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REVIEW ARTICLE

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Occupational exposure to electromagnetic fields and adult leukaemia: a review of the epidemiological evidence

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Abstract The relationship between occupational exposure to extremely low-frequency electromagnetic fields and adult leukaemia has been studied extensively during the last decade. The first studies were based on crude exposure assessments, estimated through job titles, with no or only limited control of confounding factors. The results were often inconsistent, indicating no effects in about 50% of the studies, while the other half showed only small to moderate effects. Concern has been raised that crude exposure-assessment methods might have diluted the effect estimates, and that improvement of the methods used for exposure assessment would result in more consistent associations. The present review emphasises the latest studies with considerably improved exposure assessments, as well as the control of confounding factors. Results from studies where exposure was assessed through measurements of the magnetic fields at the workplace are still inconsistent. These studies provide some support for the hypothesis of an association between magnetic field exposure and adult leukaemia, especially for chronic lymphocytic leukaemia, but inconsistencies between and within studies weaken the evidence. The lack of consistency regarding the type of leukaemia associated with magnetic field exposure might be explained by differences between the study designs or the populations studied, but based on the existing evidence, no firm conclusions can be drawn.

Introduction

The interest in a possible association between extremely low frequency (ELF) electromagnetic field exposure and cancer dates back to 1979 when Wertheimer and Leeper [1] reported an excess of cancer mortality among children living in homes with presumedly elevated magnetic fields. Since then, a large number of epidemiological studies of the association between residential or occupational exposure to electromagnetic fields and cancer has been published. Several reviews of this research have been performed by different task groups, such as the Oak Ridge Associated Universities panel in the USA and the British Radiological Protection Board, and by independent researchers [2–6]. This review will focus on studies dealing with the association between occupational electromagnetic field exposure and adult leukaemia which were published between 1993 and 1995 [7–14].

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Magnetic fields are able to penetrate buildings, trees and other objects, in contrast to electric fields, which are easily shielded. Therefore, studies of residential exposure to electromagnetic fields have focused on magnetic field exposure. In general, occupational exposure is due to a combination of both magnetic and electric fields, although most of the epidemiological studies have limited the exposure assessment to the magnetic fields.

It is difficult to evaluate the existing research on a possible association between occupational exposure to magnetic fields and adult leukaemia. Today, no mechanism is known which describes a potential interaction between ELF magnetic fields and biological systems that could produce leukaemia. As a consequence, the biologically relevant aspects of magnetic field exposure are unknown. Even if the majority of the later studies focused on magnetic fields, the electric fields might also be relevant, and moreover, different patterns of magnetic field exposure might produce different effects. For example, it is unknown whether the effect of a long-term exposure to moderately elevated magnetic fields is comparable to that of a short term exposure to very high fields. Intermittent magnetic field exposure may be more relevant, or perhaps time spent above a certain magnetic field strength level. Furthermore, magnetic fields are ubiquitous in the environment, and nobody is unexposed. Thus, there is always a certain amount of misclassification of the exposure in studies of possible health effects due to magnetic field exposure.

The first group of studies performed can be characterised as ones exploring existing data with regard to indices of magnetic field exposure. Only those studies published within the last few years have utilised thoroughly developed methods for exposure assessment. This review will focus on research concerned with occupational exposure estimated through actual measurements of magnetic fields in workplaces. Readers who are interested in a more comprehensive overview of the first generation of studies are referred to earlier reviews (e.g. [6]).

First generation of studies

The first generation of studies used rather crude methods to assess magnetic field exposure, mainly through job titles [15–31]. Virtually no direct measurements of the magnetic fields in different occupations were performed, and the grouping of job titles into “electrical occupations” was made rather intuitively. Separate analyses for occupations believed to be highly exposed, such as electricians, linemen and welders, were often provided. Later studies designed to investigate the exposure within different occupations confirmed that workers within occupations originally classified as “electrical” generally have a higher exposure to magnetic fields than workers in other occupations [32]. There may, however, be a large variation in the level of exposure within and between “electrical” job titles, which would create a non-differential misclassification of the exposure. In most studies, no or only a limited control of potential confounding factors was made. Several of these early studies were designed as proportional mortality (or morbidity) studies, while others were cohort studies based on historical registries containing information about occupation, such as census registries. In some case-control studies, magnetic field exposure was one of the risk factors studied. In these studies, the occupational history among cases was compared with that among controls, but assessment of the exposure was still based on job titles alone.

Results of the first generation of studies

Approximately 20 studies were published before 1991. In about one-half of those reporting results for all leukaemias combined, a modest increase of risk for “electrical occupations” was found, the risk estimates ranging from 1.2 to 1.5. The other half did not report any association. The same holds true for acute myeloid leukaemia, although fewer studies are available, and the risk estimates are slightly higher when elevated and less precise. Several studies describe results for specific occupations assumed to be associated with high magnetic field exposure. For electricians, about half of the studies found slightly increased risk estimates for total leukaemia, whereas for linemen, the association with total leukaemia was more consistent, with nine of ten studies showing risk estimates >1. In several studies, modest associations were found for electrical engineers, but virtually none for welders.

The majority of the studies provide no or only limited information on potential confounding factors, yet confounding may have affected the results in several of the studies.

The possibility that non-differential exposure misclassification may have diluted the risk estimates in studies using job titles as the basis for exposure assessment have been discussed. If this is true, higher and more consistent risk estimates would be expected in studies in which the exposure assessment has been improved.

Measurement studies

During the last few years, a number of studies have been published in which a considerable improvement of the assessment of occupational exposure to magnetic fields was achieved, as well as of potential confounding factors. This review will focus on eight studies based on magnetic field measurements for exposure assessment. Table 1 presents some design characteristics of these eight studies. That by Savitz and Loomis [11] and one of them by Tynes et al. [14] are cohort studies, that by Sahl et al. is both a cohort and a case-control study and all others are case-control studies. The majority of studies were performed within certain industries, while those by Floderus et al. [7] and by London et al. [8] were based on the general population. The study by Matanoski et al. [9] involved telephone and telegraph workers, the studies by Sahl et al. [10], Thériault et al. [12], and Savitz and Loomis [11] involved electric utility workers, the case-control study by Tynes et al. [13] involved railway workers, and the cohort study by Tynes et al. [14] involved hydroelectric power workers. The two studies by Tynes et al. [13, 14] and the study by Sahl et al. [10] are based on rather small numbers of cases, and give results only for all leukaemia diagnoses combined. Matanoski et al. [9] excluded all cases of chronic lymphocytic leukaemia, and reported results for all other leukaemia diagnoses combined. The other studies present results for subgroups of leukaemia.

Matanoski et al. [9], Sahl et al. [10] and Savitz and Loomis [11] examined mortality as the outcome, while the other studies investigated incident cases.

None of the studies measured the magnetic field exposure for each individual subject included, but rather for categories of occupations, through a number of workers within each job category or through a representative sample of workdays within a job category. The exposure estimate for the job category was assigned to each individual worker within that category. The majority of the studies estimated the cumulative exposure for the individual workers, with the exception of the studies by Floderus et al. [7] and London et al. [8], the first one estimating the average exposure for the job task held longest during the 10 years preceding diagnosis, and the latter including only the latest occupation.

Table 1 Design characteristics of studies of occupational exposure to magnetic fields and adult leukaemia, with exposure estimates being based on measurements of the magnetic fields at the workplace. (All = all types of leukaemia combined, AnL = acute non-lymphocytic leukaemia, AML = acute myeloid leukaemia, ALL = acute lymphocytic leukaemia, CLL = chronic lymphocytic leukaemia, CML = chronic myeloid leukaemia)

Study	Study design	Type of outcome (leukaemia subgroups)	Location	Industry	Number of eligible cases
Matanoski et al. 1993 [9]	Case-control	Mortality (All excl. CLL)	USA	Telephone and telegraph	124
Sahl et al. 1993 [10]	Cohort and case-control	Mortality (All)	USA	Electric utility	44
Floderus et al. 1993 [7]	Case-control	Incidence (All, AML, CLL)	Sweden	Community-based	325
London et al. 1994 [8]	Case-control	Incidence (All, AnL, CLL, CML)	USA	Community-based	2355
Thériault et al. 1994 [12]	Case-control	Incidence (All, AnL, AML, ALL, CLL, CML)	Canada	Electric utility	140
Tynes et al. 1994a [13]	Case-control	Incidence (All)	Norway	Railway	53
Tynes et al. 1994b [14]	Cohort	Incidence (All)	Norway	Hydroelectric power	11
Savitz and Loomis 1995 [11]	Cohort	Mortality (All, AML, CLL)	USA	Electric utility	164

Results of measurement studies

Table 2 presents the results for all leukaemia diagnoses combined, with exposure assessment based on measurements. Effect estimates were slightly elevated in four of the eight studies. An indication of dose response was found in the studies by Floderus et al. [7] and Thériault et al. [12], but not in the others. Thériault et al. presented inconsistent results among the participating utilities, showing elevated risks for two of them, but not for the third one.

Four of the studies presented results based on job titles. London et al. [8] found a small increase in leukaemia risk for subjects working in “electrical occupations”, but this finding was not supported by the other three studies. Savitz and Loomis [11] and Sahl et al. [10] noted elevated risks for electricians, but not for other occupations. Matanoski et al. [9] did not observe an association with any of the occupations believed to involve exposure to magnetic fields, but when the material was restricted to active or recently retired workers, results indicated an association with line work.

Table 3 presents results for subgroups of leukaemia, based on magnetic field measurements. The elevated risk for leukaemia found in the Floderus study [7] was totally confined to chronic lymphocytic leukaemia, with a clear dose-response pattern. No association at all was found for acute myeloid leukaemia. In the London study [8], an elevated relative risk for chronic lymphocytic leukaemia was found only in the intermediate category, but the number of cases in the highest exposure category was small. A slightly increased risk for acute non-lymphocytic leukaemia was

Table 2 Occupational magnetic field exposure and all leukaemia diagnoses combined, results from studies with exposure estimates being based on measurements

Study	Exposure	All leukaemias combined
Matanoski et al. 1993 [9] Cumulative exposure	≥Median	2.5 (0.7–8.6)
	2nd quartile	1.4
	3rd quartile	4.6
	4th quartile	2.5
Sahl et al. 1993 [10] Cumulative exposure	≥3.5 μT-years (median)	1.0 (0.8–1.4)
Floderus et al. 1993 [7] Mean exposure	0.2–0.28 μT	1.2 (0.8–1.9)
	≥0.29 μT	1.6 (1.1–2.4)
	≥0.41 μT	1.7 (1.0–2.7)
London et al. 1994 [8] Mean exposure	0.18–0.8 μT	1.2 (1.0–1.6)
	>0.8 μT	1.4 (1.0–2.0)
Thériault et al. 1994 [12] Cumulative exposure	≥3.1 μT-years (median)	1.5 (0.9–2.6)
	3.1–6.89 μT-years	1.3 (0.7–2.4)
	6.9–15.69 μT-years	1.9 (1.0–3.8)
	≥15.7 μT-years	1.8 (0.8–4.0)
Tynes et al. 1994a [13] Cumulative exposure	0.1–310 μT-years	1.0 (0.5–2.1)
	>310 μT-years	0.6 (0.3–1.2)
Tynes et al. 1994b [14] Cumulative exposure	<5 μT-years	0.95
	5–35 μT-years	0.74
	>35 μT-years	1.04
Savitz and Loomis 1995 [11] Cumulative exposure	RR per μT-year	1.0 (0.9–1.1)

Table 3 Occupational magnetic field exposure and subgroups of leukaemia, results from studies with exposure estimates being based on measurements

Study	Exposure	AML or AnL	CLL
Floderus et al. 1993 [7]	0.2–0.28 μT	0.8 (0.4–1.6)	2.2 (1.1–4.3)
	≥0.29 μT	1.0 (0.6–1.9)	3.0 (1.6–5.8)
	≥0.41 μT	0.9 (0.4–2.1)	3.7 (1.8–7.7)
London et al. 1994 [8]	0.18–0.8 μT	1.3 (0.9–1.9)	1.6 (1.2–2.3)
	>0.8 μT	1.3 (0.7–2.3)	0.8 (0.4–1.5)
Thériault et al. 1994 [12]	≥3.1 μT-years	3.2 (1.2–8.3)	1.5 (0.5–4.4)
	3.1–6.89 μT-years	4.0 (1.4–12.0)	1.1 (0.3–3.9)
	6.9–15.69 μT-years	2.2 (0.7–7.3)	2.2 (0.6–8.3)
	≥15.7 μT-years	2.7 (0.5–14.5)	1.7 (0.4–6.7)
Savitz and Loomis 1995 [11]	RR per μT-year	1.0 (0.9–1.2)	1.0 (0.8–1.1)

found, with wide confidence intervals, especially for the highest exposure category. London et al. [8] found the highest relative risk estimate for chronic myeloid leukaemia, with an odds ratio of 2.5 (range 1.4–3.8). Thériault et al. [12] found elevated risks primarily for acute myeloid leukaemia, but no dose-response pattern. The relative risk for chronic lymphocytic leukaemia was slightly elevated but imprecise. Savitz and Loomis [11] found no association for any of the leukaemia subgroups when measurements were used to estimate exposure. Elevated risk estimates for both chronic lymphocytic and acute myeloid leukaemia were noted for electricians, the occupation with the highest exposure in the Savitz study.

No control for confounding was made in the studies by Matanoski et al. [9] and Sahl et al. [10]. In the other studies controlling was done for exposure to solvents [7, 8, 11, 13, 14], benzene, ionising radiation [7, 8], gasoline exhaust [8], herbicides [8, 13, 14], polychlorinated biphenyls [11], smoking [12, 13] and urban/rural residence [7]. Thériault et al. controlled for each chemical and physical agent listed as carcinogenic by the International Agency for Research on Cancer, and for socioeconomic status.

Discussion

To summarise the results of studies using measurements to estimate occupational exposure to magnetic fields is not an easy task. For all leukaemia diagnoses combined, half of the studies noted moderately elevated risk estimates, while the other half found no association. For leukaemia subtypes, the results are inconsistent, even if some trend can be seen for chronic lymphocytic leukaemia. However, several of the results for this subgroup of leukaemia are based on a small number of cases.

There are no obvious explanations for the discrepancies among the results. There may be systematic or random errors in individual studies, but there may also be real differences among the populations studied. Three of the studies in which no association was found were based on a small number of cases [10, 13, 14]. Furthermore, there may be a difference in the exposure pattern in studies of the general population, compared with studies of workers within a specific industry, such as electric utility workers. The relevant aspect of the exposure is unknown, and average or cumulative exposure in one study might express something different from the average or cumulative exposure in another study. The prevalence of other risk factors for leukaemia is likely to differ between the different populations studied. Assuming that magnetic fields act as a promotor rather than as an initiator, this may be crucial for the results.

The studies could include a varying degree of misclassification of the exposure. None of the studies estimated the exposure for each individual, but rather for occupational categories. In this way, the variation of the exposure within occupational categories was not taken into account. Exposure estimates in the cohort study by Tynes et al. [14] were based on spot measurements, and the exposure levels in both the cohort and the case-control study by Tynes et al. deviate considerably from exposure levels in the other studies. In the London study [8], measurements were made primarily for electrical occupations, as originally defined by Milham [20], while only a random sample of non-electrical occupations was measured.

Other characteristics of the individual studies may affect the results. The lack of data in the Matanoski study [9] was considerable; only 61% of cases plus at least one matched control had some type of information on job, and information on job history was available for only 35 matched sets. The controls in the London study [8] were subjects with cancer of other types than leukaemia and malignancies of the central nervous system. In the other case-control studies, controls were selected from the population generating the cases. In the cohort study by Tynes et al. [14], the incidence among the Norwegian male population was used for comparison, which means that the “healthy worker effect” is likely to alter the results.

The type of outcome studied may influence the comparability between studies. Studies of mortality may not be suitable for looking at subgroups of leukaemia, such as chronic lymphocytic leukaemia. This may explain the lack of an association in the Savitz study [11], and also in the study by Sahl et al. [10]. Matanoski et al. [9] did not even include chronic lymphocytic leukaemia due to this problem. In the study by Thériault et al. [12], persons above 60 years old were underrepresented due to restrictions in one of the subpopulations. This may also affect the results for chronic lymphocytic leukaemia.

Different assumptions about latency could also give different results. Most of the studies collected information about work histories and calculated a cumulative lifetime exposure. Floderus et al. [7] considered the exposure in the 10 years preceding diagnosis. In the study by Thériault et al. [12], a relative risk estimate of 4.1 (95% CI 0.9–18.0) was found for chronic lymphocytic leukaemia when the exposure window 0–20 years before diagnosis was considered, quite comparable to the results of Floderus et al. [7]. However, this pattern did not occur in the study by Savitz and Loomis [11].

Confounding as a possible explanation for the variations between studies must also be considered. However, there are only a few known or suspected risk factors for leukaemia, and in the studies where control was made for confounding, the results remained virtually unchanged.

It is noteworthy that all efforts towards a better assessment of the exposure through extensive measurement programs did not result in more precise and consistent risk estimates, as would have been expected if misclassification of the exposure was reduced.

Conclusions

There is some evidence for an association between occupational magnetic field exposure and leukaemia, especially for chronic lymphocytic leukaemia, but the inconsistencies between and within studies weaken the evidence. Currently, no firm conclusions can be drawn regarding the association between occupational magnetic field exposure and adult leukaemia.

Future studies need to improve the exposure assessment, preferably assessing the exposure for each subject in the study, and including also exposure outside work. Access to historical exposure levels would also improve the assessment considerably. Apart from that, new studies should be designed to study chronic lymphocytic leukaemia, as well as other subtypes of leukaemia. Studies that are simply repeating the design features of previous studies, especially regarding methods for exposure assessment, will probably not add much information concerning the question of an association between magnetic fields and adult leukaemia.

References

1. Wertheimer N, Leeper E (1979) Electrical wiring configurations and childhood cancer. Am J Epidemiol 109:273–284
2. Oak Ridge Associated Universities Panel for the Committee on Interagency Radiation Research and Policy Coordination (1992) Health effects of low frequency electric and magnetic fields. TN:ORAU 92/F8, Oak Ridge
3. NRPB (1992) Report of an advisory group on non-ionising radiation. Electromagnetic fields and the risk of cancer. (Documents of NRPB, Vol 3) National Radiological Protection Board, London
4. Ahlbom A (1988) A review of the epidemiologic literature on magnetic fields and cancer. Scand J Work Environ Health 14:337–343
5. Coleman M, Beral V (1988) A review of epidemiological studies of the health effects of living near or working with electricity generation and transmission equipment. Int J Epidemiol 17:1–13
6. Savitz DA, Ahlbom A (1994) Epidemiologic evidence on cancer in relation to residential and occupational exposures. In: Biologic effects of electric and magnetic fields (DO Carpenter, ed) Academic Press, New York
7. Floderus B, Persson T, Stenlund C, Wennberg A, Öst Å, Knave B (1993) Occupational exposure to electromagnetic fields in relation to leukemia and brain tumors: a case-control study in Sweden. Cancer Causes Control 4:465–476
8. London SJ, Bowman JD, Sobel E, Thomas DC, Garabrant DH, Pearce N, Bernstein L, Peters JM (1994) Exposure to magnetic fields among electrical workers in relation to leukemia risk in Los Angeles County. Am J Ind Med 26:47–60
9. Matanoski GM, Elliott EA, Breysse PN, Lynberg MC (1993) Leukemia in telephone linemen. Am J Epidemiol 137:609–619
10. Sahl JD, Kelsh MA, Greenland S (1993) Cohort and nested case-control studies of hematopoietic cancers and brain cancer among electric utility workers. Epidemiology 4:104–114
11. Savitz DA, Loomis DP (1995) Magnetic field exposure in relation to leukemia and brain cancer mortality among electric utility workers. Am J Epidemiol 141:123–134
12. Thériault G, Goldberg M, Miller AB, Armstrong B, Guénel P, Deadman J, Imbernon E, To T, Chevalier A, Cyr D, Wall C (1994) Cancer risks associated with occupational exposure to magnetic fields among electric utility workers in Ontario and Quebec, Canada, and France: 1970–1989. Am J Epidemiol 139:550–572
13. Tynes T, Jynge H, Vistnes AI (1994) Leukemia and brain tumors in Norwegian railway workers, a nested case-control study. Am J Epidemiol 139:645–653
14. Tynes T, Reitan JB, Andersen A (1994) Incidence of cancer among workers in Norwegian hydroelectric power companies. Scand J Work Environ Health 20:339–344
15. Calle E, Savitz DA (1985) Leukemia in occupational groups with presumed exposure to electrical and magnetic fields (Letter to the Editor). N Engl J Med 313:1476–1477
16. Coleman M, Bell J, Skeet R (1983) Leukemia incidence in electrical workers (Letter to the Editor). Lancet 1:982–983
17. Juutilainen J, Laara E, Pukkala E (1990) Incidence of leukemia and brain tumours in Finnish workers exposed to ELF magnetic fields. Int Arch Occup Environ Health 62:293–303
18. Loomis DP, Savitz DA (1990) Mortality from brain cancer and leukaemia among electrical workers. Br J Ind Med 47:633–638
19. McDowall ME (1983) Leukemia mortality in electrical workers in England and Wales (Letter to the Editor). Lancet 1:246
20. Milham S (1982) Mortality from leukemia in workers exposed to electrical and magnetic fields (Letter to the Editor). N Engl J Med 307:249
21. Milham S (1985) Mortality in workers exposed to electromagnetic fields. Environ Health Perspect 62:297–300
22. Pearce N, Reif J, Fraser J (1989) Case-control studies of cancer in New Zealand electrical workers. Int J Epidemiol 18:55–59
23. Robinson CF, Lalich NR, Burnett CA, Sestito JP, Frazier TM, Fine LJ (1991) Electromagnetic field exposure and leukemia mortality in the United States. J Occup Med 33:160–162
24. Wright WE, Peters JM, Mack TM (1982) Leukemia in workers exposed to electrical and magnetic fields (Letter to the Editor). Lancet 2:1160–1161
25. Flodin U, Fredriksson M, Axelson O, Persson B, Hardell L (1986) Background radiation, electrical work, and some other exposures associated with acute myeloid leukemia in a case-referent study. Arch Environ Health 41:77–84
26. Linet MS, Malker HSR, McLaughlin JK, Weiner JA, Stone BJ, Blot WJ, Ericsson JLE, Fraumeni JF (1988) Leukemias and occupation in Sweden: a registry-based analysis. Am J Ind Med 14:319–330

27. Stern FB, Waxweiler RJ, Beaumont JJ, Lee ST, Rinsky RA, Zumwalde RD, Halpering WE, Bierbaum PJ, Landrigan PJ, Murray WE Jr (1983) A case-control study of leukemia at a naval nuclear shipyard. Am J Epidemiol 123:980–992
28. Gallagher RP, McBride ML, Band PR, Spinelli JJ, Threlfall WJ, Yang P (1990) Occupational electromagnetic field exposure, solvent exposure, and leukemia (Letter). J Occup Med 32:64–65
29. Garland FC, Shaw E, Gorham ED, Garland CF, White MR, Sinsheimer PJ (1990) Incidence of leukemia in occupations with potential electromagnetic field exposure in United States Navy personnel. Am J Epidemiol 132:293–303
30. Törnqvist S, Knave B, Ahlbom A, Persson T (1991) Incidence of leukaemia and brain tumors in some “electrical occupations”. Br J Ind Med 48:597–603
31. Törnqvist S, Norell S, Ahlbom A, Knave B (1986) Cancer in the electric power industry. Br J Ind Med 43:212–213
32. Bowman JD, Garabrant DH, Sobel E, Peters JM (1988) Exposure to extremely low frequency (ELF) electromagnetic fields in occupations with elevated leukemia rates. Appl Ind Hyg 3:189–194