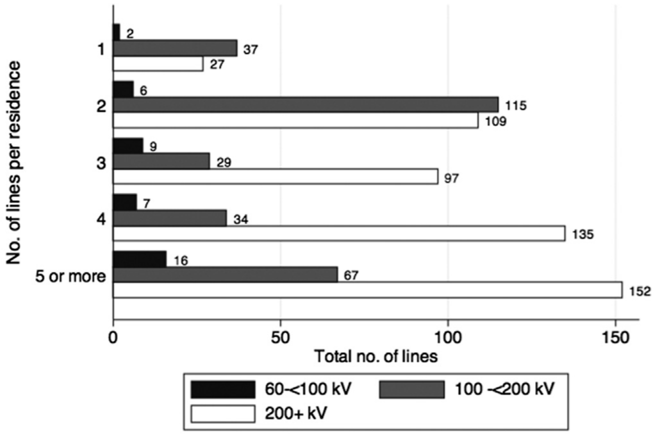
To evaluate the accuracy of our modeling of the residential magnetic fields, we compared measured and calculated fields for the site visit measurement point (Fig. 2) when the needed data were available (e.g. load on the day of measurement). The agreement was good with Pearson correlation coefficient of 0.78. During site visits, we evaluated the presence of local sources (such as underground lines, substations and other circuits) to identify and include in a sensitivity analysis, as the presence of strong local sources influences measured fields. Excluding these observations and those with some load data missing, improved the strength of the correlation between measured and calculated fields for residences with no presence of strong local sources (Pearson coefficient=0.90, $n = 118$).

For each residence we calculated and compared magnetic field levels for the date of birth and the date of diagnosis. The date of birth and date of diagnosis field distributions were very similar to one another (Pearson correlation of 0.98), with only 4 discordances among the 302 residences (1.3%) with respect to classification of $\geq 0.4\ \mu T$.

3.2. Historical extrapolation of transmission line loading data

There were 31 residences for which utilities were able to provide average annual load data for the year of birth for all lines and hence no historical extrapolation of load data was necessary. For the remaining residences, extrapolation was needed for one or more lines. The time interval from year of birth to first year with utility load data available averaged 14 years (SD 5 years) and ranged from 1 to 25 years.

To illustrate the historical load extrapolations, Fig. 3 provides available load data and extrapolations from the two modeling strategies—the no time trend model and the common time trend model—for a set of lines from one utility. In general, the time trend models estimated very gradual trends, with less than a one percent change in loadings per year. As a result, the two modeling strategies yielded similar calculated field estimates, with a Pearson correlation of 0.97 for calculated fields estimated from the no time trend model versus the common time trend model. Comparison of model predictions to historical load values, where available, suggested very good predictive performance of the models, with correlations ranging from 0.82–0.86 for the different utilities. For 65 residences, the utilities also provided their own load extrapolations, which we compared to our extrapolations from the mixed models. There was high agreement between the calculated fields based on utility extrapolations and our mixed models, with Pearson correlations of 0.98 for both the no time trend and common time trend models.



Numbers displayed on end of bars are total by voltage class

Fig. 1. Total number of lines per residence grouped by voltage class.

3.3. Uncertainty in phasing

For the vast majority of residences in the study (Fig. 1), multiple lines need to be taken into account for the calculated field estimation. The relative direction of load flow (0°, 180°) and phasing (−120°, 0°, 120°) among the lines located near a residence can have a significant effect on the magnetic field within the residence. For a number of residences (26/302), this information was unavailable or incomplete for some lines (the missing data was mostly for lines not owned by the four main utilities). In such cases, the onsite spot measurements together with contemporaneous loading data served as input to determine the most likely load direction and phasing, as described in Methods.

For 21 addresses with missing or questionable phasing, magnetic field values were well below $0.4\ \mu T$ regardless of assumed phasing. We examined two cases where classification of $\geq 0.4\ \mu T$ based on the assumption most congruent with all the data might be uncertain. The first case examined has two circuits on a pole about 14 m from a residence (Fig. 4a). With the currents shown, the maximum field modeled under the line was $0.91\ \mu T$, but the

Table 2
Frequency of residences by distance and voltage class.

	< 50 m	50–150 m	150+m	Total
< 100 kV	6 (2.0%)	3 (1.0%)	2 (0.7%)	11 (3.6%)
100–200 kV	56 (18.5%)	59 (19.5%)	5 (1.7%)	120 (39.8%)
200+kV	41 (13.8%)	106 (35.1%)	24 (8.0%)	171 (56.6%)
Total	103 (34.0%)	168 (55.6%)	31 (10.3%)	302 (100%)

Note: Residences were classified by distance to the nearest high voltage line. For those residences equidistant to several lines, the highest voltage among those lines was used.

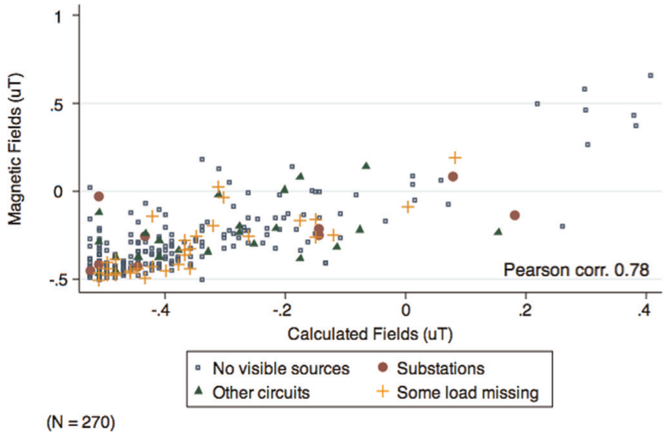


Fig. 2. Spot measurements and calculated fields on the day of site visit.
Note: all data presented are log10 (value + 0.3), adjusted to meet the Pearson linearity assumptions.

measurements yielded 1.23 μT due to a local source that was identified. Having accounted for the local source, which may or may not have impacted the residential field, the circuits were assigned as like-phased (consistent with the measurement), and the field at the residence was calculated as 0.46 μT. A second case (Fig. 4b) introduces a greater uncertainty, much of it surrounding the phase relationships among three lines next to the residence. As shown, the two >200 kV closest to the residence circuits are phased ACB-ACB (top to bottom) but their phase relationship with the two >200 kV single circuit lines is unknown. During the site visit, a field of 0.39 μT was measured 5.5 m from the closest edge of the residence, with contemporaneous load data available only for the >200–300 kV double circuit line (with the others inferred from lines of corresponding description). Field measurements were also performed at the transmission centerline for whenever possible. After evaluating various scenarios, the phasing and load flow direction on the other lines were examined for consistency between calculated fields and the spot measurements made during the site visit. Then, using those phase relationships, a field of 0.55 μT was estimated at the center of the residence applying available or extrapolated historical load data. Even with this uncertainty, both cases would be classified into the high category under most assumptions.

In addition, we examined three cases that might be classified as ≥0.4 μT if alternative phasing was correct. Two of these cases would be classified as below 0.4 μT under the majority of scenarios, and only in one of these cases, the classification might change if alternative phasing is correct. The influence of phasing will be explored in a future sensitivity analysis.

3.4. *Uncertainty in the location of residence*

Our largest uncertainty comes from residences that could not be precisely located or accessed, such as those in large apartment complexes with gated access. We could precisely identify the center of the residence for 73% of homes (Table 3). For about 12% of residences, location was known, but the exact footprint of the apartment or house had to be estimated and thus the uncertainty in this case is minimal. For about 5% precise location of residence within apartment building is not known, and thus calculations of fields and distance was based on the entire building. The largest uncertainty (for another 10%) came for residences within a residential complex with no access, and thus the entire complex was evaluated. Nevertheless, geometric means were similar for all categories. As expected for the closest point for the residences within the complexes, the fields were both higher and with wider confidence intervals.

Ten percent (29/302) of site-visited residences can be classified as above 0.4 μT with relative certainty, since their location was known and calculated fields for the center point exceed this threshold (Table 3). Considering residences with uncertain location, if classification is based on an estimated center point, an additional 2% (6/302) would be classified as above 0.4 μT, whereas if classification is based on the closest point, an additional 8%

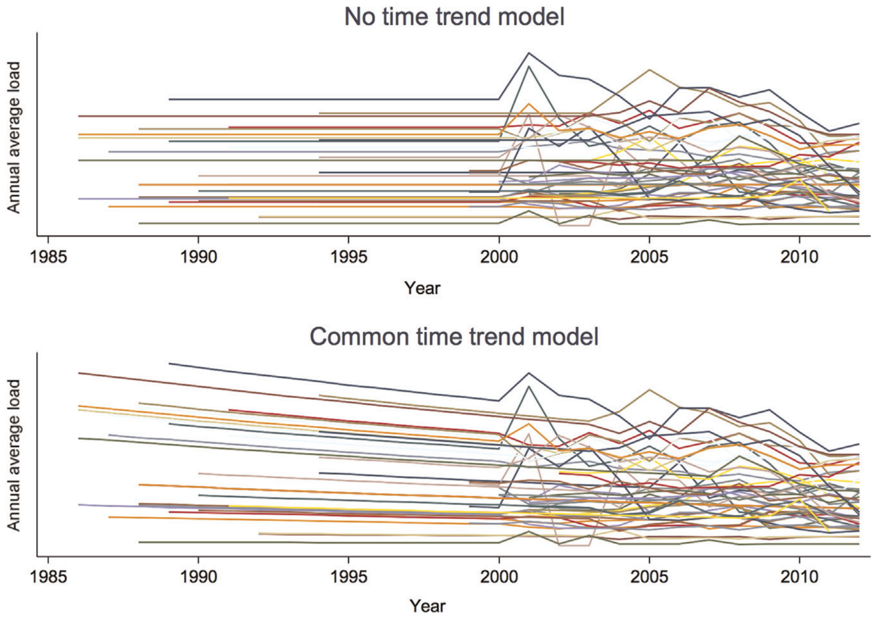


Fig. 3. Example of available annual average loading data and historical extrapolations for a set of lines from one utility from the linear mixed model. Note: indicates relatively minimal impact of historic extrapolation, prior to 2000.

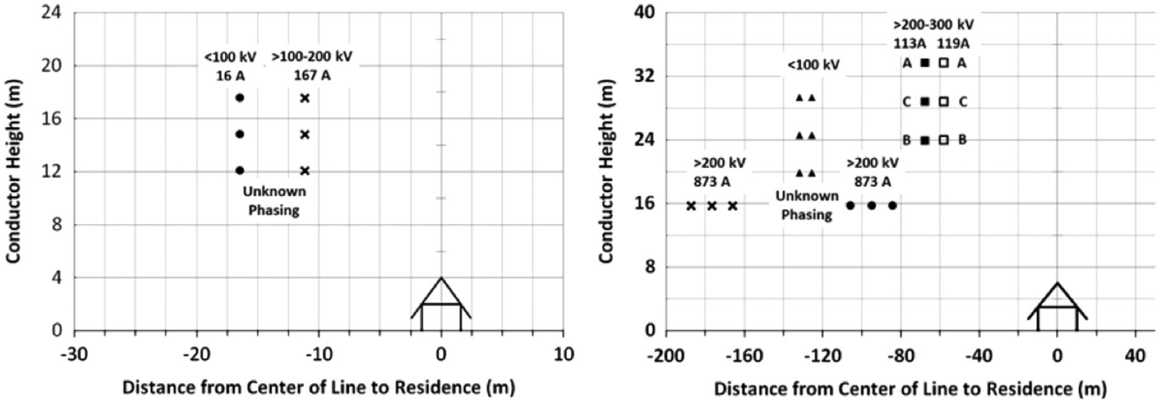


Fig. 4. Two scenarios in which phasing and load flow direction combinations were analyzed to determine the values that produced the optimal match with the measured magnetic fields. The conductor heights represent the attachment heights minus 2/3 of the sags. See text for further description.

(23/302) would exceed this threshold (Table 3). The influence of using center versus closest point on risk estimates for residences with uncertain location will be explored in a future sensitivity analysis.

3.5. *Potential for exposure misclassification*

We examined the potential for misclassification of residences with respect to their magnetic field exposure status—that is, for exposed residences to be misclassified as unexposed or unexposed residences to be misclassified as exposed—due to the various sources of uncertainty. In epidemiology studies, when exposure is rare, misclassifying unexposed individuals as exposed can severely bias relative risk estimates. As specificity (the probability of correctly classifying an unexposed individual as unexposed) decreases, the estimated odds ratio decreases rapidly towards the null. Misclassifying exposed residences as unexposed is also undesirable, but the impact of this type of misclassification on bias is minimal. Hence the first type of misclassification is more concerning.

To investigate the potential for magnetic field exposure misclassification, we compared the proportions of residences with calculated fields $\geq 0.4\,\mu T$ versus $< 0.4\,\mu T$ by the type of uncertainty. Table 4 shows that residences with uncertainty in loading, location of residence within a complex or phasing were somewhat less likely to be classified as exposed $\geq 0.4\,\mu T$. The proportions did not differ significantly for any of the three sources of uncertainty (all $p > 0.2$). Using the uncertainty index, the residences with more sources of uncertainty were less likely to be classified as exposed $\geq 0.4\,\mu T$. Overall, any exposure misclassification due to these sources of uncertainty is not likely to involve misclassifying unexposed individuals as exposed, e.g., is not likely to decrease specificity.

4. Discussion

We provide a detailed description of methods used to calculate magnetic fields from HVTL at residences as part of a large population-based case-control study of childhood leukemia in California.

The advantages of focusing on populations near power lines are threefold. First, by selecting cases through cancer registries and controls from population-based records (such as birth registries), subject participation is not required, thus minimizing selection bias. Second, record-based studies efficiently include large number of subjects. Third, historical magnetic fields within a residence, the exposure measure of primary focus, can be estimated with well-validated computer programs given accurate specifications of circuit configuration, operating characteristics and distance to residence (Zaffanella et al., 1997). Thus, a study design focused on populations adjacent to power line routes combines the advantages of a temporally stable marker (previously, the wire code served this purpose) with the capability of accurately estimating the residential magnetic field due to power lines as the exposure of primary interest.

Table 3
Uncertainty in residence locations of calculated magnetic fields (μT) based on distance from residence to power line.

	Distance from residence to power line						
		Center		Closest		Farthest	
Location of residence	N	GM[a] (CI [b])	n[c] $\geq 0.4\,\mu T$	GM (CI [b])	n[c] $\geq 0.4\,\mu T$	GM (CI [b])	n[c] $\geq 0.4\,\mu T$
Known	221	0.05 (0.04–0.07)	29	0.06 (0.04–0.08)	37	0.03 (0.02–0.04)	18
Uncertain	81	0.05 (0.03–0.07)	6	0.11 (0.07–0.17)	23	0.02 (0.01–0.04)	4
Residence Location Estimated	36	0.06 (0.03–0.11)	4	0.07 (0.03–0.13)	6	0.05 (0.02–0.09)	4
Range for Entire Apartment Building	16	0.03 (0.01–0.13)	0	0.05 (0.01–0.20)	3	0.02 (0.01–0.06)	0
Range for Entire Complex	29	0.05 (0.03–0.09)	2	0.31 (0.19–0.50)	14	0.01 (0.0–0.02)	0

[a] Geometric means of magnetic fields (GM).
[b] 95% Confidence intervals (CI).
[c] Totals of any of the estimates greater than 0.4 μT.

Table 4
Proportions of birth residences classified as exposed at $\geq 0.4\ \mu\text{T}$ versus $< 0.\ 4\ \mu\text{T}$ by uncertainty status.

Source of uncertainty	Classified as $\geq 0.4\ \mu\text{T}$ based on center point n/N (%)
Location	
Residence location known	29/221 (13%)
Residence location known but center estimated	4/36 (11%)
Building location known but location within building uncertain	0/16 (0%)
Complex location known but location within complex uncertain	2/29 (7%)
Loading	
Utility loading data available for all lines	6/31 (19%)
Historical extrapolation of loading required	29/271 (11%)
Phasing	
Phasing known	33/276 (12%)
Phasing based on best guess	2/26 (8%)
By uncertainty score [a]	
0	6/25 (24%)
1	25/216 (12%)
2	4/57 (7%)
3	0/4 (0%)
Total	35/302 (12%)

[a] Uncertainty score was calculated as sum of: 1 point if historical extrapolation of loading required, 1 point if building location known but location within building uncertain or if complex location known but location within complex uncertain, and 1 point if phasing based on best guess.

Accordingly, our study has several advantages: it is entirely based on population-based registries with complete registration of births and cancers, thus eliminating participation and differential information bias (recall bias). Our study is not only large overall, but importantly the number of exposed cases is larger than in all previous studies. In addition, we evaluate distances to power lines extended to 2000 m and include consideration of lower voltages. Our consideration of complex line configurations in the measurement of distance and calculated magnetic fields is another methodologic refinement.

The accuracy of the utility GIS information on distance from transmission lines to residences was generally good. Most discrepancies between utility distances and Google Earth validated distances were minor, and either resolved with Google Earth or verified with site visits. Our model of calculated magnetic fields (using data provided by utilities and collected at site visits) performed well, based on our validation.

The quality of the magnetic field estimate, however, reflects the quality of the input data. Thus, the lack of loading data for a given circuit (or circuits) in the subject's index year represents a potential source of exposure misclassification. Error may vary depending on the time span between the year of interest and the years for which loading data are available. Thus, the error may be relatively modest if data are available for years reasonably close to the year of interest, or appreciably greater if no load data are available and estimates require use of secondary sources for information (e.g., loading on other lines of similar voltage and temporal extrapolation). These errors may also arise from various phasing arrangements on multiple transmission lines within common rights-of-way, direction of load flow, and use of an annual average load which does not capture diurnal and/or seasonal variations.

When multiple transmission lines are present, our approach was to calculate fields using phasing information and a 3-D program. For situations where relative phasing is unknown for multiple lines, one approach is to make separate calculations for individual transmission lines and combine them in quadrature to produce a single resultant. For the present study we obtained phasing for over 90% of the transmission lines. For the remaining lines, we had loading on transmission lines with concurrent residential magnetic field measurements, we computed magnetic field extrema using phasing combinations to arrive at the most likely relative phasing best matching the site visit measurement. This approach produces a more reliable estimate than just adding in quadrature.

These many challenges, however, apply to all studies of calculated fields, with some studies having even less data, thus having to rely only on expert estimate of annual average load (Bessou et al., 2013; Sermage-Faure et al., 2013), others having to extrapolate further back and base estimates on the winter peak predictions (Swanson 2008). Additionally, our various load modeling strategies yielded similar calculated field estimates, and these correlated well with estimates provided by experts.

In either case, previous studies (e.g., Feychting and Ahlbom, 1993) reported positive associations of calculated fields with childhood leukemia based on annual average loading to capture a time-weighted-average metric, and this study geared itself to that same general strategy, with some potential improvements.

Our biggest uncertainties arose from situations where the residence location was estimated, similar to all studies of distance/calculated fields. Unfortunately, not all studies provide enough information to evaluate the extent of this problem, but uncertainty in residence location appears to be an exposure assessment issue also for studies that did evaluate it. In our study, we found similar geometric means regardless of how precisely we were able to locate a residence, however, residences within a complex were somewhat less likely to be classified as exposed $\geq 0.4\ \mu\text{T}$. Our methodology allows us to evaluate to what extent taking closest point versus the center of the residence influences our results. Further, the type of misclassification from residence location uncertainty should not affect the specificity of exposure assessment, key in maintaining our ability to detect an association should one exist.

A potential disadvantage of basing exposure on HVTL is that other sources of residential high magnetic fields are ignored and hence some individuals may be misclassified as not highly exposed. However, when exposure prevalence is low, the odds ratio estimate is more sensitive to false-positive misclassification error than to false-negative error, because false positives arise from a larger group and can easily overwhelm the true positives (Greenland and Lash, 2008). In our study, uncertainty in load, phasing or location lead to residences being slightly less likely to be classified as high exposure. Thus by focusing on high specificity, we designed the epidemiologic study to make bias towards the null unlikely.

We were able to collect and verify a large amount of detailed data on both residences and nearby power lines. Some data items were missing, but only from a small percent of the site-visited sample and a much smaller percent of the overall study. Further, with our approach of creating uncertainty variables, we plan to examine whether data quality influences epidemiologic risk estimates.

5. Conclusions

In conclusion, we describe the exposure assessment methods, including evaluation of distance and calculation of magnetic fields, for a large case-control epidemiologic study of residential proximity to HVTL and childhood leukemia in California. With improvements in exposure assessment and an opportunity to systematically examine biases, we will be able to evaluate the association of distance to and magnetic fields from power lines with childhood leukemia with a greater number of cases in the highest exposure category than was previously possible.

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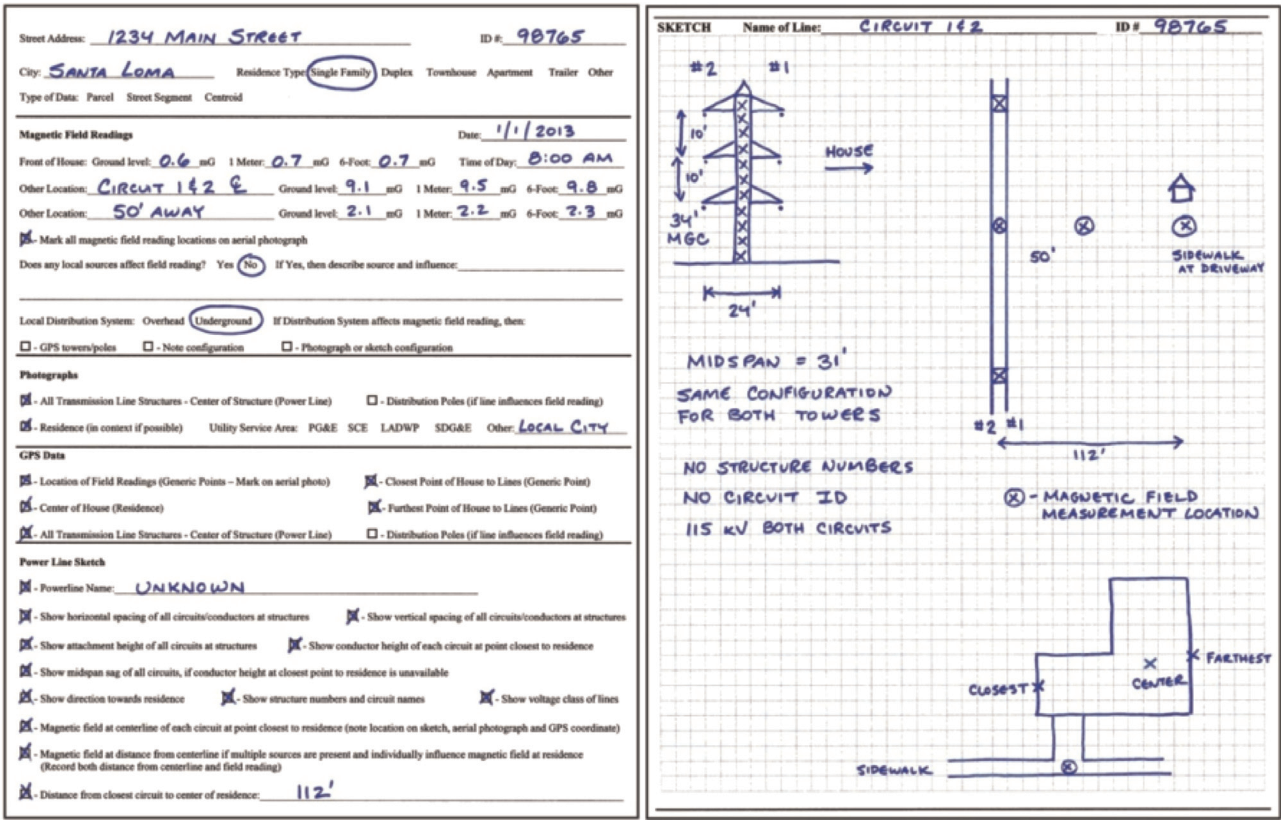
Appendix A.

See Fig A1.



Street Address: 1234 MAIN STREET ID #: 98765

City: SANTA LOMA Residence Type: [✓ Single Family] Duplex Townhouse Apartment Trailer Other

Type of Data: Parcel Street Segment Centroid

Magnetic Field Readings Date: 1/1/2013

Front of House: Ground level: 0.6 mG 1 Meter: 0.7 mG 6-Foot: 0.7 mG Time of Day: 8:00 AM

Other Location: CIRCUIT 1&2 ℄ Ground level: 9.1 mG 1 Meter: 9.5 mG 6-Foot: 9.8 mG

Other Location: 50' AWAY Ground level: 2.1 mG 1 Meter: 2.2 mG 6-Foot: 2.3 mG

☒ - Mark all magnetic field reading locations on aerial photograph

Does any local sources affect field reading? Yes [✓ No] If Yes, then describe source and influence:

Local Distribution System: Overhead [✓ Underground] If Distribution System affects magnetic field reading, then:

☐ - GPS towers/poles ☐ - Note configuration ☐ - Photograph or sketch configuration

Photographs

☒ - All Transmission Line Structures - Center of Structure (Power Line) ☐ - Distribution Poles (if line influences field reading)

☒ - Residence (in context if possible) Utility Service Area: PG&E SCE LADWP SDG&E Other: LOCAL CITY

GPS Data

☒ - Location of Field Readings (Generic Points – Mark on aerial photo) ☒ - Closest Point of House to Lines (Generic Point)

☒ - Center of House (Residence) ☒ - Furthest Point of House to Lines (Generic Point)

☒ - All Transmission Line Structures - Center of Structure (Power Line) ☐ - Distribution Poles (if line influences field reading)

Power Line Sketch

☒ - Powerline Name: UNKNOWN

☒ - Show horizontal spacing of all circuits/conductors at structures ☒ - Show vertical spacing of all circuits/conductors at structures

☒ - Show attachment height of all circuits at structures ☒ - Show conductor height of each circuit at point closest to residence

☒ - Show midspan sag of all circuits, if conductor height at closest point to residence is unavailable

☒ - Show direction towards residence ☒ - Show structure numbers and circuit names ☒ - Show voltage class of lines

☒ - Magnetic field at centerline of each circuit at point closest to residence (note location on sketch, aerial photograph and GPS coordinate)

☒ - Magnetic field at distance from centerline if multiple sources are present and individually influence magnetic field at residence (Record both distance from centerline and field reading)

☒ - Distance from closest circuit to center of residence: 112'

SKETCH Name of Line: CIRCUIT 1&2 ID # 98765

MIDSPAN = 31'

SAME CONFIGURATION FOR BOTH TOWERS

NO STRUCTURE NUMBERS

NO CIRCUIT ID

115 kV BOTH CIRCUITS

⊗ - MAGNETIC FIELD MEASUREMENT LOCATION

Fig. A.1. Sample of residential site visit data sheets—Left: site visit checklist, Right: power line sketch sheet.

References

Bessou, J., Deschamps, F., et al., 2013. Methods used to estimate residential exposure to 50 Hz magnetic fields from overhead power lines in an epidemiological study in France. J. Radiol. Prot. 33 (2), 349–365.

Bunch, K.J., Keegan, T.J., et al., 2014. Residential distance at birth from overhead high-voltage powerlines: childhood cancer risk in Britain 1962-2008. Br. J Cancer 110 (5), 1402–1408.

Draper, G., Vincent, T., et al., 2005. Cancer in relation to distance from high voltage power lines in England and Wales: a case-control study. BMJ 330 (7503), 1290.

EPRI, 2013. The EMF Workstation Software Help System User Manual: Versions 2010–2013. Electric Power Research Institute (EPRI), Palo Alto, CA.

Feychting, M., Ahlbom, A., 1993. Magnetic fields and cancer in children residing near Swedish high-voltage power lines. Am. J. Epidemiol. 138 (7), 467–481.

Google, 2014. Google Earth Software. Mountain View, CA.

Greenland, S., Lash, T., 2008. Bias Analysis. In: Rothman, K.J., Greenland, S., Lash, T. (Eds.), Modern Epidemiology. Lippincott Williams and Wilkins, Philadelphia, PA.

Hatch, E.E., Kleinerman, R.A., et al., 2000. Do confounding or selection factors of residential wiring codes and magnetic fields distort findings of electromagnetic fields studies? Epidemiology 11 (2), 189–198.

IARC, 2002. Non-ionizing radiation Part 1: Static and extremely low-frequency (ELF) electric and magnetic fields. World Health Organization, pp. 1–397.

Kavet, R., 1995. Magnetic Field Exposure Assessment. In: Blank, M. (Ed.), Electromagnetic Fields: Biological Interactions and Mechanisms. American Chemical Society, Washington, DC, p. **250**.

Kavet, R., Silva, J.M., et al., 1992. Magnetic field exposure assessment for adult residents of Maine who live near and far away from overhead transmission lines. Bioelectromagnetics 13 (1), 35–55.

Kheifets, L., Crespi, C.M., et al., 2013. Epidemiologic study of residential proximity to transmission lines and childhood cancer in California: description of design, epidemiologic methods and study population. J. Expo. Sci. Environ. Epidemiol.

Kheifets, L.I., Kavet, R., et al., 1997. Wire codes, magnetic fields, and childhood cancer. Bioelectromagnetics 18 (2), 99–110.

Kroll, M.E., Swanson, J., et al., 2010. Childhood cancer and magnetic fields from high-voltage power lines in England and Wales: a case-control study. Br. J. Cancer 103 (7), 1122–1127.

Levallois, P., Gauvin, D., et al., 1995. Electric and magnetic field exposures for people living near a 735-kilovolt power line. Environ. Health Perspect. 103 (9), 832–837.

London, S.J., Thomas, D.C., et al., 1991. Exposure to residential electric and magnetic fields and risk of childhood leukemia. Am. J. Epidemiol. 134 (9), 923–937.

Lowenthal, R.M., Tuck, D.M., et al., 2007. Residential exposure to electric power transmission lines and risk of lymphoproliferative and myeloproliferative disorders: a case-control study. Int. Med. J. 37 (9), 614–619.

Maslanyj, M., Simpson, J., et al., 2009. Power frequency magnetic fields and risk of childhood leukaemia: misclassification of exposure from the use of the 'distance from power line' exposure surrogate. Bioelectromagnetics 30 (3), 183–188.

McCulloch, C., Searle, S., 2001. Generalized, Linear and Mixed Models. John Wiley and Sons, New York, NY.

Mezei, G., Spinelli, J.J., et al., 2008. Assessment of selection bias in the Canadian case-control study of residential magnetic field exposure and childhood leukemia. Am. J. Epidemiol. 167 (12), 1504–1510.

Oksuzyan, S., Crespi, C.M., et al., 2012. Birth weight and other perinatal characteristics and childhood leukemia in California. Cancer Epidemiol. 36 (6), e359–e365.

Oksuzyan, S., Crespi, C.M., et al., 2013. Birth weight and other perinatal factors and childhood CNS tumors: a case-control study in California. Cancer Epidemiol. 37 (4), 402–409.

Olsen, J.H., Nielsen, A., et al., 1993. Residence near high voltage facilities and risk of cancer in children. BMJ 307 (6909), 891–895.

Rankin, R.F., Bracken, T.D., et al., 2002. Results of a multisite study of U.S. residential magnetic fields. J. Expo. Anal. Environ. Epidemiol. 12 (1), 9–20.

Pedersen, C., Raaschou-Nielsen, O., et al., 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.

Savitz, D.A., Wachtel, H., et al., 1988. Case-control study of childhood cancer and exposure to 60-Hz magnetic fields. Am. J. Epidemiol. 128 (1), 21–38.

Sermage-Faure, C., Demoury, C., et al., 2013. Childhood leukaemia close to high-voltage power lines–the Geocap study, 2002–2007. Br. J. Cancer 108 (9), 1899–1906.

Severson, R.K., Stevens, R.G., et al., 1988. Acute nonlymphocytic leukemia and residential exposure to power frequency magnetic fields. Am. J. Epidemiol. 128 (1), 10–20.

Swanson, J., 2008. Methods used to calculate exposures in two epidemiological studies of power lines in the UK. J. Radiol. Prot. 28 (1), 45–59.

Tynes, T., Haldorsen, T., 1997. Electromagnetic fields and cancer in children residing near Norwegian high-voltage power lines. Am. J. Epidemiol. 145 (3), 219–226.

Verkasalo, P.K., Pukkala, E., et al., 1993. Risk of cancer in Finnish children living close to power lines. BMJ 307 (6909), 895–899.

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

Wertheimer, N., Leeper, E., 1982. Adult cancer related to electrical wires near the home. Int. J. Epidemiol. 11 (4), 345–355.

Zaffanella, L.E., Kavet, R., et al., 1997. Modeling magnetic fields in residences: validation of the resicalc program. J. Expo. Anal. Environ. Epidemiol. 7 (2), 241–259.