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Mortality from Neurodegenerative Disease and Exposure to Extremely Low-Frequency Magnetic Fields: 31 Years of Observations on Swiss Railway Employees

Martin Röösli[a] Manfred Lörtscher[b] Matthias Egger[a, f] Dominik Pfluger[c] Nadja Schreier[a] Emanuel Lörtscher[d] Peter Locher[e] Adrian Spoerri[a] Christoph Minder[a]

[a]Department of Social and Preventive Medicine, University of Berne, and [b]Federal Office of Transport, Berne, [c]datametrix AG, Zurich, [d]LOITS, Bonstetten, and [e]ENOTRAC AG, Uetendorf, Switzerland; [f]Department of Social Medicine, University of Bristol, Bristol, UK

Key Words

Electromagnetic fields · Neurodegenerative diseases · Amyotrophic lateral sclerosis · Alzheimer's disease · Parkinson's disease · Multiple sclerosis · Occupational exposure

Abstract

Aims: The objective of the present study was to investigate the relationship between extremely low-frequency magnetic field (ELF-MF) exposure and mortality from several neurodegenerative conditions in Swiss railway employees. ***Methods:*** We studied a cohort of 20,141 Swiss railway employees with 464,129 person-years of follow-up between 1972 and 2002. For each individual, cumulative exposure was calculated from on-site measurements and modelling of past exposure. We compared cause-specific mortality in highly exposed train drivers (mean exposure: 21 μT) with less exposed occupational groups (for example station masters: 1 μT). ***Results:*** The hazard ratio for train drivers compared to station masters was 1.96 [95% confidence interval (CI) = 0.98–3.92] for senile dementia and 3.15 (95% CI = 0.90–11.04) for Alzheimer's disease. For every 10 μT years of cumulative exposure senile dementia mortality increased by 5.7% (95% CI = 1.3–10.4), Alzheimer's disease by 9.4% (95% CI = 2.7–16.4) and amyotrophic lateral sclerosis by 2.1% (95% CI = –6.8 to 11.7). There was no evidence for an increase in mortality from Parkinson's disease and multiple sclerosis. ***Conclusions:*** This study suggests a link between exposure to ELF-MF and Alzheimer's disease and indicates that ELF-MF might act in later stages of the disease process.

Occupational exposure to extremely low-frequency magnetic fields (ELF-MF) may or may not be a causal factor in chronic disease. In a comprehensive review [1], the International Commission on Non-Ionizing Radiation Protection (ICNIRP) stated that the results from occupational ELF-MF studies on amyotrophic lateral sclerosis (ALS) 'point toward a possible risk increase in subjects with EMF exposure'. A pooled relative risk comparing exposed with non-exposed occupations of 1.5 [95% confidence interval (CI) = 1.2–1.7] was calculated from 7 studies. For Alzheimer's disease (AD), a pooled risk estimate of 2.2 (95% CI = 1.5–3.2) was obtained from 5 studies [1]. However, according to ICNIRP, 'excess risk is constrained to studies with weaker designs, thus support for

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Dr. Martin Röösli
Institut für Sozial- und Präventivmedizin
Finkenhubelweg 11
CH–3012 Bern (Switzerland)
Tel. +41 31 631 3867, Fax +41 31 631 3520, E-Mail Roeoesli@ispm.unibe.ch

the hypothesis of a link between EMF and AD is weak'. Since the publication of the Commission's 2003 review, additional studies reported an association between occupational ELF-MF exposure and AD (reviewed in Hug et al. [2]). In contrast, data on other neurodegenerative diseases such as Parkinson's disease, epilepsy and multiple sclerosis and their relation to ELF-MF are sparse, precluding from any conclusions [3].

The assessment of exposure is a particular challenge in this research area. ELF-MF has multiple sources and exposure levels may vary substantially over time and between different locations. Swiss railway employees are an appealing study population for several reasons. They are generally employed long-term, with limited job changes. The exposure circumstances at a given workplace are well characterized but vary greatly across different occupations, with train drivers being exposed to very high ELF-MF levels, whereas exposure in other employees is comparable to the general population. Detailed company registers reduce the potential for selection bias and allow assessments of ELF-MF exposure that are based on individual job histories. Exposures to chemicals or electric shocks, which often occur in other occupational settings (for example in electric utility workers or welders) are rare. Previous studies of railway workers have focussed on cancer risks [4–8], chromosomal aberrations [9] and cardiovascular disease [10, 11]. Only 1 such study has so far investigated the risk of neurodegenerative diseases in railway employees [12].

The objective of the present study was to investigate the relationship between ELF-MF exposure and mortality from several neurodegenerative conditions in a cohort of Swiss railway employees.

Materials and Methods

The study was approved by the Federal Commission of Experts for Professional Secrecy in Medical Research (http://www.bag.admin.ch/org/02329/).

Study Population

Our study includes all men who were registered as employed or retired in the personnel and pension records of the Swiss Federal Railways between January 1, 1972, and December 31, 2002. The following occupations, which differed in terms of average exposure to ELF-MF, were included: train drivers, shunting yard engineers, train attendants and station masters. The records included data on the start and end of employment, as well as demographic characteristics (date of birth, place of residence and, if applicable, date of marriage and date of death).

Record Linkage

We obtained causes of death from death certificates. In Switzerland, death certificates are filled in either by the family doctor or by a physician from the hospital where the death occurred. We used a probabilistic record linkage method [13], implemented in the software LinkPro 3.0 [14] to match employee records with death certificates. Records were linked by an investigator blinded to occupation and exposure status. Linkage variables were date of birth, date of death, place of residence at time of death, occupation, marital status and duration of marriage, if married.

In a first linkage cycle, only railway data with a date of death were linked. Death certificates were accepted if there was complete agreement on dates of birth and death and if a probabilistic weight calculated from the other linkage variables was positive. In a second cycle, records without a date of death were considered, and death certificates were accepted if the dates of birth matched and if the probabilistic weight was at least 40% of the maximum weight. Results were checked against a database that included all men employed on December 31, 1992, and on December 31, 2002. None of the workers assumed to have died before these dates, based on probabilistic record linkage, were found in the database.

Outcomes

We considered deaths from 4 neurodegenerative diseases: Parkinson's disease, ALS, senile dementia (incl. AD) and multiple sclerosis. Additionally, we analyzed respiratory tumours, cardiovascular diseases and all-cause mortality for comparison. An analysis of leukaemia and brain tumour mortality is published elsewhere [15]. Neurodegenerative diseases were mostly coded as concomitant cause of death. Immediate causes of death were certified for senile dementia (1% of the cases), multiple sclerosis (40%), Parkinson's disease (41%) and ALS (60%). From 1972 to 1994, deaths were coded according to the 8th revision of the International Classification of Diseases (ICD-8) and since 1995 according to the 10th revision (ICD-10) [16]. AD was coded separately after 1995, when ICD-10 codes were introduced. All codes are listed in table 1.

Overview of Exposure Assessments

Swiss trains run on 16.7-Hz alternating current. Line engines are exclusively electrical, whereas both electric and diesel engines are used for shunting in the rail yard. Railway employees retire at the age of 65 years at the latest. Train drivers generally operated different engines daily, with the exception of drivers serving on the alpine transit line, who used essentially the same engines from 1919 to 1960. Shunting yard engineers drive several smaller engines to set up train compositions. Train attendants accompany passenger trains, whereas station masters work partly in an office and partly on the station platforms. Each man was assigned the occupational group he held when he left the cohort.

For each occupation group, we determined the average exposure for each year based on measurements [17] and modelling. The first set of measurements was carried out in 1993–1994 using a commercial Bramur gaussmeter (Bramur, Lee, Mass., USA) [18]. A second series was done in 2003–2004 using an EFA device from Wandel & Goltermann (now Narda Safety Test Solution, Germany [17]). In total, 139 measurement runs were performed in numerous engines under real service conditions, representing 198 operating hours. A 16.7-Hz bandpass filter and a sampling inter-

Table 1. Frequency of death among 20,141 Swiss railway workers, by cause and occupational group

Variable	ICD-8	ICD-10	Train drivers	Shunting yard engineers	Train attendants	Station masters	Total
Exposed individuals			7,097	1,378	6,909	4,757	20,141
Person-years at risk			151,139[a]	33,752	160,819	118,418	464,129
Deaths (all causes)			1,652 (100)	394 (100)	2,089 (100)	1,278 (100)	5,413 (100)
Deaths from cardiovascular diseases	390–458	I00–99	1,103 (66.8)	259 (65.7)	1,368 (65.5)	862 (67.4)	3,592 (66.4)
Deaths from respiratory tumour	160–163	C30–39, G450	112 (6.8)	30 (7.6)	147 (7.0)	89 (7.0)	378 (7.0)
Deaths from multiple sclerosis	340	G35	1 (0.1)	0 (0)	3 (0.1)	1 (0.1)	5 (0.1)
Deaths from Parkinson's disease	342	G20–21, G25.9	35 (2.1)	9 (2.3)	44 (2.1)	30 (2.3)	118 (2.2)
Deaths from ALS	348	G12.2	5 (0.3)	3 (0.8)	4 (0.2)	3 (0.2)	15 (0.3)
Senile dementia including AD	290.0, 290.1	G30, F00	30 (1.8)	3 (0.8)	17 (0.8)	11 (0.9)	61 (1.1)
Isolated AD	[b]	G30	14 (0.8)	2 (0.5)	6 (0.3)	3 (0.2)	25 (0.5)

Figures are numbers with percentages in parentheses.
[a] There were 20,491 person-years of observation for alpine train drivers.
[b] Not coded in ICD-8.

val of 5 s (mean root mean square values) were used. Simultaneously for 21 episodes, broadband measurements in the range of 5 Hz to 2 kHz were performed in order to elucidate non-16.7-Hz exposure contributions. In all engines, the 3rd and the 5th harmonics were present in addition to the 16.7-Hz fundamental frequency. Harmonics were most distinctly observed in 4-quadrant controlled engines (fig. 1). In the range of 100 Hz to 1 kHz, no significant signals were detected. Exclusively for 4-quadrant controlled engines, contributions above 1 kHz were observed, showing magnetic inductions of less than 1% of the 16.7-Hz amplitude (fig. 1). In passenger coaches and the workplaces of station masters, an additional 41 measurement runs were conducted with a total duration of 21.3 h. The Swiss Railway engine fleet consists of about 2,000 engines of 30 different line and shunting engine types. Our measurements covered 90% of the fleet, representing 96% of the total electric power installed.

Exposure Assessment for Train Drivers

For each engine an average exposure value was calculated from measurements under the current real service conditions. Meters were placed in 3 positions in the engine cab: at the driver's feet, thorax and head. The thorax meter was either fixed at the back of the driver's seat or carried as a 'backpack'. For this study, the thorax value was used.

Past exposure levels were estimated using the FABEL simulation software (http://www.enotrac.com/tps/index.htm) based on the engine-specific association between traction effort, speed and magnetic flux density, which was obtained from measurements during well-defined operation conditions. These estimates allowed us to take into account the kind of train (freight, normal or fast train), the driving cycle and the trainload. For some engines, these factors were considerably different in the past than today. For each year, the average exposure of train drivers was calculated based on an engine-specific weighted average according to the engine fleet of the railway company in the respective year. For the period 1919–1965, these calculations were done separately for the alpine and the lowland lines because more powerful engines were used in the alpine region, with particularly high field levels at the driver's workplace [19]. Train drivers were classified as alpine or lowland drivers, according to their place of residence.

Exposure Assessment for Shunting Yard Engineers

Average annual exposure for shunting yard engines was derived from measurements under service conditions by calculating weighted means according to the shunting yard engine composition. Magnetic field levels in diesel engines were assumed to originate only from overhead contact lines (1 μT until 1960, 2 μT from 1960 through 2002) because much shunting work is done near or directly under these lines.

Exposure Assessment for Train Attendant and Station Masters

Average annual exposure for train attendants was derived from measurements under real service conditions by calculating weighted means according to the wagon compositions used. Past exposures were corrected for change in the emission from contact wires over time. Based on sample measurements at several stations, a mean exposure level of 1 μT was determined for station masters taking into account their average work time on the platform and in the office. Past exposures were linearly approximated, resulting in 0 μT in the year 1919.

Statistical Methods

We analyzed data using Cox proportional hazard models. The primary time axis was age, period effects were allowed for by splitting the data set into 5-year periods. All models were stratified for the period before and after 1995, thus taking into account the change in coding for cause of death. Age was introduced as a linear, quadratic and cubic term. We tested all models successfully for the proportionality assumption using Nelson-Aalen survivor functions and statistical tests based on Schoenfeld residuals. Data were analyzed using STATA 9.0 (Stata Corporation, College Station, Tex., USA).

The association between mortality and exposure was modelled using several approaches. First, occupational groups served as a proxy for exposure. Second, cumulative exposure, expressed as microtesla years, was entered as a time-varying covariate. Cumulative exposure was obtained by summing the annual average exposure values from the start of the employment until the end of each 5-year period. We assumed an exposure duration of 7.5 h per day and 240 working days per year. Third, we examined the evidence for a threshold effect, latency effect or an effect of more

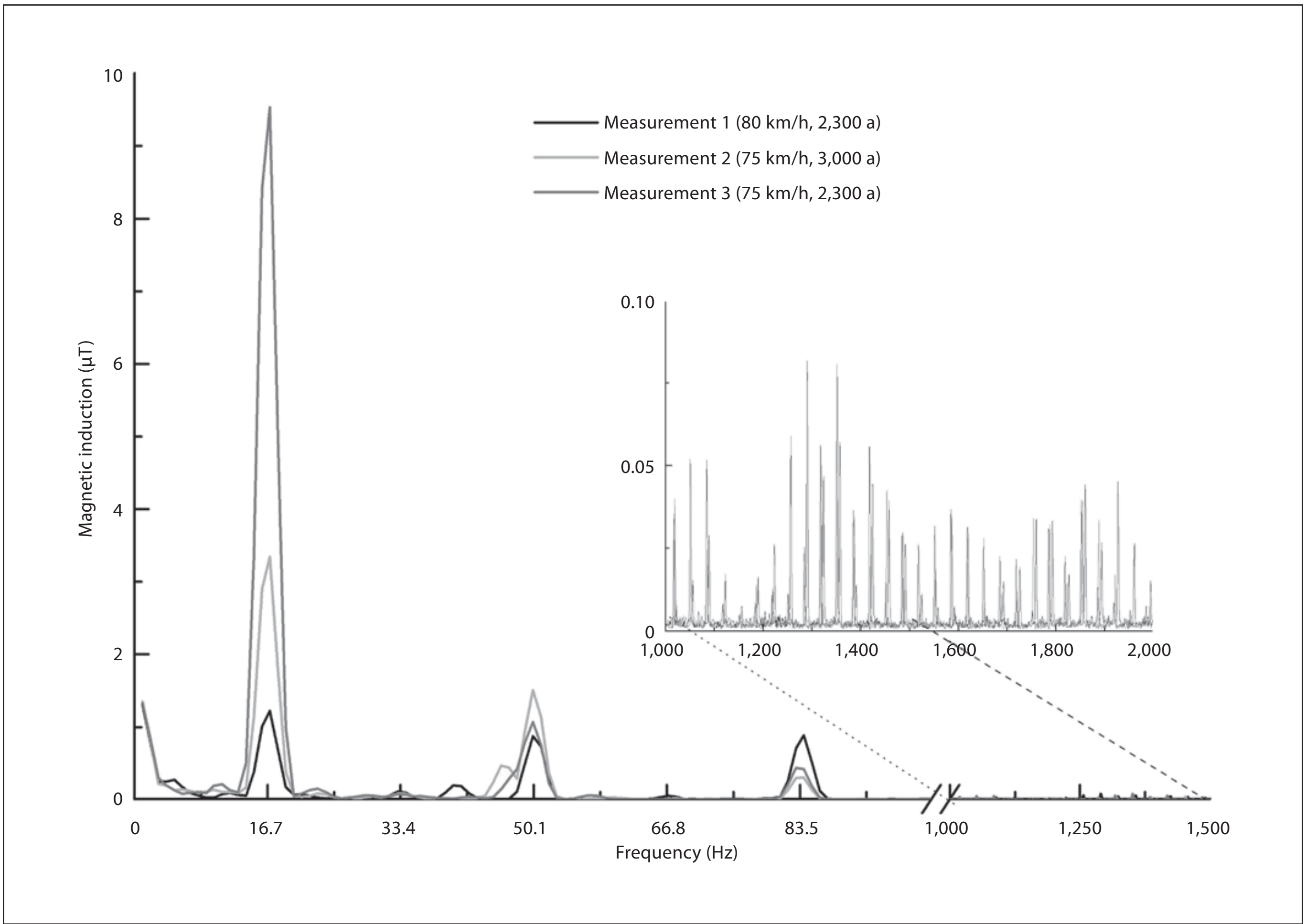

Fig. 1. Three measurements of the frequency spectrum of the magnetic induction in the range 0–1,500 Hz in a 4-quadrant controlled engine (engine type Re 460).

recent exposure. The cumulative time spent above a threshold of 10 μT was calculated. A possible latency effect was investigated by restricting the analysis to the exposure that had accumulated up to 10 years prior to death or study closure, and the importance of more recent exposure by restricting it to the exposure experienced within 20 years before death or study closure. For each of these measures, we divided the cohort into men exposed below or at the median and men exposed above the median to allow comparisons of the hazard ratios (HR).

Results

Cohort Characteristics

The cohort consists of 20,141 men, with a follow-up of 464,129 person-years (table 1). Personnel and pension records contained files for 3,406 men with an exact date or year of death. Among these, 76 men (2.2%) could not be linked to a death certificate. Most of them were probably foreigners who returned to their country of origin. These deaths were included as deaths with unknown cause. A total of 1,968 additional deaths were identified among the remaining 16,735 men. None of these matched more than 1 death certificate: there were no unresolved links. Data from the 39 men found to be older than 100 years at study end (December 31, 2002) were censored at the age of 100 years. The proportion of censored individuals and deaths with unknown cause was similar across occupations.

There were limited job changes in our cohort. Among the men registered as train drivers in 1993, 98.4% were also registered as train drivers in 2002 or when they left the railway company. The corresponding figure was 97.5% for shunting yard engineers, 94.3% for train atten-

Table 2. Magnetic field exposure among 20,141 Swiss railway workers, by occupational group

Exposure measure	Train drivers	Shunting yard engineers	Train attendants	Station masters
Mean year of starting work	1965	1960	1958	1955
Mean duration of employment, years	27.4	31.7	31.0	36.3
Mean exposure at work in 1940, μT	22.1[a]	3.6	1.1	0.3
Mean exposure at work in 1960, μT	19.2[a]	5.2	1.7	0.5
Mean exposure at work in 1980, μT	21.4	5.5	1.8	0.7
Mean exposure at work in 2000, μT	21.0	6.0	4.2	1.0
Cumulative lifetime exposure, μT years				
Minimum	0.0	0.8	0.4	0.4
First quartile	69.0	34.8	10.4	4.1
Median	120.5	42.1	13.3	5.7
Third quartile	147.9	49.2	15.1	6.6
Maximum	385.1	58.9	22.1	8.7
Time spent above 10 μT, years				
Minimum	0.0	0.0	0.0	0.0
First quartile	1.3	1.5	0.1	0.0
Median	2.5	1.8	0.2	0.0
Third quartile	3.1	2.1	0.3	0.0
Maximum	4.3	2.5	0.5	0.0
Time spent above 100 μT, years				
Minimum	0.0	0.0	0.0	0.0
First quartile	0.16	0.0	0.0	0.0
Median	0.24	0.0	0.0	0.0
Third quartile	0.33	0.0	0.0	0.0
Maximum	1.7	0.0	0.0	0.0

[a] Weighted mean according to the number of lowland and alpine train drivers (1940, 1960).

dants and 85.3% for station masters. Train attendants and station masters who changed jobs tended to move to another low-exposed job within the company, but only 3 became train drivers.

Exposure Levels

For all train drivers, the annual average exposure was approximately 21 μT (table 2). Up to the 1960s, considerable differences were found between lowland and alpine train drivers, with much higher exposure levels in the latter (fig. 2). The reduction in exposure values of alpine line train drivers in the early 1960s was caused by the replacement of high-exposure engines (type Ce 6/8) with low-exposure engines (type Ae 6/6). Shunting yard engineers were on average exposed to 3.6 μT in 1940, increasing to 6.0 μT in 2000. The exposure of train attendants was below 2 μT up to 1980. Since then, exposure values have been increasing as a result of the introduction of new coaches. The exposure of station masters increased from 0.3 to 1.0 μT.

The average (median) cumulative lifetime exposure of train drivers was about 3 times higher than the average exposure of shunting yard engineers and about 9 times higher than that of train attendants (table 2). The median cumulative exposure was 141.7 μT years for alpine train drivers and 116.5 μT for lowland drivers. Station masters were only minimally exposed. Only train drivers and shunting yard engineers spent more than 1 year above 10 μT, and only train drivers were exposed to levels above 100 μT.

Mortality

All-cause, cardiovascular disease and respiratory tumour mortality of train drivers and station masters was similar, however, somewhat higher in shunting yard engineers and train attendants (table 3). Train drivers had a higher risk of dying from, or dying with, senile dementia than did station masters (HR = 1.96; 95% CI = 0.98–3.92). This HR was 3.15 (95% CI = 0.90–11.04) when the analysis was restricted to AD. The HR for ALS was increased

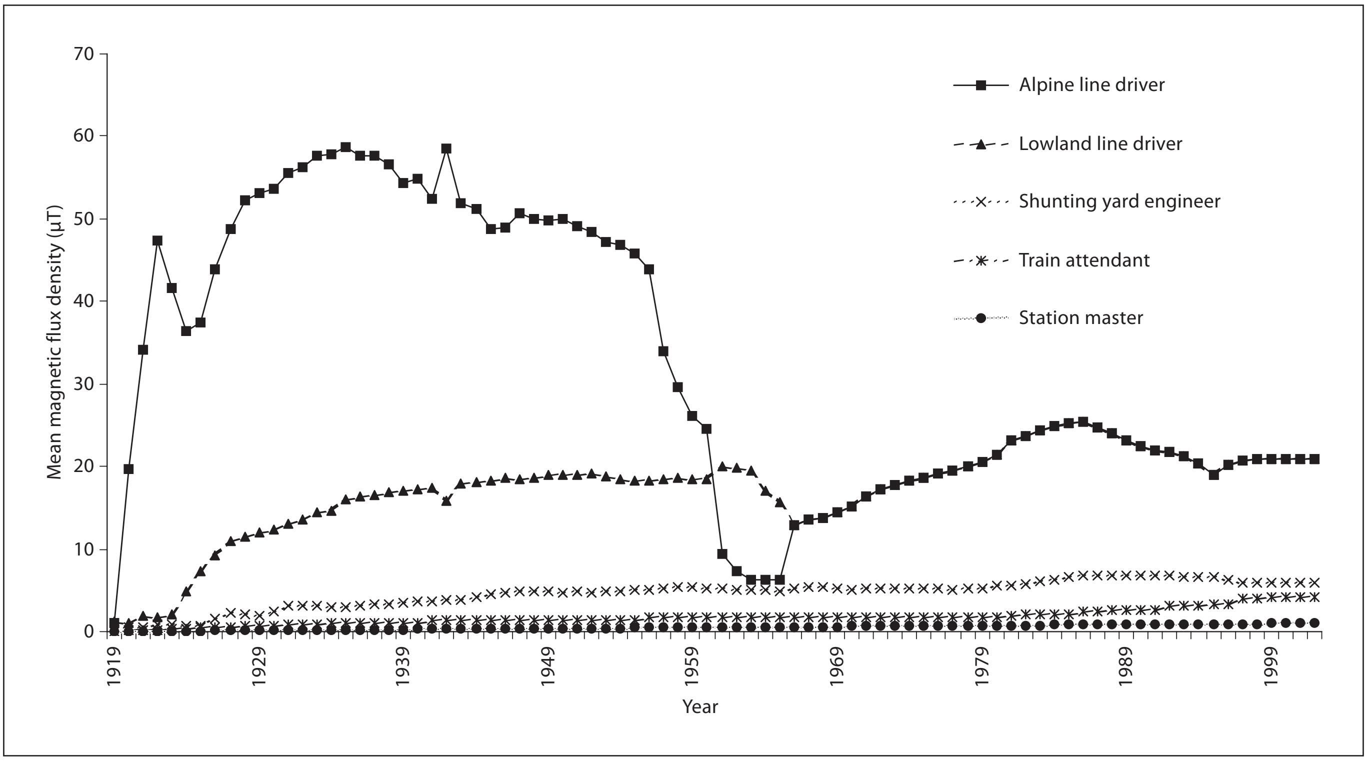

Fig. 2. Average exposure to ELF-MF among 20,141 Swiss railway workers, by occupational group, 1972 through 2002. Until 1965, records differentiated between alpine and lowland engineers.

Table 3. HR for various diseases among 20,141 Swiss railway workers, by occupational group

Disease	Train drivers	Shunting yard engineers	Train attendants	Station masters
All-cause mortality	1.02 (0.95–1.10)	1.12 (1.00–1.26)	1.13 (1.05–1.21)	1
Cardiovascular diseases	0.99 (0.90–1.08)	1.12 (0.98–1.29)	1.09 (1.00–1.19)	1
Respiratory tumour	0.99 (0.74–1.30)	1.05 (0.70–1.60)	1.11 (0.85–1.44)	1
Multiple sclerosis	0.74 (0.04–12.18)	–	2.10 (0.21–21.19)	1
Parkinson's disease	0.83 (0.51–1.36)	1.11 (0.52–2.35)	0.90 (0.57–1.44)	1
ALS	1.31 (0.31–5.59)	3.11 (0.61–15.86)	0.91 (0.20–4.13)	1
Senile dementia, including AD	1.96 (0.98–3.92)	0.95 (0.26–3.44)	1.00 (0.46–2.14)	1
Isolated AD	3.15 (0.90–11.04)	2.07 (0.34–12.45)	0.93 (0.23–3.74)	1

Figures are HRs with 95% CIs in parentheses. Station masters: reference category. Isolated AD: based on data from 1995 to 2002.

in train drivers (HR = 1.31; 95% CI = 0.31–5.59) and shunting yard engineers (HR = 3.11; 95% CI = 0.61–15.90), but the CIs were wide and included 1. We found no consistent associations with causes of death involving other neurodegenerative diseases.

There was some evidence for an increase in the risk of death from or with senile dementia, AD and ALS with increasing cumulative exposure (fig. 3). Senile dementia mortality increased by 5.7% (95% CI = 1.3–10.4) for every 10 μT years of cumulative exposure (table 4). The corre-

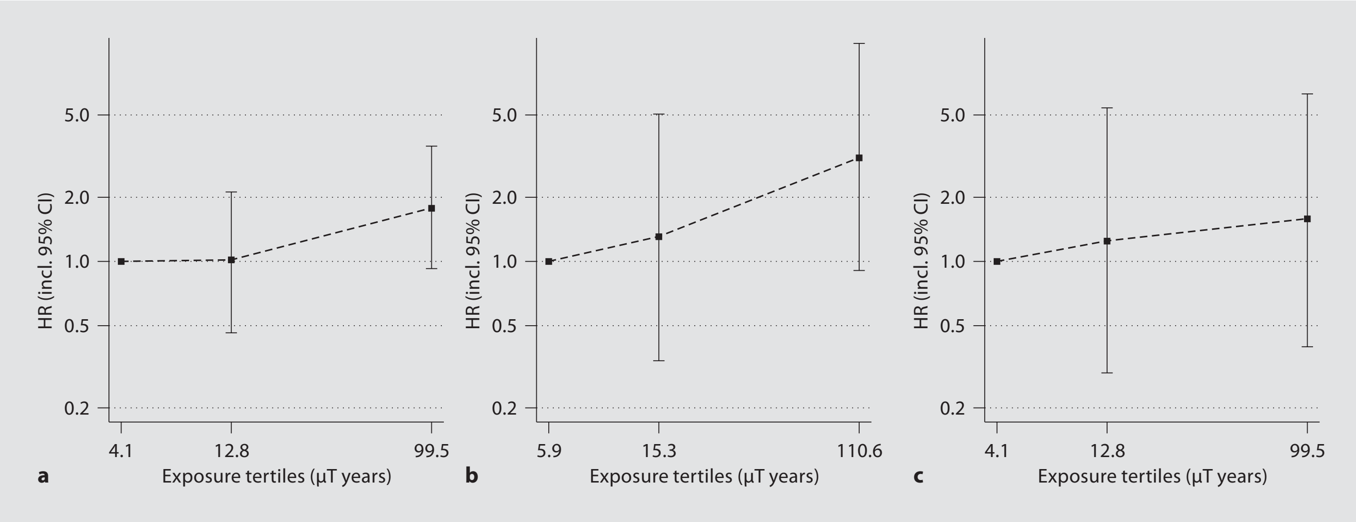

Fig. 3. Exposure-response associations for senile dementia (**a**), AD (**b**) and ALS (**c**) among 20,141 Swiss railway workers exposed to ELF-MF, according to models based on tertiles of cumulative exposure. The x-axis labels refer to the median of each exposure tertile. (AD based on data from 1995 to 2002.)

sponding figures were 9.4% (95% CI = 2.7–16.4) for AD and 2.1% (95% CI = –6.7 to 11.7) for ALS.

We investigated the evidence for threshold and latency effects and the effect of more recent exposure (table 5). HR for senile dementia, AD and ALS were generally further from unity for the time spent above a threshold of 10 μT and for the exposure restricted to a time window of 20 years before death or study closure. In contrast, considering a latency of 10 years in the calculation of the cumulative exposure reduced HRs compared to the cumulative lifetime exposure.

Table 4. Increase in HR (incl. 95% CI) per increase of exposure by 10 μT years

Disease	HR	95% CI
All-cause mortality	0.995	0.990–1.000
Cardiovascular diseases	0.994	0.988–1.000
Respiratory tumour	0.992	0.973–1.010
Multiple sclerosis	0.956	0.798–1.146
Parkinson's disease	0.990	0.957–1.023
ALS	1.021	0.932–1.117
Senile dementia including AD	1.057	1.013–1.104
Isolated AD	1.094	1.027–1.164

Isolated AD: based on data from 1995 to 2002.

Discussion

Principal Findings

Our data provide some evidence of an association between exposure to ELF-MF and senile dementia, including AD. Time window exposure analyses suggest that more recent exposure has a stronger association than earlier exposure. Mortality from ALS among train drivers and shunting yard engineers was increased, but the CIs were wide and included 1. Other neurodegenerative diseases were not associated with magnetic field exposure.

Strengths and Limitations

The strengths of this study are the marked exposure contrasts and the limited job changes among the sample population. We chose 4 adequately sized occupational groups with considerably different exposures to magnetic fields. The exposure circumstances in these 4 occupational groups were well defined, which allowed the effective magnetic flux density to be measured during work condition and modelling of past exposures. For each employee, the start and end dates of employment (exposure) were available. These data allowed us to calculate different exposure measures that accounted for possible threshold or window effects or a latency period between exposure and occurrence of disease. An additional advantage of the railway cohort is that railway employees are rarely exposed to

Table 5. Risk of various neurodegenerative diseases among 20,141 Swiss railway workers for different exposure measures

Disease	Cumulative lifetime exposure µT years	Cumulative exposure time exposure >10 µT years	Cumulative lifetime exposure including 10 years latency µT years	Cumulative lifetime exposure 20 years preceding µT years
Parkinson	1	1	1	1
> median	0.91 (0.62–1.32)	0.93 (0.64–1.36)	0.93 (0.61–1.42)	1.24 (0.69–2.21)
ALS	1	1	1	1
> median	2.32 (0.70–7.73)	3.11 (0.97–10.00)	1.57 (0.41–5.96)	2.32 (0.80–6.76)
Senile dementia including AD	1	1	1	1
> median	1.31 (0.76–2.24)	1.65 (0.99–2.76)	1.45 (0.76–2.79)	2.02 (0.99–4.14)
AD	1	1	1	1
> median	2.56 (1.12–5.82)	3.07 (1.35–6.96)	1.69 (0.57–5.03)	3.34 (1.33–8.42)

HR (95% CI) were calculated for exposure above the median compared to the exposure below or at the median. AD: based on data from 1995 to 2002.

chemicals and electric shocks, as in other occupations with high magnetic field exposure. The HRs obtained for drivers may underestimate associations because the reference group was not unexposed but exposed to considerably lower electromagnetic field levels than railway drivers.

The main limitation of this study are the few cases that occurred despite a follow-up period of 31 years, in particular for multiple sclerosis (5 deaths) and ALS (15). In our study we have to face possible misclassification of the outcome and the exposure. Identifying the cause of death from death certificates introduces 2 types of error. First, neurodegenerative diseases are not always mentioned on death certificates. In Switzerland, this problem existed up to 1995 for senile dementia. In 1995, the ICD-8 coding system was replaced with the ICD-10 coding system and priority rules changed [16], resulting in more consistent reporting of neurodegenerative diseases, including the separate reporting of AD. A code for vascular dementia, which has rarely been found to be associated with magnetic field exposure, was also introduced. Reassuringly, we did not observe an increase of vascular dementia risk with increasing cumulative exposure in a sensitivity analysis (HR per 10 µT years = 0.99; 95% CI = 0.93–1.06). More consistent coding probably reduced non-differential misclassification, which might explain why we observed a stronger association for AD than for senile dementia.

The second type of classification error comes from the need to obtain cause-of-death information from death certificates by probabilistic record linkage. The fact that we did not produce any unresolved link indicates that the linkage strategy was restrictive, which minimized false links. In order to evaluate bias from that side, we performed additional analyses with 2 data sets obtained from a separate linkage procedure. These analyses yielded similar results. Neither type of classification error is likely to be correlated with the exposure, and both can therefore be assumed to be non-differential. Non-differential outcome misclassification is unlikely to introduce a spurious exposure-outcome association, rather it will attenuate any outcome-exposure association.

A possible disadvantage of this study is that Swiss railway workers are mainly exposed to magnetic fields with a relatively rare frequency of 16.7 Hz and only to a small extent to harmonics (50.1 and 83.5 Hz). Such exposures occur also in the Swedish, Norwegian, German and Austrian railway systems. Worldwide, 38% of electric traction is provided by direct current and 62% is provided by alternating current (in 48% 50 Hz; 14% 16.7 Hz; and rarely, 25 or 60 Hz) [20]. The most common frequencies of magnetic fields for power transmission and distribution are 50 and 60 Hz. All of these frequencies fall within the ELF range and have similar biophysical properties. Thus, given the uncertainty about mechanisms of biologic interaction, it is worthwhile to compare the health consequences from exposure to different frequencies in the ELF range. A future meta-analysis of all relevant studies might allow the formulation of hypotheses about frequency-specific health effects, which could inform the research agenda.

Comparison with Previous Studies

The most consistent finding of our study is an association between AD and ELF-MF exposure. This finding is in line with a Swedish study [12] reporting a relative risk for AD of 2.7 (95% CI = 1.6–4.5) for railway engine drivers compared to the general population. Similarly, most of the occupational studies focusing on power frequency magnetic fields have reported an increased risk of senile dementia or AD among exposed persons [1, 21–25], although a contradictory study has also been published [26]. With respect to latency period previous studies have been inconsistent. Our results are in line with 2 Swedish studies finding an association with exposure in the most recent occupation [12, 27] and contradict the results from a study in electric utility workers [28] which showed an association with exposure in the distant past.

The risk of ALS in occupations with exposures to power frequency magnetic fields has been investigated in several studies [1, 21, 22, 26, 29]. Increased risks seem to be restricted to electric utility workers and welders and were generally not found in other occupations with high exposure to magnetic fields [2]. For instance, the risk of ALS was not increased in Swedish railway engine drivers (relative risk = 0.9; 95% CI = 0.4–2.1) [12]. Our results for ALS were ambiguous, with risk slightly increased among highly exposed occupations. In our study, neither Parkinson's disease nor any other neurodegenerative diseases were associated with magnetic field exposure, as in most other studies [1, 21, 22, 25]. To our knowledge, only 1 study has reported an association between ELF-MF exposure and Parkinson's disease [26].

Confounding

In the analysis we controlled for potential confounding from age and period but cannot exclude confounding from other sources as an explanation for the findings. Known or suspected risk factors for AD are age, genetic predisposition, high blood pressure, diabetes, smoking, oxidative stress, atherosclerosis, female sex and brain injury, as well as exposure to metals, pesticides and solvents [30, 31]. However, it is unlikely that the association between AD and magnetic field exposure can be fully attributed to confounding because there is no reason to believe that these risk factors are unequally distributed among the 4 occupational groups, given the relatively similar working environments of the groups.

In an unpublished survey of 378 railway employees carried out in 1994, we found that station masters and train drivers were less likely to smoke (8 and 12%, respectively) than shunting yard engineers and train attendants (38 and 29%, respectively). This is in line with the observed all-cause, cardiovascular and respiratory tumour mortality of the 4 occupations. It is possible that the smoking rates are a surrogate for the socioeconomic status of the 4 occupational groups. This would imply that train drivers and station masters have a similar socioeconomic status, supporting the notion that the differences in the AD mortality rates observed between these 2 groups are unlikely to be explained by socioeconomic status or smoking. Shift work and exposure to heat in the driver's cabin may be more prevalent among train drivers than among station masters. The latter 2 occupations experience more social interactions than train drivers. However, none of these conditions are known to be a risk factor for neurodegenerative diseases.

Another argument against strong confounding is the fact that all-cause mortality as well as lung cancer mortality was not associated with magnetic field exposure. Thus, any potential confounding factor would have to be a very specific risk factor for AD. Electrical shocks are considered to be possible confounding factors in studies of ALS and magnetic fields [3], but this is not a common exposure among railway employees.

Biological Mechanism

Observed associations are difficult to interpret in the absence of a known biological mechanism or reproducible experimental support. We examined a possible threshold, latency or time window effect using different exposure measures. To our knowledge, no theory which indicates the most crucial exposure circumstances for neurodegenerative diseases has been published. For senile dementia, ALS and AD, we found some indications that the exposure time above a threshold is more crucial than the cumulative exposure and that more recent exposure is more strongly associated with risk than earlier exposure. Although the power is limited to differentiate between these different exposure measures, our results suggest that ELF-MF exposure may represent a late-acting influence in the disease process.

Conclusions and Directions for Future Research

Our study supports an association between occupational exposure to ELF-MF and senile dementia, in particular AD. We found some evidence that the time spent above a threshold may be more important than overall cumulative exposure and that more recent exposure is more strongly associated with risk than earlier exposure. These findings should be confirmed in additional studies as well as combined analyses of existing data. Furthermore, research on the possible biologic mechanisms is required.

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