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Possible Health Benefits from Reducing Occupational Magnetic Fields
SUPPORTING INFORMATION
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The online Supplemental Information describes in detail the mathematical calculations in this risk assessment and derives all original formulas used in this paper.

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A. Dose-Response Functions for Cancer Mortality and Incidence

As discussed in the main paper, the dose-response (DR) functions for brain cancer and leukemia from exposures to occupational magnetic fields (MF) were calculated by combining the original data from five electric utility studies.[1] For both cancers, logistic regression with a log-linear model was used with matched case-control data to estimate odds ratios, which Kheifets et al. called "relative risks" under the rare-disease assumption. The resulting relative risks (RR) have an exponential dependence on the worker's cumulative exposure C:

$$RR = \exp[\beta C] = RR'^{\,C/10} \qquad \text{(S1)}$$

where $RR' \equiv \exp(10\beta)$ is the DR slope. These slopes are given in Table III of the main paper, along with their published confidence limits and the resulting p-values from a one-tailed test: $p = 1 - N[2\, z_{0.975} \ln RR' / \ln(UCL/LCL)]$ where N is a cumulative normal distribution.

The cumulative exposure C was calculated from the time-weighted average (TWA) magnetic field B_j from a job j multiplied by the time period Δt_j of employment:

$$C = \sum_{j=1} \Delta t_j \times B(t_j - 1\ \text{yr}) \qquad \text{(S2)}$$

where the time of exposure is lagged by one year.

For high cumulative exposures, we use a linear dose response model RR = a + bC, as explained in the main paper. The slope and intercept are fixed so that the linear and exponential models are equal in RR and slope d(RR)/dC at a transition point on the outer tail of the exposure distribution (Figure 2 in the main paper). A reasonable choice for this transition point is the cumulative exposure at which the exponential model equals the relative risk $RR_{hi\,C}$ in the highest exposure category ($C \geq 16$ μT-yr) from the electric utility studies (Table II and Figure 2). With these conditions, the linear RR model becomes:

$$RR_{lin}(C) = RR_{hi\,C}\left[1 + \frac{C}{10} \ln RR' - \ln RR_{hi\,C}\right] \qquad \text{(S3)}$$

for $C \geq 10$ μT-yr $\ln RR_{hi\,C} / \ln RR'$. The transition points are 51.2 μT-yr brain cancer and 41.1 μT-yr for leukemia.

Annual mortality rates λ_M and incidence rates λ_I are calculated for a given cumulative MF exposure by multiplying the appropriate DR function (eqs. S1 or S3) with the corresponding baseline rate λ_0:

$$\lambda_{M/I}(C) = \lambda_{M0/I0}\, RR(C) \qquad \text{(S4)}$$

The baseline incidence / mortality rates $\lambda_{M0/I0}$ for cancer depend on age and are reported by the U.S. government as averages over five-year age spans from ages 0-5 to 100+ years. For occupational exposures, we start the cancer rate calculations with ages 20-25 (Table S1).

Derivation of 5-year Average Cumulative Exposures with a 1-year Lag Time

Because age-dependent cancer mortality and incidence rates are reported as averages over five-year spans, the lagged cumulative exposure for age span i:

$$C(i) = \sum_{j=1}^{i} 5\ \text{yr} \times B(t_j - 1)$$

must also be averaged over the same five-year spans.

To derive the average cumulative exposure with a 1-year lag time, first define the cumulative magnetic field exposure of a continuous time t with a one-year lag:

$$C(t) = \int_0^t B(\tau - 1)\, d\tau$$

If $B(\tau)$ is a series of constant exposures B_i for five-year spans $\tau_i \in [5i\text{-}5, 5i | i \geq 1]$, then the instantaneous cumulative exposure is the piece-wise function in Figure S1 where each line segment has a slope B_i.

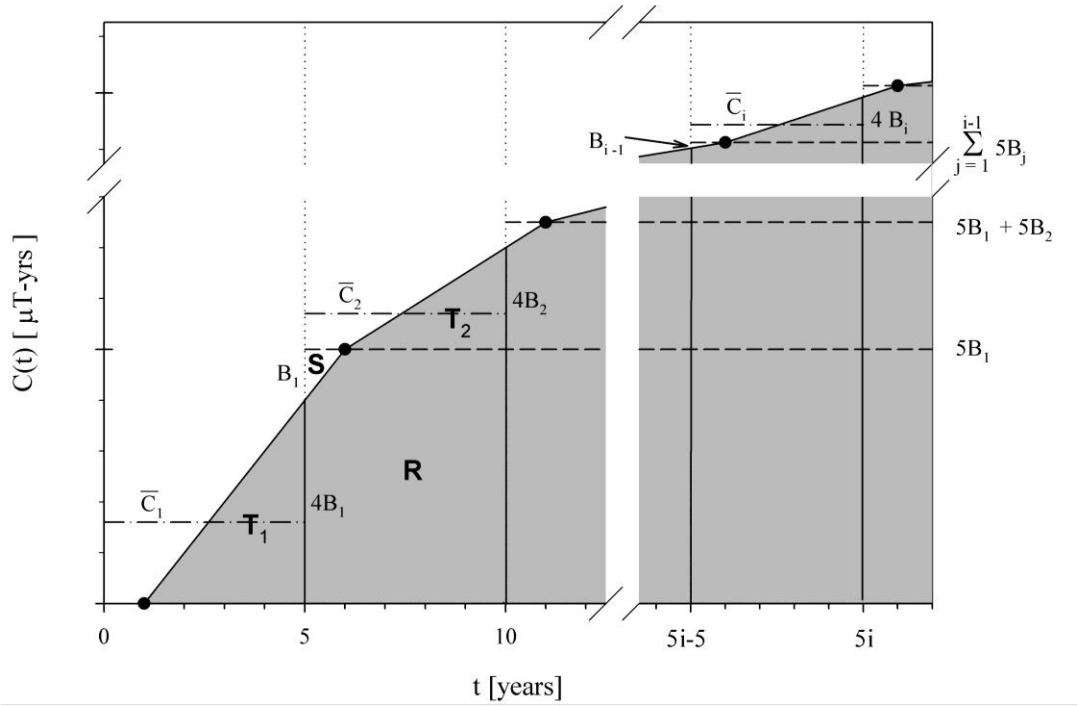

Figure S-1. Graphic derivation of the average cumulative exposure.

The areas of the triangles $\mathbf{T}_i$ and **S** and the rectangle **R** are used to derive average cumulative exposures $\overline{C}_i$ (dash-dot lines) for the 5-year spans [5i-5, 5i].

In order to calculate lifetime disease risks as sums of 5-year average mortality or incidence rates, we must also average the cumulative magnetic fields over the same 5-year age spans: $\overline{C}_i = \frac{1}{5}\int_{5i-5}^{5i} C(t)dt$.

By inspecting Figure S-1, this integral for i=1 can be expressed as the area of triangle $\mathbf{T}_1$:

$$\overline{C}_1 = \frac{1}{5}(\text{Area of Triangle } T_1) = \frac{1}{5}\left(\frac{1}{2}\text{base}\times\text{height}\right) = \frac{1}{5}\left(\frac{1}{2}4\times 4B_1\right) = \frac{8}{5}B_1$$

Similarly,

$$\bar{C}_2 = \frac{1}{5}\ (\text{Triangle } T_2 \text{ -Triangle S } + \text{ Rectangle R})$$

$$= \frac{1}{5}\left[8B_2 - \frac{1}{2}B_1 + 25B_1 \right] = \frac{8}{5}B_2 - \frac{1}{10}B_1 + 5B_1$$

and

$$\bar{C}_i = \frac{8}{5}B_i - \frac{1}{10}B_{i-1} + \sum_{j=1}^{i-1} 5B_j$$

for i = 2, 3….

Computations are more efficient if we use the iterative form of the expression above:

$$\bar{C}_i = \bar{C}_{i-1} + \frac{8}{5}B_i + \frac{33}{10}B_{i-1} + \frac{1}{10}B_{i-2}$$

for i = 3, 4…

If B_i is a constant B for an entire working career from ages 20-64 (i=1-9) and zero after retirement ($i \leq 10$), then:

$$\bar{C}_1 = \frac{8}{5}B$$

$$\bar{C}_i = \left(5i + \tfrac{3}{2}\right)B \qquad \text{for i = 2,3...9} \qquad \text{(S5)}$$

$$= \bar{C}_{i-1} + 5B \qquad \text{for i = 3,4...9}$$

$$\bar{C}_{10} = \bar{C}_9 + 3\tfrac{2}{5}B = 44\tfrac{9}{10}\ B$$

$$\bar{C}_{11} = \bar{C}_{10} + \tfrac{1}{10}B = 45\ B$$

In other words, the cumulative exposure is (5i – 3/2)B for 5-year periods up to retirement, and 45B after age 70 when workplace exposures have ceased. Digital values for this series is given in Table S-I where B = 1 μT.

B. Lifetable Calculation of Excess Cancer Mortality and Incidence

The increased mortality / incidence rate from a history of TWA exposures {B(j)| j=1,i} can then be calculated by substituting the average lagged cumulative exposure C(i) (eq. S5) into the DR model (eq. S1):

$$\lambda_{M/I}\left(i, C(i)\right) = \lambda_{M/I,\,0}(i)\ RR'^{\,C(i)/10} \qquad \text{(S6)}$$

The DR is then used to calculate the *excess lifetime mortality rates* attributable to a TWA magnetic field exposure. The calculation started with the government's life-table for the U.S. population.[2] In particular, we used the published values for the probability q_{0i} of dying from any cause during the i^{th} five-year interval, the life expectancy e_i at the interval's beginning, and the number of people l_i surviving from a cohort of 100,000 at age 20 (Table S-I).

To perform a life table calculation with a hazardous exposure, [3] we converted the published number of survivors l_i to the *survival function*: $S_0(20,i) = l_i / l_{20\text{-}24}$, which is the probability of a 20-year old worker surviving to start of the i^{th} age interval. Next, the mortality probability q_i over each interval is converted into the average annual mortality rate from all causes $\lambda_{M0}(i)^*$, using a relationship derived from the differential equation (*i.e.* continuous time) model for life expectancy:[4]

$$\lambda_{M0}(i)^* = 100{,}000\ \ln\left(1-q_{0i}\right)\Big/\ 5\ \text{yr}\,. \qquad \text{(S7)}$$

In the absence of exposure, the age-specific mortality rates from a cancer are then the number of workers surviving to interval's onset = 100,000 $S_0(20,i)$ multiplied by the probability of dying within the five-year span = q_{0i} multiplied by the fraction of the all-cause mortality rate due to the cancer. The *lifetime mortality rate* from the cancer in the absence of MF exposures can now be calculated:

$$M_0 = 100{,}000 \sum_i S_0\left(20,i\right)\ q_{0i}\ \frac{\lambda_{M0}(i)}{\lambda_{M0}(i)^*} \qquad \text{(S8)}$$

where the sum is from ages 20-24 to 100+, the last age group in the published life table.

Table S-I. Lifetable spreadsheet for the years of life lost (YLL).

Segments of the spreadsheet for calculating the excess mortality and YLL for an assumed TWA magnetic field. (Columns for intermediate variables and for leukemia are not shown.)

Age	Assume TWA = 1 μT		Population life table		Brain and other CNS cancers			
	TWA magnetic field (μT)	Cumulative exposure C(i) (μT-yr)	All-cause mortality rate $\lambda_M(i)$* (per 100,000 per yr)	Survival function S(20,i)	RR′ = 1.13 per μT-yr RR for C(i)	Cancer mortality rate $\bar{\lambda}_M(i)$ (per 100,000 per yr)	5-yr excess mortality $M_x(i)$ (per 100,000 exposed)	YLL(i) per 100,000 exposed (yr)
20-24	1	1.6	96.4	1.000	1.02	0.57	0.1	3
25-29	1	6.5	95.2	0.995	1.08	0.77	0.3	15
30-34	1	11.5	111.1	0.990	1.15	1.24	0.8	40
35-39	1	16.5	158.3	0.985	1.22	1.86	1.7	77
40-44	1	21.5	241.3	0.977	1.30	2.82	3.4	136
45-49	1	26.5	360.5	0.965	1.38	4.05	6.0	212
50-54	1	31.5	519.8	0.948	1.47	6.06	10.6	323
55-59	1	36.5	765.6	0.924	1.56	8.40	16.6	436
60-64	1	41.5	1,195.4	0.889	1.66	11.33	24.3	541
65-69	0	44.9	1,804.8	0.838	1.73	14.38	31.1	574
70-74	0	45.0	2,786.9	0.765	1.73	17.53	33.8	504
75-79	0	45.0	4,397.1	0.666	1.73	19.62	31.4	370
80-84	0	45.0	7,096.0	0.534	1.73	19.86	23.8	215
85-89	0	45.0	10,999.9	0.375	1.73	16.18	12.3	84
90-94	0	45.0	17,318.7	0.216	1.73	16.18**	6.1	+
95-99	0	45.0	26,696.3	0.091	1.73	16.18**	2.1	+
100+	0	45.0	26,696.3*	0.024	1.73	16.18**	0.7	+
Lifetime totals							**205.2**	**3,529**

*Assumed to be the same as 95-99.

**Assumed to be the same as 85+.

+Following procedures in Ref. 32, the YLL calculation is truncated at age 90.

The next step in the calculation is mortality rates with magnetic field exposures. The baseline rates from all causes (eq. S7) are adjusted for the excess death rates for both brain cancer and leukemia in each time period (eq. S6):

$$\lambda_M(i,B)^* = \lambda_{M0}(i)^* + \lambda_{M0}(\text{brain, i})[RR_{brain}(i,B)-1] + \lambda_{M0}(\text{leuk, i})[RR_{leuk}(i,B)-1] \quad \text{(S9)}$$

Then, the age-specific probabilities of death with MF exposures are derived by re-arranging eq. S7 and replacing the annual death rates with eq. S9:

$$q_i = 1\text{- exp}\left(-\lambda_M(i,B)^* \, 5 \text{ yr} \Big/ 100{,}000\right) \quad \text{(S10)}$$

The survival function has a similar adjustment for the additional cancer deaths:

$$S(20,i) = S_0(20,i)\prod_{j=0}^{i-1}\exp\left[-\left(\lambda_M(i,B)^* - \lambda_{M0}(i)^*\right)5 \text{ yr} \Big/ 100{,}000\right] \quad \text{(S11)}$$

Paralleling eq. S8, the lifetime mortality rate from a particular cancer for exposed workers is now:

$$M(B) = 100{,}000 \sum_i \frac{\lambda(i,B)}{\lambda(i,B)^*} q_i \, S(20,i) \quad \text{(S12)}$$

For a given history of 5-year TWA exposures over a working career, a spreadsheet (Table S-I) calculates the numbers of excess cancer cases across age strata and, from this, the lifetime excess mortality risks $M_x(B) = M(B) - M_0$ from brain cancer and leukemia.

To calculate the excess cancer incidence, the results comparable to life-table formulas are:

$$I_0 = \sum_i 5 \text{ yr } \lambda_{I0}(i) \, S_0(0,i) \quad \text{(S13)}$$

$$I(B) = \sum_i 5 \text{ yr } \lambda_I(i,B) \, S(0,i)$$

from which the lifetime excess incident rates: $I_x(B) = I(B) - I_0$ can be calculated for brain cancer and leukemia as a function of the TWA magnetic field.

Baseline Mortality and Incidence Rates Corrected for U.S. MF Exposures

Age-specific cancer mortality and mortality rates $\lambda_{M/I}(i)$ can be obtained from National Center for Health Statistics (NCHS) [5] and the Surveillance, Epidemiology, and End Results (SEER) program.[6] However, the published rates are presumably greater than the no-exposure rates $\lambda_{M/I,\,0}(i)$, due to the cancers from workplace MFs. Accordingly, the published cancer mortality rates are averages of the exposure-specific rates (eq. S4) over the distribution of MF exposures for U.S. workers:

$$\bar{\lambda}_{M/I}(i) = \sum_n p_n(i)\,\lambda_{M/I,\,0}(i)\; RR'^{\,C_n(i)/10} \qquad \text{(S14)}$$

where $p_n(i)$ is the proportion of workers in age group i with cumulative exposure $C_n(i)$. However, the best available MF data for the general working population are not cumulative exposures but measurements of the TWA by a 1000-person randomized surveillance study in the U.S.[7] To get baseline (no-exposure) cancer rates to use in eq. S6 and the formulas that follow, we assume that the NIOSH exposure scenario applies to all workers in the U.S. Therefore, the constant exposure formulas for the cumulative exposure in Section A.1 can be substituted into eq. 8, and solved for the no-exposure rates as a function of the published rates. For ages 25-64 (i=2-9), for example, the baseline rates are:

$$\lambda_{M/I,\,0}(i) = \bar{\lambda}_{M/I}(i) \Big/ \sum_n p_n\; RR'^{\,(5i\,-\,3/2)B_n/10} \qquad \text{(S15)}$$

where p_n is now the proportion of workers with mean TWA exposure B_n.

To use this equation, we derived a categorical MF distribution $\{p_n, B_n\}$ from the published percentiles Pn for n=1,5,10,25,50 etc.[7] as shown in Table S-III and Figure S-2. This distribution is approximately log-normal because its median P50 = 0.099 μT is closer to the geometric mean = 0.103 μT than to the arithmetic mean = 0.173 μT. Therefore, the mean exposure for a category between two successive percentiles Pn_1 and Pn_2 is well represented by the geometric mean of the percentiles $B_n = \sqrt{Pn_1\ Pn_2}$.

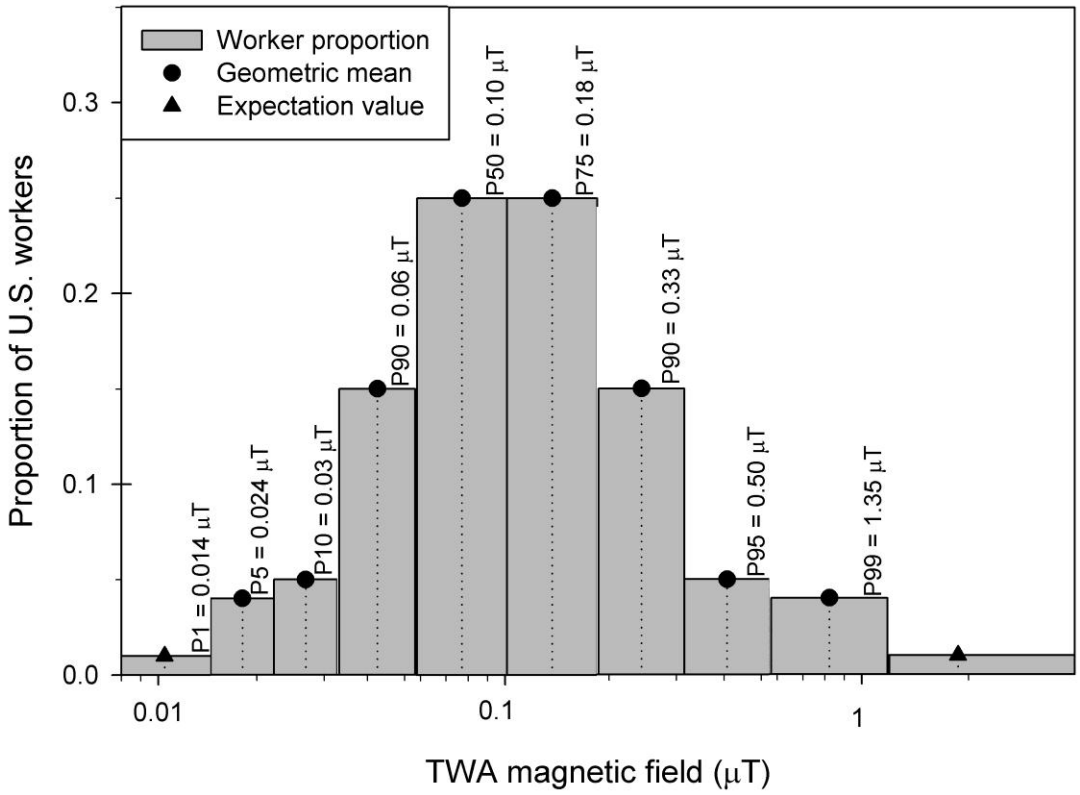

Figure S-2. Categorical distribution of occupational magnetic field exposures derived from the percentiles Pn of measurements from a random sample (N=525) of the U.S. population.[30]

The proportion of workers in this category is $p_n = [n_2 – n_1]/100$. The mean exposures for the tails of the distribution (< P1 and > P99) are the expectation values of B from a log-normal distribution with the above geometric mean and the measured geometric standard deviation = 2.57.[7]

The resulting MF distribution $\{p_n, B_n\}$ is then substituted in eq. S15 in order to obtain baseline incidence and mortality rates for the lifetable calculations (Section B).

C. Calculating Disability-adjusted Life Years (DALY)

DALYs are calculated as the sum of the years of life lost due to premature mortality (YLL) in the population and the adjusted "years lived with disability" (YLD) for incident cases of the health condition:

$$\mathrm{DALY}(B) = \mathrm{YLD}(B) + \mathrm{YLL}(B) \qquad \text{(S16)}$$

First, YLL is calculated from the published age-specific life-expectancy e_i and the excess cancer deaths for all five-year age intervals:

$$\mathrm{YLL}(B) = \sum_i e_i \, M_x(i,B) \qquad \text{(S17)}$$

where the sum goes up to 90 years of age.

Next, YLD are calculated from the age-specific excess incidence $I_x(I,B)$ (eq. S13) for brain cancer and the four major sub-types of leukemia (acute and chronic myeloid leukemia; acute and chronic lymphocytic leukemia), plus all other leukemia sub-types grouped together. For each of these cancer sub-types, the formula for YLD then combines the incidence rates, the probability of surviving with the cancer S_p, and disability weights DW_j provided by a burden of disease study in Victoria, Australia:[8, 9]

$$\mathrm{YLD}(B) = \sum_i I_x(i,B)\left[S_p \sum_{j=1}^{J} DW_j \, \Delta t_j + (1 - S_p) \sum_{k=1}^{K} DW_k \, \Delta t_k \right] \qquad \text{(S18)}$$

where the index j=1 … J goes over time intervals Δt_j from the cancer's diagnosis to its remission and the index k=1 … K goes from diagnosis to premature death from the cancer.

Discounted DALYs

With a discount rate = d, the discounted YLL and YLD are:

$$YLL_d(B) = \sum_i e_i \, M_x(i,B) \frac{1-\exp[-d\, e_i]}{d} \tag{S19}$$

$$YLD_d(B) = \sum_i I_x(i,B) \left[\begin{array}{l} S_p \sum_{j=1}^{J} DW_j \; \frac{\exp(1-d\,\Delta t_j)}{d} + \\ (1-S_p) \sum_{k=1}^{K} DW_k \; \frac{\exp(1-d\,\Delta t_j)}{d} \end{array} \right]$$

To re-capitulate all the steps in this preceding sections, Table S-II compiles a calculation for a single age range and TWA = 1 μT.

D. Quantification of Uncertainties

We first identified all sources of variability and error in our risk metrics and when possible, quantified the uncertainty of the input variables for the risk calculations (Table III in the main paper). The quantified uncertainties fall into two groups – the DR parameters and exposure distribution whose statistical properties can be rigorously characterized, and the parameters for which we only have a range of possible values (the monetary value of the DALY and the posterior probability). For the DR parameters, our uncertainty analysis consisted of a rigorous propagation of errors,[11] which results in 95% confidence limits and one-tailed hypothesis tests. For the more poorly characterized parameters, our sensitivity analysis also used the propagation of error formulas, but with approximate standard errors derived from the range of possible values. The limits derived from these more approximate error estimates have been called *uncertainty limits.*[12]

For the sensitivity analysis, random errors are quantified as the variable's standard error (SE), and systematic errors are given as the bias $\delta \equiv x_{true} - \bar{x}$ (where x_{true} is an estimate of the true value and $\bar{x}$ is the mean used in our primary metric calculations). For the DR

.

Table S-II. Sample calculation of the discounted DALYs (per 100,000 exposed)

Variable	Symbol	Equation #	Brain cancer		Leukemia	
Age span			55-59	Lifetime (20 - 100+ yr)	55-59	Lifetime
Age index	i		7			
TWA magnetic field (uT)	B	Input	1.0			
Cumulative Exposure (uT-yr)	C	S5	36.5	45.0		
All-cause mortality						
Probability of death	q_{0i}	Input	0.0376		same values as brain cancer	
Survival function w/o exposure	$S_0(20,i)$	Input	0.9239			
Survival function with exposure	S(20,i)	S11	0.9232			
Annual mortality rate w/o exposure	$\lambda_{M0}(i)$*	S7	765.63			
Rate with MF exposure	$\lambda_{M0}(I,B)$*	S9	771.82			
Cancer						
DR slope	RR'	Input	1.13		1.10	
Relative risk	RR(C)	S1	1.56	1.73	1.42	1.53
Mortality						
Annual rate for US population	$\bar{\lambda}_M(i)$	Input	8.4002		7.4721	
Rate with no MF exposures	$\lambda_{M0}(i)$	S15	6.5167		6.0641	
Exposure-free mortality	M_0	S8	29.536	332.07	27.484	673.53
Excess mortality	$M_x(B)$	S12+	16.563	205.24	11.400	327.88
Life expectancy w/o exposure (yr)	e_i	Input	26.3074		26.3074	
Years of life lost	YLL(B)	S17	435.72	3,529.2	299.89	4,306.7
Discounted YLL	$YLL_d(B)$	S19	301.33	2,613.8	207.40	3,252.6
Incidence						
Annual rate for US population	$\bar{\lambda}_I(i)$	Input	11.100		16.047	
Rate with no MF exposures	$\lambda_{I0}(i)$	S15	8.611		13.023	
Exposure-free incidence	I_0	S13	39.780	445.41	60.162	1,080.2
Excess incidence	$I_x(B)$	S13+	22.317	245.17	24.966	512.96
Excess incidence for leukemia subtypes:**				Acute lymphocytic leukemia:	1.531	17.58
				Chronic lymphocytic leukemia:	9.860	194.65
				Acute myelogenous leukemia:	7.537	157.27
				Chronic myelogenous leukemia:	2.808	64.21
				Other subtypes:	3.230	79.25
Year lost to disability	YLD(B)	S18	11.17	117.72	26.95	398.52
Discounted YLD	$YLD_d(B)$	S19	10.93	115.15	25.75	380.77
Disability adjusted life years	DALY(B)	S16	446.89	3,646.9	326.84	4,705.2
Discounted DALY	$DALY_d(B)$	S16	312.26	2,728.9	233.14	3,633.4

+Equation is in following paragraph.

**Calculated with the above incidence formulas using the appropriate annual U.S. rates as input

parameters, the random errors from chance and inter-study variability among the five electric utility studies[1] can be quantified from the 95% confidence limits on the relative risks (Table III). Since the pooling of the five epidemiologic databases is a large sample (291 cases of brain cancer and 348 cases of leukemia), normal distributions can be assumed for the logs of the relative risks in the dose-response functions: $\ln RR'/10 \equiv \beta$ (eq. 1) and $\ln RR_{hi\,C} \equiv \beta_{hi}$ (eq. 4). Using the published confidence levels on the relative risks, the standard errors for these beta coefficients can then be calculated from:

$$SE_{\beta} = \frac{\ln(UCL/LCL)}{2z_{0.975}} \qquad (S24)$$

The biases in these DR coefficients could be quantified in two cases – first for the "single company bias" where the electric utility studies[1] calculated their subjects' lifetime cumulative MF exposure from their employment at a single company (see Methods in the main paper for more details). To quantify this single company bias in the β coefficients (brain cancer and leukemia, DR slope and highest exposure category), we first observe that the electric utility studies report employment durations that average 21.8 yrs, which does not correspond with the 60 yr. median age of the cancer diagnosis or death.[1] To estimate the resulting bias, a better figure for the employment duration is the U.S. population average of 36.9 yr.[13] Now, assume the epidemiologic studies accurately observed the relative risks and the TWA magnetic fields on average, so the observed and true employment duration T are related by:

$$RR_{obs} = \exp \beta_{obs} C_{obs} \approx \exp \beta_{obs} T_{obs} B_{obs} = \exp \beta_{true} T_{true} B_{obs}$$

So the bias is:

$$\delta \equiv \beta_{true} - \beta_{obs} = \beta_{obs}\left(\frac{T_{obs}}{T_{true}} - 1\right)$$

where β_{obs} and T_{obs} are the values from the combined electric utility studies,[1] and T_{true} is the U.S. average. The results are in Table S-II.

Another quantifiable bias comes from the reported synergism between elevated occupational MFs and selected chemicals in a brain cancer study.[14] For lead, mercury,

pesticides/herbicides, solvents, and arsenic, the bias δ in the brain cancer risks for the highest exposure category (β_{hi}) can be estimated from the difference between the significant βs with and without that chemical exposure. These bias estimates for β_{hi} are extended to the DR β by using the formula for the brain cancer's exponential-linear transition point (eq. S3): 51.2 μT-yr = 10 μT-yr ln $RR_{hi\,C}$ / ln $RR' = \beta_{hi} / \beta$. By assuming that the chemical exposure does not change the transition point, we get the bias in the DR slope as: $\delta = \delta_{hi}$ / 51.2 μT-yr for each chemical (Table S-III). For the metrics like the population attributable fraction and the U.S. disease burden, the bias δ_c for each chemical c is weighted by the proportion of workers exposed p_c, which we estimate from the proportion of cases $p_c = N_c / N_{total}$ exposed in Navas-Acien et al.[14] (Table S-III).

We also conducted a sensitivity analysis on the posterior probability, the DALY's value and the discount rate – parameters with large uncertainties but undetermined statistical properties. A simple sensitivity analysis with the extremes values for these parameters (Table IV) gives bounds on the metrics ranging from 2–830% of the predicted values. To obtain more realistic limits, we treated the extremes in Table IV as 95% confidence limits on random variables distributed normally or log-normally so that expanded uncertainty limits could be calculated with the same methods used with the true random errors (Section G below). For the value of a statistical life year (VSLY), our chosen value of \$100,000 and the extremes of \$24,777[15] and \$482,487[16] suggest a log-normal distribution, so its approximate "standard error" (designated SE) can be calculated from eq. S24 (Table S-III). For P, the chosen value of 0.6 with extremes 0.2 – 1.0 indicates a normal distribution, whose SE_P = (max - min)/2 $z_{0.975}$ = 0.22. The extreme values of the discount rate have only a ±30% impact on the economic burden, far less than the other uncertainty sources, and can therefore be neglected.

E. Propagation of Errors for the Economic Burden

Given estimates for the various sources of uncertainty, we used the derivative method for the propagation of errors[11] to obtain confidence limits and uncertainty limits on the expected values of the metrics in Table II (except for the action level which is discussed

in Section I). With this method, the SE of any metric Z which depends on multiple variables $\mathbf{x}=\{x_1, x_2, \ldots\}$ is given by:

$$SE_Z^2 = \sum_i \left(\frac{\partial Z(\bar{\mathbf{x}})}{\partial x_i} \right)^2 SE_i^2 + 2 \sum_{i>j} \frac{\partial Z(\bar{\mathbf{x}})}{\partial x_i} \frac{\partial Z(\bar{\mathbf{x}})}{\partial x_j} \rho_{ij} \, SE_i \, SE_j \qquad \text{(S25)}$$

where ρ_{jk} is the correlation between two independent variables. Assuming the errors in the metric Z are normally distributed, the 95% confidence limits for the mean metric value equal $Z(\bar{\mathbf{x}}) \pm z_{0.975} \, SE_Z$. The p-value from one-tailed tests is: $p=1-N\left[Z(\bar{\mathbf{x}}) / SE_Z \right]$. For the metric's expectation value P z from the posterior probability of causality P, the confidence limits are $P\,Z(\bar{\mathbf{x}}) \pm z_{0.975} \, P\,SE_Z$, and the p-value is unchanged.

For each source of bias in variables x_i, the calculated value for metric Z can be corrected to our approximation to its true value:

$$Z(\mathbf{x}_{true}) = Z(\bar{\mathbf{x}}) + \sum_i \frac{\partial Z(\bar{\mathbf{x}})}{\partial x_i} \delta_i \qquad \text{(S26)}$$

The 95% confidence limits on the corrected metric value = $Z(\mathbf{x}_{true}) \pm z_{0.975} \, SE_Z$ have been called *uncertainty limits* on $Z(\bar{\mathbf{x}})$ when the bias correction lacks rigor.[12] Likewise, uncertainty limits on the bias-adjusted expectation value are $P\,Z(\mathbf{x}_{true}) \pm z_{0.975} \, P\,SE_Z$. Since the data for the single company bias and chemical biases are less robust than the other input data, the metric values corrected for these biases in this Supplemental Online Material is not reported in the main paper, which only gives means with their 95% confidence limits and uncertainty limits.

Note: By definition,[12] an uncertainty limit that violates some physical or biological principle is replaced by the rational limit in all reports. For DALY(B) or $b_\$(B)$, negative values are irrational because they imply MFs prevent cancer. When their lower bound from the uncertainty limit formula (above) is negative, the lower uncertainty limit is therefore reported as zero (*i.e.* no risk).

The partial derivatives in eqs. S25 – S26 were calculated in two ways. First, they were calculated analytically with *Mathematica* software (Wolfram Media, Champaign, IL) after first replacing the iterative dependence of the survival function on the DR parameters (eq. S11) with the exposure-independent survival function $S_0(0,i)$. To test this assumption, the partial derivatives of YLL were also calculated by finite differences,[17] using our spreadsheets to change each independent variable by 10%. The two approaches agreed within 7%.

Since these derivatives depend on the TWA magnetic field, the uncertainty calculations are done for 0.05, 1.0 and 50 μT (Table S-III). We omitted YLD in the derivatives of the economic burden since it is only 6-7% of YLL (Tables IV and V). All the independent variables in Table S-III would appear to be uncorrelated except for the betas for the continuous DR and the highest exposure category with the same cancer. In eq. S25, the correlation coefficient ρ between β and β_{hi} were assumed to be 0.9 for both brain cancer and leukemia.

Next, the uncertainties in the posterior probability and the value of the statistical life year (VSLY) were treated as random errors whose variances could be propagated to the expectation value of the discounted economic burden:

$$b_\$ \equiv P\ VSLY\ DALY_d = P\ e^{\ln VSLY}\ DALY_d \qquad \text{(S27)}$$

where the log transform makes the uncertainty in VSLY log-normal. Then, the approximate standard error $SE_{b_\$}$ for the economic burden's expectation value can be derived from eq. S25 and S27 by assuming the uncertainties are uncorrelated:

$$SE^2_{b_\$} = b^2_\$\left(SE^2_{\ln VSLY} + SE^2_P/P^2\right) + P^2 VSLY^2\ SE^2_{DALY} \qquad \text{(S28)}$$

where the standard error for the DALY is obtained rigorously from eq. S25.

Finally, "uncertainty limits" on the expected values of the economic burden and other metrics are estimated as $P\ Z(\mathbf{x}_{true}) \pm z_{0.975}\ SE_Z$ by assuming the combined random errors in Z are normally distributed.

The results of the sensitivity analysis for the expectation values of the monetary burdens from a fixed TWA magnetic field exposure are summarized in Table S-III. The appropriate chemical bias depends on the chemical(s) observed on the particular job. As an illustration, these summary results give uncertainty limits only for mercury – the chemical with the highest risk and therefore the greatest impact on the uncertainty. For the slopes, linear regressions were performed on the TWA-specific limits in Table S-III, giving the confidence and uncertainty limits reported in Table VI of the main paper.

From Table S-III, a variable's contribution to a metric's confidence and uncertainty intervals can be determined as a percent of the mean. The contribution of the random variables equals $z_{0.975}$ %RSE, which is 80 – 100% for the DR slopes, making the economic burden statistically significant for all TWA values. (Note: The one-tailed means test is significant for %RSE ≤ 60.8%.) When P and VSLY are added, random errors contribute 180 – 190% of the mean's expected value to the burden's uncertainty intervals, which makes their lower uncertainty limit zero. The single company bias reduces the upper uncertainty limit by 41% of the mean. A chemical that reportedly increase brain cancer risks increases the upper uncertainty limit by 30 – 50% of the mean for each chemical present at a work location. For the lower uncertainty limit to be above \$0, a worker would have to be exposed to a 1 μT MF, mercury, arsenic, lead and solvents.

Table S-III. Propagation of random errors, biases and other uncertainties in the economic cancer burden of magnetic field exposures.

Independent variables	Metric derivatives	Population attributable fraction		Disease burden [DALY per year]	
		Brain cancer	Leukemia	Brain cancer	Leukemia
Brain cancer DR (βB)	$\partial z / \partial \beta B$	7.16	0.0	$8.45\ 10^5$	$-1.36\ 10^5$
Leukemia DR (βL)	$\partial z / \partial \beta L$	0.0	7.66	$-6.31\ 10^4$	$1.21\ 10^6$
Population MF distribution: <P1	$\partial z / \partial \bar{B}_1$	0.004	0.003	552	665
P1 – P5	$\partial z / \partial \bar{B}_2$	0.015	0.014	2,210	2,670
P5 – P10	$\partial z / \partial \bar{B}_3$	0.019	0.017	2,780	3,340
P10 – P25	$\partial z / \partial \bar{B}_4$	0.059	0.052	8,390	10,090
P25 – P50	$\partial z / \partial \bar{B}_5$	0.099	0.088	14,200	17,000
P50 – P75	$\partial z / \partial \bar{B}_6$	0.102	0.090	14,500	17,400
P75 – P90	$\partial z / \partial \bar{B}_7$	0.065	0.056	9,150	10,900
P90 – P95	$\partial z / \partial \bar{B}_8$	0.023	0.020	3,280	3,850
P95 – P99	$\partial z / \partial \bar{B}_9$	0.023	0.019	3,150	3,590
>P99	$\partial z / \partial \bar{B}_{10}$	0.010	0.007	1,260	1,330
Metric's mean		0.082	0.070	10,000	11,300
Random errors from DR & population MF distribution	**SE (%RSE):**	0.046 (55%)	0.044 (63%)	5,400 (54%)	6,970 (62%)
Single company bias	**Bias (% of mean):**	-0.036 (-44%)	-0.030 (-43%)	-3,990 (-40%)	-4,050 (36%)
Chemical exposure bias	**Bias (% of mean):**	+0.004 (+5%)	*	+454 (+5%)	*
Posterior probability (P)	**SE *(%RSE):***	*0.032 (65%)*	*0.030 (71%)*	*3,830 (64%)*	*4,770 (71%)*
Expected value of metric means *for P = 0.6*		*0.049*	*0.042*	*6,010*	*6,760*
95% confidence limits *from random errors*		*-0.004 – 0.10*	*-0.01 – 0.09*	*-340 – 12,000*	*-1,400 – 15,000*
P-value from one-tailed tests		*p = 0.035*	*p = 0.055*	*p = 0.032*	*p = 0.053*
Uncertainty limits *with posterior probability*		*0 – 0.11*	*0 – 0.10*	*0 – 14,000*	*0 – 16,000*
with single company bias added		*0 – 0.09*	*0 – 0.08*	*0 – 11,000*	*0 – 14,000*
With chemical exposures added		*0 – 0.08*	*	*0 – 11,000*	*

Quantities calculated for the expected value. %RSE = percent relative standard error.

F. The Precautionary Level and its Uncertainty Analysis

The precautionary level (PL) is determined by setting the expectation values of either the excess incidence $I_x(B)$ or the discounted economic burden EB(B) to a *de minimis* value. For an arbitrary metric Z(B), this relationship is:

$$P\ Z(PL) = Z_{dm} \qquad \text{(S30)}$$

where Z_{dm} is the metric's *de minimis* value. Since the metrics are highly non-linear functions of B (Section B), an analytic solution of the eq. S30 for PL appears impossible. For accurate determinations, candidate PLs were therefore calculated by trial-and-error with the lifetable spreadsheet until the metric equaled a postulated *de minimis* value within three significant figures.

Since the PL is the inverse of the metrics analyzed in Section G, a new approach is needed for its sensitivity analysis. First, an analytic form of PL was determined approximately by taking first taking a power series expansion of Z(B) about B = 0:

$$Z(B) = B\ (\beta_{brain}\ U + \beta_{leuk}\ V) + \mathcal{O}(B^2) \qquad \text{(S31)}$$

where U and V depend on the DR parameters and the MF exposure distribution. Then,

$$PL \cong \frac{Z_{dm}}{P\left(\beta_{brain} U + \beta_{leuk} V\right)} \equiv \frac{Z_{dm}}{P\ f} \qquad \text{(S32)}$$

Since the errors in the βs and P are normally distributed, the errors in the AL belong to an *inverse* normal distribution, so its confidence and uncertainty limits must be derived from this little-known function.[21]

To derive these confidence limits, we first follow eq. S32 in defining the variability in PL by a random variable $y = Z_{dm}/x$. This second random variable x belongs to a normal distribution with mean = P f and variance σ^2. Since y is the inverse of x, it has the probability density function of an inverse normal distribution: [21]

$$pdf(y) = \frac{Z_{dm}}{\sqrt{2\pi}\sigma y^2} \exp\left[-\frac{\left(\frac{Z_{dm}}{y} - \mathrm{P\ f}\right)^2}{2\sigma^2} \right]$$

The 95% confidence limits on the AL are given by:

$$\int_0^{LCL} \mathrm{dy}\ pdf\,(\mathrm{y}) = 0.025$$

$$\int_0^{UCL} \mathrm{dy}\ pdf\,(\mathrm{y}) = 0.975$$

In order to solve these integrals, substitute the following:

$$\xi = \frac{1}{y}$$

$$\mathrm{d}\xi = -\frac{1}{y^2}\mathrm{dy}$$

$$\mathrm{P\ f} = \frac{Z_{dm}}{\mathrm{AL}}$$

$$\mathrm{s} = \frac{\sigma}{Z_{dm}}$$

into the confidence level integral and re-arrange to get:

$$\frac{1}{\sqrt{2\pi}\mathrm{s}} \int_{1/\mathrm{CL}}^{\infty} \mathrm{d}\xi \exp\left[-\frac{\left(\xi - \frac{1}{\mathrm{AL}}\right)^2}{2s^2} \right] = 1 - \mathrm{N}\left[\frac{\frac{1}{\mathrm{CL}} - \frac{1}{\mathrm{AL}}}{s} \right]$$

So the lower confidence limit can be derived from:

$$\frac{\frac{1}{\mathrm{LCL}} - \frac{1}{\mathrm{PL}}}{\sigma / Z_{dm}} = \mathrm{N}^{-1}\left[1 - 0.025\right] = z_{0.975}$$

or:

$$\mathrm{LCL} = \frac{Z_{dm}\ \mathrm{PL}}{Z_{dm} + z_{0.975}\ \sigma\ \mathrm{PL}} \qquad \text{(S33)}$$

We now note that σ PL in the above denominator is the first term in a power series of the standard error of the metric's expectation value for B = PL:

$$\mathrm{SE[P\ Z(B)]} = \mathrm{SE[P\ f\ B} + \mathcal{O}(\mathrm{B}^2)]$$

$$= \mathrm{SE[P\ f]\ B} + \mathcal{O}(\mathrm{B}^2)$$

$$= \sigma\ \mathrm{B} + \mathcal{O}(\mathrm{B}^2)$$

Furthermore, Z_{dm} = Mean[P Z(PL)], according to the definition of the action level (eq. S30). Therefore, eq. S33 can be re-written:

$$\begin{aligned} \mathrm{LCL}\left[\mathrm{PL}\right] &= \frac{Z_{dm}\ \mathrm{PL}}{\mathrm{Mean}\left[\mathrm{P\ Z}\left(\mathrm{PL}\right)\right] + \ z_{0.975}\ \mathrm{SE}\left[\mathrm{P\ Z}\left(\mathrm{PL}\right)\right]} \\ &= \frac{Z_{dm}\ \mathrm{PL}}{\mathrm{UCL}\left[\mathrm{P\ Z}\left(\mathrm{PL}\right)\right]} \end{aligned} \qquad \text{(S34a)}$$

In other words, the lower confidence level and mean of the action level would be inversely proportional to those of the metric's expected value, except that lower and upper confidence levels are switched in eq. S34a. Likewise,

$$\mathrm{UCL}\left[\mathrm{PL}\right] = \frac{Z_{dm}\ \mathrm{PL}}{\mathrm{LCL}\left[\mathrm{P\ Z}\left(\mathrm{PL}\right)\right]} \qquad \text{(S34b)}$$

Thus, upper and lower limits on the action level follow simply from the confidence and uncertainty limits on Z derived by the methods in section G.

According to eq. S34b, a negative, non-significant lower limit for Z means a negative UCL[PL], which is *less* than LCL[PL]. This non-sense result derives from the fact that $\mathrm{PL} \to \infty$ as $\mathrm{Z} \to 0$, so the PL is undefined for negative Z. In these cases, we report the upper limit on PL as infinity.

Furthermore, the null hypothesis in this case is $\mathrm{PL} = \infty$ (i.e. an intervention is never needed). To avoid this infinity, significant tests for the PL were performed instead on the null hypothesis: $\mathrm{Z(PL)} \leq 0$.

Finally, consider biases in Z and their propagation to PL. As in section G, define a bias by:

$$\mathrm{Z}_{\mathrm{true}}\left(\mathrm{B}\right) = \mathrm{Z}\left(\mathrm{B}\right) + \delta_{Z}\left(\mathrm{B}\right)$$

From PL's definition (eq. S30), the bias in the PL is given by:

$$Z_{dm} = \mathrm{P\ Z}\left(\mathrm{PL} + \delta_{PL}\right) = \mathrm{P}\left[\mathrm{Z}\left(\mathrm{PL} + \delta_{PL}\right) + \delta_{Z}\left(\mathrm{PL} + \delta_{PL}\right)\right] \qquad \text{(S35)}$$

Now, use the approximations:

$$Z\left(PL + \delta_{PL}\right) \cong Z\left(PL\right) + \delta_{PL} \frac{dZ\left(PL\right)}{dB} = \frac{Z_{dm}}{P} + \delta_{PL} \frac{dZ\left(PL\right)}{dB}$$

$$\delta_Z\left(PL + \delta_{PL}\right) \cong \delta_Z\left(PL\right)$$

so that eq. S35 can be solved for the PL's bias:

$$\delta_{PL} = {-\delta_Z\left(AL\right)} \Big/ {\frac{dZ\left(AL\right)}{dB}} \tag{S36}$$

This result can be applied to the single company bias and chemical biases which were quantified in Section F.

Table S-VI reports sensitivity analyses for action levels derived from selected *de minimis* values for both the risk ($Z = I_x$) and the discounted economic burden ($Z = EB$). The standard error and biases for the metrics are calculated by propagation of errors (eqs. S25 – S28) with derivatives calculated by the *Mathematica* software, as in Section G.

Table S-IV. Uncertainty analysis of selected action levels

Independent variables	Metric derivatives	Risk-based precautionary level		Burden-based PL	
		Excess Incidence I_x [cases per 100,00]	**Action level [μT]**	**Discounted economic burden**	**Action level [μT]**
Brain cancer DR (βB)	$\partial z / \partial \beta B$	5,210	--	$36,900	--
Leukemia DR (βL)	$\partial z / \partial \beta L$	13,500	--	$59,200	--
	$\partial z / \partial B$	829 μT^{-1}	--	$3,240 μT^{-1}	--
	Metric's mean:	167	–	$1,667	–
Random errors from DR	**SE (%RSE*):**	84 (50%)	--	$440 (44%)	--
Single company bias	**Bias (% of mean*):**	-79 (-47%)	+0.095 (+34%)	-$440 (-44%)	+0.14 (+44%)
Bias from mercury exposure	**Bias (% of mean*):**	+53 (+32%)	-0.063 (-23%)	+$390 (+23%)	-0.12 (-39%)
***Random errors** from P & VSLY*	**SE *(%RSE**):***	*61 (61%)*	–	*$910 (55%)*	–
***Expected value of the mean** for P = 0.6*		***100***	*0.254*	***$1,000***	*0.310*
***95% confidence limits** from errors in DR*		*1.3 – 199*	*0.13 – 19*	*$140 – 1,900*	*0.17 – 2.2*
P-value from one-tailed tests		*p = 0.02*	*ND*	*p = 0.01*	*ND*
***Uncertainty limits** with P & VSLY added*		*0 – 219*	*0.12 – ∞*	*$0 – 2,800*	*0.13 – ∞*
Expected value of the mean (uncertainty limits)		*53*	*0.31*	*$660*	*0.37*
with single company bias added		*(0 – 170)*	*(0.18 – ∞)*	*($0 – 2,400)*	*(0.15 – ∞)*
with mercury exposure added		*84*	*0.27*	*$950*	*0.31*
		(0 – 200)	*(0.12 – ∞)*	*($0 – 2,700)*	*(0.12 – ∞)*

Quantity calculated for the expected value. ***De minimis* value of metric**

ND = Not Defined because the action level's null hypothesis = ∞.

G. Abbreviations and Units

$b_{\$}(B)$	Economic burden from a magnetic field exposure [$]
B	TWA magnetic field magnitude (AKA magnetic flux density) [μT]
B_n	Average TWA magnetic field exposure of the n-th category of the occupational magnetic field exposure distribution [μT]
c	Monetary costs of an intervention [$]
C	Cumulative magnetic field exposure [μT-yr]
CI	Confidence interval
DALY	Disability adjusted life years [yr]
DALY(B)	Lifetime DALY due to workplace MF exposure [yr/person exposed]
DALY(i,B)	DALY due to an exposure in the i^{th} 5-year period [yr/person exposed]
DR	Dose response
E[x]	Expectation value of variable x
ELF	Extremely low frequencies (3 – 3000 Hz)
EMF	Electric and magnetic fields
GM	Geometric mean
GSD	Geometric standard deviation
i	Age index for 5-yr intervals (i=1 for 20-24 yr)
LCL	Lower confidence interval
M(B), I(B)	Total lifetime mortality and incidence of a cancer with TWA magnetic field exposure B [cases per 100,000 exposed]
M_0, I_0	Lifetime mortality and incidence of a cancer with no exposure [cases per 100,000]
MF	Magnetic fields
$M_x(B)$, $I_x(B)$	Excess lifetime mortality and incidence of a cancer due to TWA magnetic field exposure [cases per 100,000 exposed]
N_i	Number ever employed in age group i
N[z]	Cumulative normal distribution of a standard random variable z
p	P-value from hypothesis test
P	Posterior probability that occupational magnetic fields cause a cancer
PAF	Population attributable fraction
Pdf(x)	Probability density function of a random variable x
PL	Precautionary level
Pn	n-th percentile
p_n	Proportion of workers in the n-th category of a categorical exposure distribution
QALY	Quality adjusted life years
RR	Relative risk (or rate ratio)
RR′	Dose-response slope [Multiplicative increase in RR per unit exposure]
$RR_{hi\ C}$	Relative risk for the highest cumulative exposure category
RR_{lin}	Linear dose-response model
%RSE	Percent relative standard error = 100% * SE / mean
SE	Standard error of estimate
T_{obs},T_{true}	Employment duration (observed from company records and the true working career)
TWA	Time-weighted average exposure over a workday
UCL	Upper confidence interval
VSLY	Value of a statistical life year [$]

YLD	Years lost to disability
YLD(B)	YLD due to an exposure [yr/person exposed]
YLL	Years of life lost
YLL(B)	YLL due to an exposure [yr/person exposed]
z_p	Standard normal random variable for probability p
Z,x,f,s,U,V,ξ	Dummy variables
Z_{dm}	*De minimis* value of an exposure metric Z
β	Slope in the logistic regression model. Also, log-transform of the RR.
ΔDALY	Change in DALYs due to an intervention
λ_M (i,B)*	Age-specific mortality rates from all causes with TWA magnetic field exposure B [cases/100,000/yr]
λ_M (i,B), λ_I (i,B)	Age-specific mortality and incidence rates from a cancer with TWA magnetic field exposure B [cases/100,000/yr]
λ_M, λ_I	Mortality and incidence rates [Cases/100,000/yr]
λ_{M0}(i)*	Age-specific baseline mortality rates from all causes [cases/100,000/yr]
λ_{M0}(i), λ_{I0}(i)	Age-specific baseline mortality and incidence rates from a cancer [cases/100,000/yr]
λ_{M0}, λ_{I0}	Baseline mortality and incidence rates with no exposure [Cases/100,000/yr]
$\bar{\lambda}_M(\mathbf{i})$, $\bar{\lambda}_I(\mathbf{i})$	Published age-specific cancer mortality and incidence rates, which are assumed to be averages over the population's magnetic field exposure [cases/100,000/yr]
μT	Microtesla (unit for the magnetic flux density)
X	Bold characters denote vectors

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