ORIGINAL ARTICLE

Leukaemia, brain tumours and exposure to extremely low frequency magnetic fields: cohort study of Swiss railway employees

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Aims: To investigate the relationship between extremely low frequency magnetic field (ELF-MF) exposure and mortality from leukaemia and brain tumour in a cohort of Swiss railway workers.

Methods: 20 141 Swiss railway employees with 464 129 person-years of follow-up between 1972 and 2002 were studied. Mortality rates for leukaemia and brain tumour of highly exposed train drivers (21 μ T average annual exposure) were compared with medium and low exposed occupational groups (i.e. station masters with an average exposure of 1 μ T). In addition, individual cumulative exposure was calculated from on-site measurements and modelling of past exposures.

Results: The hazard ratio (HR) for leukaemia mortality of train drivers was 1.43 (95% CI 0.74 to 2.77) compared with station masters. For myeloid leukaemia the HR of train drivers was 4.74 (95% CI 1.04 to 21.60) and for Hodgkin's disease 3.29 (95% CI 0.69 to 15.63). Lymphoid leukaemia, non-Hodgkin's disease and brain tumour mortality were not associated with magnetic field exposure. Concordant results were obtained from analyses based on individual cumulative exposure.

Conclusions: Some evidence of an exposure-response association was found for myeloid leukaemia and Hodgkin's disease, but not for other haematopoietic and lymphatic malignancies and brain tumours.

Whether occupational exposure to extremely low frequency magnetic fields (ELF-MF) is causative for any neoplastic disease is still unresolved. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) stated in their comprehensive review that studies on the risk of brain tumour and adult leukaemia in relation to occupational magnetic field exposure have ranged from null to rather strong positive associations.¹ The ICNIRP did not find a clear pattern in which the better studies were more or less likely to produce positive associations for either leukaemia or brain tumours. Thus, assuming that random error accounts for differences between studies, the ICNIRP concluded that the results were most consistent with a weak positive association, with relative risks for the more highly exposed groups in the order of 1.1–1.3.

Given the challenges of exposure assessment in this area, railway employees are an attractive group for cohort studies into magnetic fields. In Switzerland railway workers are generally employed long term, resulting in limited job changes. The exposure conditions at a given workplace are well characterised but vary greatly across different occupations, with train drivers being exposed to very high ELF-MF levels and exposure in other employees comparable to that of the general population. Furthermore, 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 chemical pollutants or electric shocks, which often occur in other occupational settings (for example, in electric utility workers or welders), are rare. Previous studies on the cancer risk^{2–6} and chromosomal aberrations⁷ of railway workers yielded inconclusive results. The aim of the present study was to investigate further a previously observed association between ELF-MF exposure and risk for leukaemia in Swiss railway employees.⁵ We extended the follow-up period by 9 years from 1 January 1994 to 31 December 2002, resulting in 1834 additional deaths and 194 000 additional person-years at

risk. In addition, ELF-MF exposure assessment methods were improved by performing additional measurements and by modelling past exposure.

METHODS

The study was approved by the Federal Commission of Experts for Professional Secrecy in Medical Research (<http://www.bag.admin.ch/org/02329/>, accessed 23 March 2007).

Study population

All men from the Swiss Federal Railways personnel and pension records, who were recorded as actively employed or retired at any time between 1972 and 2002 were included in the cohort. The following occupations, which differed in their average exposure to ELF-MF, were included: train drivers, shunting yard drivers, train attendants and station masters. The records included data on the beginning 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).

Vital status

Causes of death were derived from death certificates obtained from the Swiss Federal Statistical Office. In Switzerland, death certificates are completed either by the family doctor or by a physician from the hospital where the death occurred. We used a probabilistic record linkage method,⁸ implemented in the software LinkPro 3.0⁹ to match employee records with anonymous death certificates. An investigator unaware of both occupation and exposure status linked the records. Linkage variables were date of birth, date of death, place of residence at time of death, occupation, marital status and duration of marriage.

Abbreviations: ELF-MF, extremely low frequency magnetic field; HR, hazards ratio; ICNIRP, International Commission on Non-Ionizing Radiation Protection

In the 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 the 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 31 December 1992 and on 31 December 2002. None of the workers assumed to have died before these dates, based on probabilistic record linkage, were found in the database.

Outcomes

The primary outcomes of this study were deaths from any haematopoietic or lymphatic malignancies as well as brain tumour. All deaths with a relevant diagnosis on the death certificate were included, independently of whether the diagnosis was coded as the underlying, immediate or a contributing cause. We analysed respiratory tumours, all types of tumour and all-cause mortality for comparison. An analysis on neurodegenerative disease mortality will be reported elsewhere (Röögli M *et al*, unpublished data). 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).¹⁰ Table 1 gives the ICD codes used.

Exposure assessment

Swiss trains run on a 16.7 Hz alternating current. The Swiss Railway engine fleet consists of about 2000 engines of 30 different line and shunting engine types. Line engines are exclusively electrical, whereas both electric and diesel engines are used for shunting in the rail yard. Coal driven steam engines were used until the 1960s, at the end mainly for shunting. Railway employees retire at age 65 at the latest. Train drivers generally operate a variety of engines every day, with the exception of drivers serving on the Alpine transit line, who essentially used the same engines from 1919 to 1960. Shunting yard drivers drive several smaller engines to set up train compositions. Train attendants are found on all passenger trains, checking tickets and assisting travellers with queries. Station masters work between their offices and the station platforms. Each man was assigned the occupational group he held when he left the cohort, which was usually the same as that when he began.

For each occupational group, average exposure for each year was determined based on measurements and modelling. The first set of measurements was carried out in 1993–4 using a commercial Bramur Gaussmeter (Bramur, Lee, MA, USA).¹¹ A second set was done in 2003–4 using an EFA device from Wandel and Goltermann (now Narda Safety Test Solution, Germany).¹² A 16.7 Hz bandpass filter was used. For 21 measurement runs, a broadband filter (5 Hz to 2 kHz) was used for comparison with simultaneously performed measurements using the 16.7 Hz filter. In total, 139 measurement runs were performed in numerous engines under real service conditions, representing 198 operating hours. In passenger coaches and the workplaces of station masters, an additional 41 measurement runs were conducted with a total duration of 21.3 hours. 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 taken under the current real service conditions. Meters were placed at three positions of the driver in the engine cab: feet, thorax and head. The thorax meter was either fixed at

the back of the driver's seat or carried as a "back-pack". For this study, only the thorax value was used.

Past exposure levels were estimated using the FABEL simulation software (<http://www.enotrac.com/tps/index.htm>, accessed 23 March 2007) based on the engine-specific association between traction effort, speed and magnetic flux density, which was obtained from measurements during well-defined operating conditions. These estimates allowed us to take into account the kind of train (freight, normal or fast), the driving cycle and the trainload. For some engines, these factors changed over time. The average yearly 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 1919–65, these calculations were done separately for the Alpine and lowland lines because more powerful engines were used in the Alpine region, with particularly high field levels in the driver's cabin.¹³ Train drivers were classified as Alpine or lowland drivers, according to their place of residence.

Exposure assessment for shunting yard drivers

Average annual exposures for shunting yard drivers were derived from measurements taken under service conditions by calculating weighted means according to the shunting yard engine fleet of the respective year. For diesel engines, magnetic fields were assumed to originate only from electric overhead contact lines (1 μ T until 1960, 2 μ T from 1960 through 2002), because much shunting work was done near to, or directly under, these lines.

Exposure assessment for train attendant and station masters

Average annual exposures for train attendants were derived from measurements under real service conditions by calculating weighted means according to the wagon compositions used. Past exposures were corrected for changes in emissions from contact wires over time. Based on sample measurements at several stations, a mean exposure level of 1 μ T was determined for the year 2002 and was linearly extrapolated to 0 μ T in the year 1919.

Data analysis

Statistical analyses

We analysed data using Cox proportional hazards 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 changes in ICD codes. Age at entry into the cohort was introduced as linear, quadratic and cubic terms. The association between mortality and exposure was modelled using two approaches. First, occupational groups served as a proxy for exposure, and a Mantel–Cox score test of trends was calculated to evaluate exposure–response associations. Second, cumulative exposure, expressed as microtesla-years (μ T-years), was entered as a time-varying covariate into the model. 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 hours a day and 240 working days a year.

We tested all models successfully for the proportionality assumption using Nelson–Aalen survivor functions and statistical tests based on Schoenfeld residuals. Data were analysed using STATA 9.0 (Stata Corporation, College Station, Texas, USA).

Assessment of excess cancer cases from diagnostic x ray exposure

Different diagnostic x ray practices were routinely applied to the various Swiss railway occupations (personal communication,

Table 1 Swiss railway cohort: numbers of male railway employees, person-years at risk and numbers of deaths, by cause and occupational group

	ICD-8	ICD-10	Alpine train drivers No (%)	Lowland train drivers No (%)	Shunting yard engineers No (%)	Train attendants No (%)	Station masters No (%)	Total No (%)
Number of people at risk			925	6172	1378	6909	4757	20 141
Person-years at risk			20 491	130 648	33 752	160 819	118 418	464 129*
Number of deaths (all causes)			211 (100)	1441 (100)	394 (100)	2089 (100)	1278 (100)	5413 (100)
Tumour, all	140-239	C00-97, D00-48	87 (41.2)	482 (33.4)	135 (34.3)	633 (30.3)	419 (32.8)	1756 (32.4)
Respiratory tumour	160-163	C30-39, G450	15 (7.1)	97 (6.7)	30 (7.6)	147 (7.0)	89 (7.0)	378 (7.0)
Haematopoietic and lymphatic malignancies	200-209	C81-85, C90-96	9 (4.3)	46 (3.2)	17 (4.3)	52 (2.5)	38 (3.0)	162 (3.0)
Hodgkin's disease	201	C81	1 (0.5)	7 (0.5)	1 (0.3)	4 (0.2)	2 (0.2)	15 (0.3)
Non-Hodgkin's disease	200, 202	C82-85	3 (1.4)	10 (0.7)	6 (1.5)	15 (0.7)	12 (0.9)	46 (0.8)
Leukaemia	204-207	C91-95	2 (0.9)	23 (1.6)	6 (1.5)	21 (1.0)	14 (1.1)	66 (1.2)
Lymphoid leukaemia,	204	C91	0 (0.0)	9 (0.6)	4 (1.0)	11 (0.5)	12 (0.9)	36 (0.7)
Myeloid leukaemia	205	C92	2 (0.9)	9 (0.6)	2 (0.5)	8 (0.4)	2 (0.2)	23 (0.4)
Brain tumour	191	C71	0 (0.0)	6 (0.4)	5 (1.3)	17 (0.8)	10 (0.8)	38 (0.7)

*Person years at-risk do not add up to total owing to rounding error.

Voumard, P-A, Medical Service, 2006): until 1986 all four occupational groups had a chest *x* ray every third year. From 1987 to 1994, line and shunting yard drivers were regularly chest *x* rayed (until the age of 45 years: every fifth year; after 45 years: every third year), but train attendants and station masters were not. In 1995, the Swiss railways abandoned routine *x* ray examinations.

To evaluate whether diagnostic *x* ray examinations acted as confounding factor, we estimated the excess number of cases due to the additional diagnostic *x* ray exposure of train and shunting yards drivers between 1987 and 1994. The average cumulative equivalent dose to ionising radiation was multiplied by the excess risk published by the International Commission on Radiological Protection¹⁴ (0.05 additional cancer cases per 1 Sv equivalent dose) and the person-years at risk (53 000).

RESULTS

Characteristics of the cohort

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 3406 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 these were probably foreigners who had returned to their country of origin. These deaths were included as deaths from unknown cause. A total of 1968 additional deaths were identified among the remaining 16 735 men. None of these matched more than one death certificate: so there were no unresolved links. Data from the 39 men found to be older than 100 years at the study end point (31 December 2002) were censored at the age of 100 years.

There were few job changes in our cohort. Among men registered as train drivers in 1993, 98.4% were still 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 attendants, and 85.3% for station masters. Train attendants and station masters who changed jobs tended to move to another low-level exposure job within the company; only three became train drivers.

Exposure assessment

For all train drivers, the annual average exposure was approximately 21 μ T (table 2). However, until the 1960s, considerable differences were found between lowland and Alpine train drivers, with much higher exposure levels in the latter. These high exposure values were mainly caused by one engine type (type Ce 6/8), which was exclusively used for Alpine transit traffic until 1960. Shunting yard engineers were on average exposed to 3.6 μ T in 1940, increasing to 6.0 μ T in 2000. The exposure of train attendants was below 2 μ T 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 μ T to 1.0 μ T.

The median cumulative lifetime exposure of train drivers (120 μ T-years) was about three times higher than the average exposure of shunting yard engineers (42 μ T-years) and about nine times higher than that of train attendants (13 μ T-years). Station masters were only minimally exposed (6 μ T-years). The median cumulative exposure was 141.7 μ T-years for Alpine train drivers and 116.5 μ T for lowland line drivers. The average cumulative time period spent above 10 μ T was 2.5 years for train drivers and 1.8 years for shunting yard engineers. Only train drivers were exposed to levels above 100 μ T (0.24 years on average).

Outcomes

Table 3 shows the association between cancer and occupational group. All-cause mortality is slightly higher in the group of shunting yard drivers and train attendants than in train drivers

Table 2 Exposure in the four occupational groups

Average exposure	Alpine train drivers (μ T)	Lowland train drivers (μ T)	Shunting yard engineers (μ T)	Train attendants (μ T)	Station masters (μ T)
In 1940	54.9	17.2	3.6	1.1	0.3
In 1960	24.5	18.4	5.2	1.7	0.5
In 1980	21.4	21.4	5.5	1.8	0.7
In 2000	21.0	21.0	6.0	4.2	1.0

Table 3 Hazard ratios (HR) including 95% CI for selected neoplastic causes of death, ordered by decreasing exposure of occupation (highest exposure: Alpine train drivers, lowest exposure (reference): station masters)

Outcome	Alpine train drivers HR (95% CI)	Lowland train drivers HR (95% CI)	Shunting yard engineers HR (95% CI)	Train attendants HR (95% CI)	Station masters (ref.) HR	Test for trend† p Value
All-cause mortality	1.01 (0.87 to 1.17)	1.02 (0.95 to 1.10)	1.12 (1.00 to 1.26)	1.13 (1.05 to 1.21)	1	0.787
Tumour, all	1.25 (0.99 to 1.58)	1.04 (0.91 to 1.18)	1.06 (0.87 to 1.29)	1.03 (0.91 to 1.17)	1	0.119
Respiratory tumour	1.04 (0.60 to 1.80)	0.98 (0.73 to 1.31)	1.05 (0.70 to 1.60)	1.11 (0.85 to 1.44)	1	0.865
Haematopoietic and lymphatic malignancies	1.46 (0.70 to 3.02)	1.12 (0.73 to 1.73)	1.44 (0.81 to 2.57)	0.95 (0.62 to 1.45)	1	0.250
Hodgkin's disease	3.32 (0.30 to 36.89)	3.28 (0.68 to 15.97)	1.50 (0.13 to 16.78)	1.51 (0.27 to 8.32)	1	0.062
Non-Hodgkin's disease	1.68 (0.47 to 6.03)	0.80 (0.34 to 1.87)	1.49 (0.56 to 4.00)	0.87 (0.40 to 1.88)	1	0.947
Leukaemia	0.87 (0.20 to 3.83)	1.52 (0.78 to 2.97)	1.49 (0.57 to 3.92)	1.07 (0.54 to 2.11)	1	0.280
Lymphoid leukaemia	—*	0.68 (0.28 to 1.62)	1.27 (0.40 to 4.02)	0.58 (0.26 to 1.34)	1	0.263
Myeloid leukaemia	6.44 (0.90 to 45.95)	4.46 (0.95 to 20.89)	3.08 (0.43 to 22.05)	3.07 (0.65 to 14.57)	1	0.035
Brain tumour	—*	0.64 (0.23 to 1.79)	1.54 (0.52 to 4.54)	1.28 (0.58 to 2.86)	1	0.130

*No cases.

†Mantel-Cox score test for trends.

and station masters. For brain, respiratory and all tumour mortality, differences between groups were minor, except some increase in all-tumour mortality in Alpine train drivers. A trend of increasing hazard ratios (HRs) with increasing magnetic field exposure was observed for myeloid leukaemia and Hodgkin's disease (table 3). The HR for all types of leukaemia mortality of Alpine and lowland train drivers combined was 1.43 (95% CI 0.74 to 2.77) compared with station masters. The increased leukaemia risk of train drivers was restricted to myeloid leukaemia (HR = 4.74 (95% CI 1.04 to 21.60)). The HR for Hodgkin's disease of Alpine and lowland train drivers was 3.29 (95% CI 0.69 to 15.63) compared with station masters. No evidence of an exposure-response association was obtained for lymphoid leukaemia, non-Hodgkin's disease and brain tumour mortality.

Models based on cumulative lifetime exposure instead of the occupational groups yielded similar results (table 4). Indication of an exposure-response association was found for myeloid leukaemia with an HR of 1.06 (95% CI 0.99 to 1.14) per 10 μ T-years of cumulative exposure to ELF-MF. The corresponding HR for Hodgkin's disease was 1.09 (95% CI 1.00 to 1.19). For other outcomes there was little evidence for an association.

In train and shunting yard drivers leukaemia rates have remained fairly stable over the course of the follow-up period, whereas in train attendants and station masters an increasing rate has been seen since 1994 (fig 1A). However, the observed increase in the leukaemia rates of train attendants and station masters failed to reach conventional levels of statistical significance ($p = 0.07$), using a spline-based Poisson regression model with a knot in the year 1994. Corresponding p values for lymphatic and myeloid leukaemia rates were 0.07 and 0.39 respectively.

Table 4 Increase in hazard ratios (HR incl. 95% CI) per increase of exposure by 10 μ T-years

Outcome	HR (95% CI)
All-cause mortality	0.99 (0.99 to 1.00)
Tumour, all	1.00 (0.99 to 1.01)
Respiratory tumour	0.99 (0.97 to 1.01)
Haematopoietic and lymphatic malignancies	1.01 (0.98 to 1.04)
Hodgkin's disease	1.09 (1.00 to 1.19)
Non-Hodgkin's disease	0.99 (0.94 to 1.05)
Leukaemia	1.02 (0.98 to 1.07)
Lymphoid leukaemia	0.98 (0.92 to 1.04)
Myeloid leukaemia	1.06 (0.99 to 1.14)
Brain tumour	0.94 (0.88 to 1.01)

Analyses restricted to the extended follow-up period from 1994 to 2002 yielded a cohort of 16 491 people with a mortality follow-up of 140 863 person years. For that period HRs for all investigated haematopoietic and lymphatic malignancies were below unity for the more exposed train and shunting yard drivers compared with train attendants and station masters.

Estimated excess cancer cases from exposure to diagnostic x rays

From 1987 to 1994 only train and shunting yard drivers had regular chest x rays, resulting in an additional equivalent dose of ionising radiation of about 0.3 mSv (personal communication Martin Meier, Swiss Federal Office of Public Health, 2006). Based on this, we estimated that there were 0.8 excess cancer cases, as a result of this exposure during the study period.

DISCUSSION

Summary

We found indications of an exposure-response association for myeloid leukaemia and Hodgkin's disease, but, not for other haematopoietic and lymphatic malignancies and brain tumours. Interestingly, the differences in leukaemia mortality rates among the occupations tended to decrease over the course of the follow-up period.

Strengths and limitations

The strengths of this study were the large differences in exposure between the occupations and the fact that most remained in the same job over the whole study period. The exposure circumstances in the occupational groups were well defined, which allowed the effective magnetic flux density to be measured during work conditions and past exposures to be modelled. For each employee, the beginning and end dates of employment (exposure) were available. These data allowed us to calculate a cumulative exposure measure. A small number of Alpine train drivers were exposed to very high magnetic field levels until the early 1960s.

The main limitation of this study was the small number of deaths from cancer observed, despite a follow-up period of 31 years, in particular for Hodgkin's disease (15 cases), myeloid leukaemia (23), lymphoid leukaemia (36) and brain tumour (38). We also have to consider possible misclassification of the outcome and the exposure. In the absence of a cancer registry with national coverage we used mortality data, which will underestimate the incidence of leukaemia and brain tumours. We assessed the completeness of ascertainment of cases by comparing the number of deaths with the number of predicted

Figure 1 Total leukaemia (A), lymphoid leukaemia (B) and myeloid leukaemia (C) rates and cases per year among high- (railway and shunting yard drivers) and low-exposed occupations (train attendant and station masters). The connected lines show 5-year moving averages, the dots at the bottom represent the number of cases.

incident cases, based on data from the 13 cantonal cancer registries that cover 58% of the population. We found that in the age group 50 years and older, brain tumour and leukaemia deaths accounted for 95% and 89%, respectively, of the number of incident cancer cases between 1993 and 2003. For Hodgkin's and non-Hodgkin's disease, the corresponding figures were 55% and 53%, respectively.

The second type of classification error could have come from the probabilistic record linkage process. The fact that we did not

have any unresolved links probably indicates that the linkage strategy was restrictive, which minimised false links. Neither type of classification error was likely to have been correlated with the exposure, and can be assumed to have been non-differential. Non-differential outcome misclassification is unlikely to introduce a spurious exposure–outcome association; it is more likely to attenuate any outcome–exposure association. Moreover, we had no indication that the degree of misclassification or levels of ascertainment had changed over the course of the follow-up period.

Comparison with the previous study and the literature

In this study the association between magnetic field exposure and leukaemia was less pronounced than seen in our previous study⁵ because leukaemia mortality rates among train attendants and station masters have been increasing since the early 1990s. Analysis restricted to the new follow-up data from 1994 onwards produced no evidence for an association between leukaemia and magnetic field exposure, although confidence intervals were wide. In the previous study a substantially increased brain tumour risk was observed for shunting yard engineers, which was not evident in this follow-up study.

Leukaemia and brain tumour risks of railway workers exposed to a 16.7 Hz magnetic field have been investigated in two Swedish^{3,4} and one Norwegian⁶ study. Whereas none of these studies found evidence for an increased brain tumour and lymphoma risk in exposed workers, results for leukaemia were contradictory. In the Norwegian study, the risk for leukaemia in railway employees working on electrified railways was not increased compared with employees working on non-electrified railways. In the Swedish studies an increased leukaemia risk was associated with magnetic field exposure. Alfredsson and colleagues reported an increased lymphoid leukaemia risk in Swedish railway drivers, based on a follow-up period from 1976 to 1990.³ Interestingly, Floderus and colleagues, in another Swedish study, divided their follow-up time into two periods (1961–9 and 1970–9) and found increased HRs for railway drivers for the first decade but not for the second.⁴ They speculated that the effects of EMF may manifest themselves within a relatively short time after exposure and that people exposed for several decades may to some extent have become resistant to them.

Beside railways, the most common frequencies in the ELF range are 50 and 60 Hz, which are used for power transmission and distribution. Research on the risk of adult leukaemia and brain tumour risk in workers exposed to these fields has also yielded inconclusive results.¹⁵

Confounding

In our analysis, we controlled for potential confounding by age and time period but could not exclude confounding from other sources. Most relevant known risk factors for leukaemia are ionising radiation, exposure to chemotherapy, tobacco smoking, benzene and infections.¹⁶

Exposure to chemicals seemed an unlikely explanation: benzene was never used as a cleaning fluid in the Swiss railway (Lauber P, Cleaning Services, personal communication, 2001), and polychlorinated biphenyls were also never used in Swiss Railways transformers (Gerber M, Motive Power Construction Division, personal communication, 2001). 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 yard engineers and train attendants (38% and 29%, respectively). This is in line with the observed all-cause and respiratory tumour mortality of the four occupations. Possibly, the smoking rates are a surrogate for the socioeconomic status of the four occupational

Main messages

- Large differences in magnetic field exposure exist between some railway occupations: train drivers, shunting yard drivers, train attendants, station masters.
- We found some evidence for an exposure–response association for myeloid leukaemia and Hodgkin's disease.
- We found little evidence for an exposure–response association for lymphoid leukaemia, Non-Hodgkin's diseases and brain tumours.
- The leukaemia mortality rates of the selected railway occupations became more similar during the course of the follow-up period.

Policy implications

- Train passengers spend considerably less time in trains than the people with the occupations studied and their exposure levels and potential health risk are therefore negligible.
- As a precautionary measure, ELF-MF exposure in new rolling stock should be minimised, in particular at the drivers' workplaces.

groups. This would imply that train drivers and station masters have a similar socioeconomic status, and supports the notion that the differences in the leukaemia rates observed between these two groups are unlikely to be explained by socioeconomic factors or smoking. In addition, none of the potential confounders are expected to have changed markedly over time and it is therefore unlikely that they explain the increase in leukaemia mortality rates seen in train attendants and station masters since the early nineties.

It is well established that diagnostic *x* rays are a known risk factor for myeloid leukaemia but not for lymphoid leukaemia and lymphomas.^{16–19} For myeloid leukaemia we observed a considerably increased HR for train drivers. However, we found little evidence for confounding from diagnostic *x* ray exposure. The number of excess cancer cases in train and shunting yard drivers due to additional *x* ray exposure is estimated to be below one. In addition, models obtained from splitting the data set into three time periods corresponding to different diagnostic *x* ray practices (1972–86, 1987–94; 1995–2002) did not suggest confounding from diagnostic *x* ray exposure.

Exposure to coal driven steam engines may also have been a potential confounding factor. Engine drivers might be more exposed to steamers' exhaust until 1960. However, the risk of leukaemia appears to decline rapidly 5–10 years after exposure,¹⁶ suggesting that a longlasting effect from exposure to steamers into the 1970s and 1980s is rather unlikely.

Electric arcs occur occasionally in railway engines when switching during acceleration. This might have resulted in higher exposure to air ions for engine drivers compared with train attendants and station masters. Similarly, shift work and exposure to heat in the driver's cabin may be more prevalent among drivers than for station masters. However, all of these factors are not known to be strong risk factors for leukaemia and thus, are unlikely to explain the observed differences in the leukaemia rates between the four occupational groups. Additionally, they have not changed much over the study

period. Survival has improved over the course of the follow-up period, particularly for patients with lymphomas. Health insurance is universal in Switzerland and improvements in survival can therefore be expected to be similar among the four occupations. Furthermore, all railway workers undergo periodical medical examinations.

One might speculate, although we have no evidence for it, that infections may play a role in the increasing leukaemia mortality rates in train attendants and station masters over the course of the follow-up period. Both occupations have considerably more social interactions with passengers than train drivers.

CONCLUSIONS

We found indications of an exposure–response association for myeloid leukaemia and Hodgkin's disease, but, not for other haematopoietic and lymphatic malignancies and brain tumours. The association was less pronounced than previously observed because leukaemia mortality rates among train attendants and station masters, who were only exposed to low levels, have been increasing since the early nineties. A plausible explanation for this observation could not be identified and random data variability is considered to be the most likely explanation. Additional analyses in a few years may clarify this finding.

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