Cancer incidence in UK electricity generation and transmission workers, 1973–2015

T. M. Sorahan

Institute of Applied Health Research, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

Correspondence to: T. M. Sorahan, Institute of Applied Health Research, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK. Tel: +44 (0)121 414 3644; e-mail: T.M.Sorahan@bham.ac.uk

Background

Long-term health outcomes in cohorts of workers from the electricity supply industry have been studied.

Aims

The aim of the study was to examine updated cancer incidence findings among a cohort of UK electricity generation and transmission workers.

Methods

Cancer morbidity experienced by 81 616 employees of the former Central Electricity Generating Board of England and Wales was investigated for the period 1973–2015. All employees had worked for at least 6 months with some employment between 1973 and 1982. Standardized registration ratios (SRRs) were calculated based on national rates.

Results

Overall cancer morbidity was slightly below expectation in males. Significant excesses were found in male workers for mesothelioma (observed [Obs] 763, SRR 326), skin cancer (non-melanoma) (Obs 5616, SRR 106), and prostate cancer (Obs 4298, SRR 106), and in female workers for cancer of the small intestine (Obs 13, SRR 220), nasal cancer (Obs 11, SRR 407), and breast cancer (Obs 758, SRR 110). More detailed analyses showed important contrasts, particularly for mesothelioma, lung cancer, skin cancer, prostate cancer and breast cancer.

Conclusions

A clear occupational excess of mesothelioma was not matched by a corresponding excess of asbestos-induced lung cancer. Confident interpretation of the excesses of cancers of the nasal cavities and small intestine is not possible, although occupational exposures received in this industry may well not be involved. An excess of skin cancer in transmission workers may be associated with outdoor working.

Key words

Cancer incidence; electricity supply industry.

Introduction

A cohort of UK electricity supply industry workers (power stations, substation or transmission sites, non-operational sites) was established in the 1980s to investigate whether such work was the cause of non-malignant lung disease. More recently, concerns that electromagnetic field (EMF) exposure may cause brain cancer, leukaemia, or have a role in neurodegenerative or cardiovascular diseases have been the focus of epidemiological studies in this industry [1–8], and a number of reviews are available [9–12]. Kheifets et al. [12] concluded that the literature on occupational EMF exposure ‘did not indicate strong or consistent associations with cancer’. Other exposures in the industry have been little considered. In 2010, cancer registration (incidence) data were incorporated into the UK cohort, and an analysis of cancer incidence for the period 1973–2008 was published in 2012 [13]. This report showed an occupational excess of mesothelioma but no excess of asbestos-induced lung cancer. There were also significant excesses of nasal cancer, and small intestine cancer in female employees; based on relatively small numbers of cases. An updated analysis of these UK data has been carried out aiming to provide a more complete monitoring of cancer risks in this cohort, and to identify any other types of cancer that merit further investigation. Details of exposure to electric and magnetic fields in this industry have been described before [5,14]. A long list of other occupational exposures present in parts of the industry before 1997 has also been published [15]. The cohort has been used in the past to test hypotheses [5–8], but this report is designed to generate rather than test occupational hypotheses.

Methods

The study population and computerized data have been described previously [5–8,13]. The cohort comprises 83 284 employees (72 352 males and 10 932 females).
Key learning points

What is already known about this subject:
• This survey was set up in the 1980s to learn more about the long-term health of employees in the UK electricity supply industry.
• In the intervening years, a series of 11 papers have found no convincing links between estimated exposure to magnetic fields and a number of health outcomes.
• This new report was prepared to provide a more complete assessment of cancer risks in the cohort, incorporating a further 6 years of follow-up data.

What this study adds:
• The cohort continues to experience an occupational excess of mesothelioma without any matching excess of lung cancer.
• Outdoor working may have been a factor in excess of skin cancer (non-melanoma).
• Excesses in females for nasal cancer and cancer of the small intestine were not matched by similar findings in males.

What impact this may have on practice, policy or procedure:
• The findings reinforce the need for regulations that protect workers from asbestos exposure and the advice given to outdoor workers concerning sun exposure.
• The findings provide indirect evidence that further control of magnetic fields exposure is probably not needed.
• Employees who have been exposed to asbestos should continue to be encouraged not to smoke to reduce the risk of asbestos-related lung cancer.

of the former Central Electricity Generating Board (CEGB) of England and Wales. The earlier cohort [13] has been reduced in size because 639 employees who moved to Scotland had to be deleted from the study files because a Data Sharing Agreement (DSA) is no longer in place with the General Register Office (GRO) for Scotland. This small percentage change is not expected to result in an important selection bias. All employees had a minimum of 6 months of employment with some period of employment between 1973 and 1982. The total cohort was subdivided into three categories based on the work location (industry sector) of the first known job: power stations (n = 52 928), substation or transmission sites (n = 3359), and non-operational sites (n = 21 966). There were a further 3985 employees for whom no job history was available and 1046 employees whose work history could not be classified. These latter two were combined into a single ‘unclassifiable industry sector’ category.

NHS Digital (and its forerunners) supplied mortality and cancer registration follow-up particulars. NHS Digital is the national provider of information, data and IT systems for commissioners, analysts and clinicians in health and social care in England. By the study closing date (31 December 2015), 36 302 workers had died, 1090 workers had emigrated, 44 543 workers were traced alive and 1046 employees whose work history could not be classified. This latter two were combined into a single ‘unclassifiable industry sector’ category.

A total of 81 616 employees were considered for the cancer incidence analysis.

Cancer incidence in the cohort was compared with expected values based on incidence rates for England and Wales, taking sex, age and calendar period into account; calculations were carried out with the EPICURE programme [16], using the double precision DOS version 2.12 (2002) of DATAB. Study subjects were entered into the person-years-at-risk (pyr) after the first 6 months of employment or the date of computerization for the region of their employment, whichever was later. Individuals were removed from the pyr on the date of death, date of emigration or the end of 2015, whichever was the earlier. Study subjects did not contribute to observed or expected numbers after their 100th birthday, in case some subjects in later age groups had been traced alive incorrectly.

Standardized registration ratios (SRRs) by malignant neoplasm (MN) site were provided by the ratios of observed and expected numbers of cancer cases to a baseline of 100. P-values and 95% confidence intervals (CIs) were calculated on the basis that cancer occurs as a Poisson process, and all tests of statistical significance were two-tailed. More detailed analyses were also carried out by year of hire (1926–59, 1960–69, 1970–82), period from hire irrespective of how long any individual works in the industry (0–19, 20–29, 30–39, ≥40 years), period from leaving employment (still employed or left employment <10 years ago, left employment 10–19 years ago, left employment 20–29 years ago, left employment >30 years ago), duration of employment (<10 years (i.e.
0.5–9.9 years), 10–19 years, ≥20 years), industry sector of first known employment in the industry (power stations, transmission facilities, non-operational sites), and type of work (manager, engineer, administrative and clerical, industrial worker, building construction). For the first four variables, tests for trend (linear component) [17] were carried out (e.g. was there a tendency for SRRs to increase or decrease with year of hire). Tests for heterogeneity [17] were carried out for the last two variables (e.g. could the differences in SRRs by industry sector represent no more than random variation in sub-groups). These tests assumed a similar null hypothesis: no trend and homogeneous SRRs. All analyses only consider contemporaneous categories for the summation of pyr.

This study was established with the approval of the Central Ethical Committee of the British Medical Association, and the author is accredited by the Office for National Statistics as an ‘Approved Researcher’. The current protocol was approved by the University of Birmingham’ Science, Technology, Engineering and Mathematics Ethical Review Committee (project code ERN_13-0676). Computer analyses were carried out in accordance with the terms of an active Data Sharing Agreement (DSA) with NHS Digital. A privacy notice is available at http://www.emfs.info/research/studies/cegb-cohort/update/. One condition of the DSA was that findings based on fewer than five observed cases would not be published. The study has never contained any information on ethnicity, medical histories or lifestyle factors, and since 2013, no information on names, addresses, National Insurance or NHS numbers.

Results

Table 1 shows site-specific MNs for male and female employees. Compared with national rates, all MNs combined were slightly (though highly significantly, \( P < 0.001 \)) below expectation for males (Obs 19 223, SRR 97) and close to expectation for females (Obs 2149, SRR 101). In males, significant deficits are shown for MNs of the tongue, mouth, pharynx, oesophagus, rectum, liver, pancreas, larynx and lung. Significant excesses are shown for skin cancer (excluding melanoma) (Obs 5616, SRR 106, \( P < 0.001 \)), mesothelioma (Obs 763, SRR 326, \( P < 0.001 \)) and prostate cancer (Obs 4298, SRR 106, \( P < 0.001 \)). In females, a significant deficit is shown for MN of the cervix, and significant excesses are shown for MN of the small intestine (Obs 13, SRR 220, \( P < 0.05 \)), nasal cavities (Obs 11, SRR 407, \( P < 0.001 \)) and breast (Obs 758, SRR 110, \( P < 0.01 \)). Findings for MN of the brain and all leukaemia combined were unexceptional.

Findings in Table 1 were examined to ascertain whether smoking-related cancers other than lung cancer were in deficit in male employees. For other cancer sites identified as capable of being caused by smoking cigarettes (oral cavity, pharynx, nasal cavity and paranasal sinuses, larynx, oesophagus, stomach, pancreas, liver, kidney, ureter, urinary bladder, myeloid leukaemia) [18], the SRR was significantly below expectation (Obs 4680, SRR 91, 95% CI 88–93). The SRR for cancers not judged to be capable of being caused by smoking (and excluding skin other than melanoma and unspecified neoplasms) was significantly elevated (Obs 10 587, SRR 107, 95% CI 105–109). However, the SRR for cancers not considered to be caused by smoking or asbestos exposures (further exclusion of mesothelioma) was not significantly elevated (SRR 101, 95% CI 99–104).

Findings from Table 1 were reviewed and all MNs, mesothelioma, MN of the skin (excluding melanoma) lung, breast and prostate in male workers, and MN of the small intestine, nasal cavities and breast in female workers were selected for further investigation.

Table 2 shows observed and expected numbers of cancer registrations for all MNs in male workers by year of hire, period from hire, period from leaving employment, industry sector and type of work. There was a highly significant positive trend with the period from leaving employment although this was dependent on a low SRR in a single category (still employed and left less than 10 years ago). There was also highly significant heterogeneity in the findings by industry sector and type of work; SRRs were lower in transmission and non-operational site workers compared with those in power station workers, and SRRs were lower in managers, engineers and clerical (including administrative) workers compared with those in industrial and construction workers.

Table 2 shows findings for MN of the skin (excluding melanoma) in male workers. A significant negative trend is shown with year of hire (SRRs tend to be lower with more recent hires), and a significant positive trend is shown with a period from hire. There was also highly significant heterogeneity in the findings by industry sector and type of work; SRRs were higher in transmission workers compared with those in power station workers, and SRRs were higher in engineers and clerical workers compared with those in industrial and construction workers.

Table 3 shows findings for mesothelioma and MN of the lung in males; for mesothelioma, there was a highly significant negative trend with year of hire and a highly significant positive trend with period from hire (SRRs were higher with later periods from hire). There was a highly significant positive trend with duration of employment. There was also highly significant heterogeneity in the findings by industry sector and type of work; SRRs were higher in power station workers compared with those in transmission and non-operational site workers, and SRRs were lower in clerical workers compared with those in all other types of work. Very different patterns are shown for MN of the lung. There was a highly significant positive trend with year of hire (SRRs were higher
| Site of MN | ICD-10 | Males | | | | | | Females | | | | |
|-----------|--------|-------|---|---|---|---|---|---|---|---|---|---|---|---|---|
|           |        | Obs | Exp | SRR | 95% CI | Obs | Exp | SRR | 95% CI |
| Lip       | C00    | 30  | 31.7 | 95 | 65–133 | Sup.* | | | | | | | | |
| Tongue    | C01–02 | 75  | 108.7 | 69 | 55–86 | | 11 | 7.6 | 145 | 76–252 | | | |
| Mouth     | C03–06 | 74  | 113.1 | 65 | 52–82 | | 10 | 8.8 | 114 | 58–203 | | | |
| Salivary gland | C07–08 | 41  | 40.7 | 101 | 73–135 | Sup.* | | | | | | | | |
| Pharynx   | C09–14 | 104 | 163.8 | 63 | 52–77 | Sup.* | | | | | | | | |
| Oesophagus | C15    | 574 | 646.4 | 89 | 82–96 | 28 | 35.4 | 79 | 54–113 | | | |
| Stomach   | C16    | 899 | 902.4 | 100 | 93–106 | 44 | 41.2 | 107 | 79–142 | | | |
| Small intestine | C17 | 61  | 59.7 | 102 | 79–130 | 13 | 5.9 | 220 | 123–367 | | | |
| Large intestine | C18 | 1587 | 1604.5 | 99 | 94–104 | 158 | 155.3 | 102 | 87–119 | | | |
| Rectum    | C19–21 | 1052 | 1134.6 | 93 | 87–98 | 69 | 79.3 | 87 | 68–110 | | | |
| Liver     | C22    | 185 | 242.9 | 76 | 66–88 | 13 | 15.9 | 82 | 45–136 | | | |
| Gallbladder | C23–24 | 98  | 90.0 | 109 | 89–132 | 16 | 12.2 | 131 | 78–208 | | | |
| Pancreas  | C25    | 457 | 551.9 | 83 | 75–91 | 56 | 53.6 | 105 | 80–135 | | | |
| Other digestive | C26 | 32  | 39.0 | 82 | 57–114 | Sup.* | | | | | | | | |
| Nose and sinuses | C30–31 | 34  | 36.2 | 94 | 66–130 | 11 | 2.7 | 407 | 214–708 | | | |
| Larynx   | C32    | 186 | 279.6 | 67 | 57–77 | 5 | 6.5 | 77 | 28–171 | | | |
| Lung and bronchus | C33,34 | 3162 | 3909.3 | 81 | 78–84 | 240 | 243.1 | 99 | 87–112 | | | |
| Bone     | C40,41 | 22  | 26.1 | 84 | 54–126 | Sup.* | | | | | | | | |
| Melanoma | C43    | 444 | 446.0 | 100 | 91–109 | 69 | 67.4 | 102 | 80–129 | | | |
| Skin, other | C44 | 5616 | 5288.9 | 106 | 103–109 | 494 | 464.4 | 106 | 97–116 | | | |
| Mesothelioma | C45 | 763 | 234.0 | 326 | 304–350 | Sup.* | | | | | | | | |
| Connective tissue | C47,C49 | 98 | 96.3 | 102 | 83–124 | 10 | 9.3 | 108 | 55–192 | | | |
| Peritoneum | C48   | 21  | 20.4 | 103 | 65–155 | 7 | 5.3 | 132 | 58–261 | | | |
| Breast   | C50    | 52  | 42.0 | 124 | 93–161 | 758 | 688.9 | 110 | 102–118 | | | |
| Cervix   | C53    | —   | —    | —   | —    | 38 | 59.3 | 64 | 46–87 | | | |
| Uterus   | C54    | —   | —    | —   | —    | 95 | 103.0 | 92 | 75–112 | | | |
| Ovary    | C56    | —   | —    | —   | —    | 116 | 106.5 | 109 | 90–130 | | | |
| Prostate | C61    | 4298 | 4073.3 | 106 | 102–109 | | | | | | | | |
| Testis   | C62    | 89  | 105.9 | 84 | 68–103 | | | | | | | | |
| Other genital | rem. C51–63 | 66  | 66.7 | 99 | 77–125 | 24 | 24.0 | 100 | 66–147 | | | |
| Kidney   | C64    | 495 | 520.6 | 95 | 87–104 | 31 | 35.7 | 87 | 60–122 | | | |
| Bladder  | C67    | 1257 | 1249.9 | 101 | 95–106 | 39 | 43.7 | 89 | 64–121 | | | |
| Other urinary | C65–66, C68 | 117 | 103.8 | 113 | 94–135 | 7 | 5.8 | 121 | 53–239 | | | |
| Eye      | C69    | 34  | 34.7 | 98 | 69–135 | 5 | 3.7 | 135 | 50–300 | | | |
| Brain    | C70–72 | 335 | 324.9 | 103 | 93–115 | 21 | 29.6 | 71 | 45–107 | | | |
| Thyroid  | C73    | 48  | 49.5 | 97 | 72–128 | 11 | 16.3 | 67 | 35–117 | | | |
| Other endocrine glands | C74–75 | 12 | 14.6 | 82 | 45–140 | Sup.* | | | | | | | | |
| Secondary and unspecified cancers | C76–80 | 794 | 828.2 | 96 | 89–103 | 82 | 81.9 | 100 | 80–124 | | | |
| Hodgkin’s disease | C81 | 73 | 81.5 | 90 | 71–112 | 9 | 8.1 | 111 | 54–204 | | | |
| Non-Hodgkin’s lymphoma | C82–85 | 695 | 680.3 | 102 | 95–110 | 64 | 67.5 | 95 | 74–120 | | | |
| Multiple myeloma | C90 | 311 | 299.5 | 104 | 93–116 | 22 | 26.1 | 84 | 54–126 | | | |
| Leukaemia | C91–95 | 497 | 504.8 | 98 | 90–107 | 42 | 39.1 | 107 | 78–144 | | | |
| Acute lymphoid leukaemia | C91.0 | 12 | 15.8 | 76 | 41–129 | Sup.* | | | | | | | | |
| Chronic lymphoid leukaemia | C91.1 | 238 | 212.4 | 112 | 98–127 | 15 | 13.6 | 110 | 64–178 | | | |
| Acute myeloid leukaemia | C92.0, C92.5 | 134 | 156.0 | 86 | 72–101 | 19 | 14.6 | 130 | 81–200 | | | |
| Chronic myeloid leukaemia | C92.1 | 48 | 49.0 | 98 | 73–129 | Sup.* | | | | | | | | |
| Other leukaemia | rem. C91–95 | 65 | 71.7 | 91 | 71–115 | 5 | 5.0 | 100 | 37–222 | | | |
| All MNs | 140–209a | 19223 | 19822.0 | 97 | 96–98 | 2149 | 2122.9 | 101 | 97–106 | | | |

*a Sup = findings suppressed because of confidentiality concerns about 'disclosive' data.

*b rem = remainder.

Excluding 'skin, other', ICD-10 C44.
Table 2. Incidence of all MNs combined (excluding skin other than melanoma) and MN of the skin (excluding melanoma) in 71 185 male UK Electricity Generation and Transmission workers, by year of hire, period from hire, period from leaving employment, duration of employment, industry sector and type of work, 1973–2015

| Year of hire | All MNs | | MN of the skin | |
|--------------|---------|-------------------|-----------------|-----------------|
|              | Obs     | Exp              | SRR 95% CI     | Obs  | Exp  | SRR 95% CI |
| 1926–59      | 5850    | 6014.9           | 97 95–100       | 1668 | 1525.5| 109 104–115 |
| 1960–69      | 7764    | 7957.0           | 98 95–100       | 2302 | 2123.0| 108 104–113 |
| 1970–82      | 5609    | 5850.1           | 96 93–98        | 1646 | 1640.4| 100 96–105  |
| Test for trend | |                   | P = NS               | |                   | P = *                 |
| Period from hire (years) | |                   |                   | |                   |                   |
| 0–19          | 2006    | 2076.6           | 97 92–101       | 305  | 329.0  | 93 83–104 |
| 20–29         | 3514    | 3793.1           | 93 90–96        | 821  | 755.8  | 109 101–116 |
| 30–39         | 6011    | 6099.1           | 99 96–101       | 1576 | 1589.3 | 99 94–104  |
| ≥40           | 7692    | 7853.2           | 98 96–100       | 2914 | 2614.7 | 111 108–116 |
| Test for trend | |                   | P = NS               | |                   | P = **                 |
| Period from leaving employment (years) | |                   |                   | |                   |                   |
| <10a         | 4837    | 5373.1           | 90 88–93        | 872  | 898.0  | 97 91–104 |
| 10–19        | 6865    | 6859.1           | 100 98–103      | 1780 | 1615.3 | 110 105–115 |
| 20–29        | 5626    | 5686.7           | 99 96–102       | 2114 | 1949.7 | 108 104–113 |
| ≥30          | 1895    | 1903.2           | 100 95–104      | 850  | 825.8  | 103 96–110  |
| Test for trend | |                   | P = ***               | |                   | P = NS                 |
| Duration of employment (years) | |                   |                   | |                   |                   |
| <10          | 3564    | 3624.2           | 98 95–102       | 976  | 967.4  | 101 95–107 |
| 10–19        | 6616    | 6715.7           | 99 96–101       | 1887 | 1760.4 | 107 102–112 |
| ≥20          | 9043    | 9482.1           | 95 93–97        | 2753 | 2561.1 | 108 104–112 |
| Test for trend | |                   | P = NS               | |                   | P = NS                 |
| Industry sector | |                   |                   | |                   |                   |
| Power stations | 13 745 | 13 570.1         | 101 100–103     | 3757 | 3599.5 | 104 101–108 |
| Transmission  | 857     | 980.6            | 87 82–93        | 348  | 270.2  | 129 116–143 |
| Non-operational | 3508  | 4268.1           | 82 80–85        | 1302 | 1188.3 | 110 104–116 |
| Unclassifiableb | 1113   | 1003.1           | 111 105–118     | 209  | 230.9  | 91 79–103  |
| Test for heterogeneity | |                   | P = ***               | |                   | P = ***                 |
| Type of work | |                   |                   | |                   |                   |
| Managers     | 196     | 260.4            | 75 65–86        | 69   | 69.6  | 99 78–125 |
| Engineers    | 4294    | 5092.0           | 84 82–87        | 1703 | 1449.5 | 118 112–123 |
| Admin, clerical | 1034  | 1232.4           | 84 79–89        | 358  | 325.8  | 110 99–122 |
| Industrial   | 12 469  | 12 146.2         | 103 101–105     | 3266 | 3192.3 | 102 99–106 |
| Building, constr. | 250    | 217.0            | 115 102–130     | 52   | 54.6  | 95 72–124 |
| Not known    | 980     | 873.9            | 112 105–119     | 168  | 197.1  | 85 73–99  |
| Test for heterogeneity | |                   | P = ***               | |                   | P = ***                 |
| Total        | 19 223  | 19 822.0         | 97 96–98        | 5616 | 5288.9 | 106 103–109 |

NS, not significant.
aIncludes still employed.
bUnclassifiable work history or no work history.
*P < 0.05, **P < 0.01, ***P < 0.001,

with more recent decades of hire), and a highly significant negative trend with period from hire (SRRs were lower with later periods from hire). There was a highly significant negative trend with duration of employment. There was also highly significant heterogeneity in the findings by industry sector and type of work; SRRs were higher in power station workers compared with those in transmission and non-operational site workers, and SRRs were lower in managers, engineers and clerical (including administrative) workers compared with those in industrial and construction workers.

Table 4 shows findings for MN of the prostate. There was a significant positive trend with duration of employment. There was also highly significant heterogeneity in the findings by type of work; SRRs were higher in engineers and clerical workers compared with those in other types of work.
Corresponding findings for MN of the small intestine and the nasal cavities in female workers were also calculated. Both findings were based on small numbers and are not tabulated because of concerns about ‘disclosive’ data. There were no significant trends or heterogeneity in the findings.

Table 5 shows findings for MN of the breast for male and female workers. There was significant heterogeneity in the findings for females by type of work; SRRs were higher in clerical workers and workers with unknown job type compared with those found in engineers and industrial workers.

**Discussion**

Overall, this study showed a clear occupational excess of mesothelioma with no matching excess of lung cancer, and unexceptional findings for brain tumours and...
leukaemia. Strengths of the study include its size and length of follow-up with a correspondingly large number of cancer cases, including rare cancers. Limitations include the absence of smoking data, other lifestyle data and detailed pre-1973 work histories. The latter meant that first known job had to be used to categorize individuals by industry sector and type of work (55% of the cohort had some employment within the industry before personnel records were computerized). Some misclassification in the sub-group analyses will have occurred although only 2% of power station workers had later recorded periods of working in the transmission sector and 6% of transmission workers had later recorded periods of working in power stations.

Incidence of all MNs combined was below expected in males, and morbidity from lung cancer was markedly below expectation. Findings for other smoking-related cancers were consistent with the hypothesis that this

Table 4. Incidence of MN of the prostate in 71,185 male UK Electricity Generation and Transmission workers, by year of hire, period from hire, period from leaving employment, duration of employment, industry sector and type of work, 1973–2015

| MN of the prostate | Obs | Exp | SRR | 95% CI |
|--------------------|-----|-----|-----|--------|
| Year of hire       |     |     |     |        |
| 1926–59            | 1254| 1167.5| 107 | 102–114|
| 1960–69            | 1789| 1660.6| 108 | 103–113|
| 1970–82            | 1255| 1245.2| 101 | 95–107 |
| Test for trend     |     |     |     | P = NS |
| Period from hire (years) |     |     |     |        |
| 0–19               | 153 | 143.4| 107 | 91–125 |
| 20–29              | 548 | 565.4| 97  | 89–105 |
| 30–39              | 1448| 1356.9| 107 | 101–112|
| ≥40                | 2149| 2007.6| 107 | 103–112|
| Test for trend     |     |     |     | P = NS |
| Period from leaving employment (years) |     |     |     |        |
| <10<sup>a</sup>    | 516 | 503.3| 103 | 94–112 |
| 10–19              | 1719| 1540.7| 112 | 106–117|
| 20–29              | 1560| 1510.7| 103 | 98–109 |
| ≥30                | 503 | 518.6| 97  | 89–106 |
| Test for trend     |     |     |     | P = NS |
| Duration of employment (years) |     |     |     |        |
| <10                | 703 | 724.7| 97  | 90–104 |
| 10–19              | 1417| 1354.4| 105 | 99–110 |
| ≥20                | 2178| 1994.2| 109 | 105–114|
| Test for trend     |     |     |     | P = ** |
| Industry sector    |     |     |     |        |
| Power stations     | 2887| 2779.4| 104 | 100–108|
| Transmission       | 213 | 207.1| 103 | 90–117 |
| Non-operational    | 1002| 899.9| 111 | 105–118|
| Unclassifiable<sup>b</sup> | 196 | 186.8| 105 | 91–120 |
| Test for heterogeneity |     |     |     | P = NS |
| Type of work       |     |     |     |        |
| Managers           | 47  | 52.1 | 90  | 67–119 |
| Engineers          | 1300| 1108.9| 117 | 111–124|
| Admin, clerical    | 278 | 246.8| 113 | 100–127|
| Industrial         | 2454| 2459.5| 100 | 96–104 |
| Building, constr.  | 47  | 42.9 | 110 | 81–144 |
| Not known          | 172 | 163.1| 106 | 91–122 |
| Test for heterogeneity |     |     |     | P = ***|
| Total              | 4298| 4073.3| 106 | 102–109|

NS, not significant.
<sup>a</sup>Includes still employed.
<sup>b</sup>Unclassifiable work history or no work history.
**P < 0.01, ***P < 0.001.
skilled workforce had below average smoking habits; a low prevalence of smoking in this industry has been published previously [13].

Mesothelioma was significantly elevated for males in all industry sectors and in all types of work except administration and clerical work; with little sign of the effects of asbestos risk having played itself out (2006–2010: Obs 159, SRR 317, 95% CI 271–369; 2011–2015: Obs 169, SRR 298, 95% CI 255–345). The most likely explanation for the excess of mesothelioma in transmission and non-operational site workers is occasional or earlier (pre-1973) periods of working at power stations where asbestos was used to lag pipes and boilers [13].

It is estimated that in the UK in 2004 there were 1937 mesotheliomas and 2223 lung cancer cases caused by earlier asbestos exposure [19]. This estimate considers that there will be 1.1 lung cancers for every mesothelioma caused by asbestos. This 1.1:1 ratio does not seem to be

Table 5. Incidence of MN of the breast in 71 185 male and 10 431 female UK Electricity Generation and Transmission workers, by year of hire, period from hire, period from leaving employment, duration of employment, industry sector and type of work, 1973–2015

|                  | Males |       |       |        | Females |       |       |        |
|------------------|-------|-------|-------|--------|---------|-------|-------|--------|
|                  | Obs   | Exp   | SRR   | 95% CI | Obs     | Exp   | SRR   | 95% CI |
| Year of hire     |       |       |       |        |         |       |       |        |
| 1926–59          | 18    | 12.5  | 144   | 88–223 | 51      | 38.3  | 133   | 100–174|
| 1960–69          | 19    | 16.8  | 113   | 70–173 | 145     | 128.5 | 113   | 96–132 |
| 1970–82          | 15    | 12.8  | 117   | 68–189 | 562     | 522.1 | 108   | 99–117 |
| Test for trend P | NS    |       |       |        | NS      |       |       |        |
| Period from hire (years) |       |       |       |        |         |       |       |        |
| 0–19             | 6     | 4.7   | 128   | 52–266 | 168     | 152.7 | 110   | 94–128 |
| 20–29            | 11    | 8.2   | 134   | 71–233 | 225     | 209.0 | 108   | 94–122 |
| 30–39            | 13    | 12.9  | 101   | 56–168 | 267     | 241.0 | 111   | 98–125 |
| ≥40              | 22    | 16.2  | 136   | 87–202 | 98      | 86.2  | 114   | 93–138 |
| Test for trend P | NS    |       |       |        | NS      |       |       |        |
| Period from leaving employment (years) |       |       |       |        |         |       |       |        |
| <10              | 16    | 11.8  | 136   | 80–216 | 179     | 164.7 | 109   | 94–126 |
| 10–19            | 13    | 14.0  | 93    | 52–155 | 228     | 194.1 | 118   | 103–134|
| 20–29            | 16    | 12.3  | 130   | 77–207 | 213     | 214.7 | 99    | 87–113 |
| ≥30              | 7     | 3.9   | 180   | 79–355 | 138     | 115.5 | 120   | 101–141|
| Test for trend P | NS    |       |       |        | NS      |       |       |        |
| Duration of employment (years) |       |       |       |        |         |       |       |        |
| <10              | 10    | 7.9   | 127   | 64–226 | 428     | 400.9 | 107   | 97–117 |
| 10–19            | 16    | 14.3  | 112   | 66–178 | 240     | 211.0 | 114   | 100–129|
| ≥20              | 26    | 19.8  | 131   | 88–190 | 90      | 77.0  | 117   | 95–143 |
| Test for trend P | NS    |       |       |        | NS      |       |       |        |
| Industry sector  |       |       |       |        |         |       |       |        |
| Power stations   | 33    | 28.7  | 115   | 80–160 | 273     | 253.6 | 108   | 95–121 |
| Transmission     | 2     | 2.1   | 95    | 16–315 | 11      | 12.5  | 88    | 46–153 |
| Non-operational  | 16    | 9.1   | 176   | 104–279 | 417    | 374.0 | 112   | 101–123|
| Unclassifiableb  | Sup.c |      |       |        | 57      | 48.8  | 117   | 89–150 |
| Test for heterogeneity P | NS |       |       |        | NS      |       |       |        |
| Type of work     |       |       |       |        |         |       |       |        |
| Managers         |       |       |       |        |         |       |       |        |
| Engineers        | 18    | 10.8  | 167   | 102–258 | 13      | 13.2  | 98    | 55–164 |
| Admin, clerical  | 5     | 2.6   | 192   | 70–426 | 566     | 496.0 | 114   | 105–124|
| Industrial       | 28    | 25.7  | 109   | 74–155 | 130     | 140.0 | 93    | 78–110 |
| Building, constr.| Sup.c |      |       |        |         |       |       |        |
| Not known        | Sup.c |      |       |        | 47      | 38.4  | 122   | 91–161 |
| Test for heterogeneity P | NS |       |       |        | NS      |       |       |        |
| Total            | 52    | 42.0  | 124   | 93–161 | 758     | 688.9 | 110   | 102–118|

NS, not significant.
*aIncludes still employed.
*bUnclassifiable work history or no work history.
*cSup = findings suppressed because of confidentiality concerns about ‘disclosive’ data.
*P < 0.05.
important contrasts in more detailed analyses that were carried out for male breast cancer in this study. The excess of breast cancer in female workers was based, mainly on an excess in administrative and clerical workers; making occupational exposures involvement in this excess unlikely.

There was a significant trend for prostate cancer in relation to duration of employment. The reason for this is unclear, but it is possible that that sedentary working is involved [26]. Examination of this hypothesis would involve collection of additional work history data, possibly as part of a nested case–control study.

In conclusion, the overall elevated incidence found for mesothelioma almost certainly reflects the late health effects of earlier incidental asbestos exposure in this industry. This report highlights the need for further research in a number of areas, including the conditions that lead to some asbestos-exposed cohorts not having clear excesses of asbestos-induced lung cancer. It would be useful to review incident cancers of the nasal cavities and the small intestine in female workers in the electricity supply industry in other countries. Nested case–control studies could also be usefully carried out on skin cancer and prostate cancer. Such studies would require collection of additional data, but permissions are currently in place to obtain such data.

These findings have implications for clinicians and policymakers; they reinforce the importance of regulations that protect workers from asbestos exposure and the advice given to outdoor workers concerning sun exposure. They provide indirect evidence that further control of magnetic fields exposure is probably not needed, and indicate that employees who have been exposed to asbestos should continue to be encouraged not to smoke to reduce the risk of asbestos-related lung cancer.

**Funding**

The work and the costs of an open access publication were supported by a research award from the electricity supply industry and funding was administered by the Energy Networks Association (ENA).

**Acknowledgements**

I thank NHS Digital and its forerunners for supplying follow-up details, and for assisting in identifying those issues needed to be addressed to maintain study permissions. I also thank the Vital Statistics Offices of England and Wales for providing cancer incidence rates. Constructive criticisms of an earlier draft of this paper were requested and received from members of the Mortality Study Steering Group (MSSG); responsibility for the final version remains with the author.

**Competing interests**

The University salary of the PI is funded, in part, by the research award.
References

1. Thériault G, Goldberg M, Miller AB et al. 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 1994;139:550–572.

2. Savitz DA, Loomis DP. Magnetic field exposure in relation to leukemia and brain cancer mortality among electric utility workers. Am J Epidemiol 1995;141:123–134.

3. Kelsh MA, Sahl JD. Mortality among a cohort of electric utility workers, 1960–1991. Am J Ind Med 1997;31:534–544.

4. Johansen C, Olsen JH. Risk of cancer among Danish utility workers—a nationwide cohort study. Am J Epidemiol 1998;147:548–555.

5. Harrington JM, Nichols L, Sorahan T, van Tongeren M. Leukaemia mortality in relation to magnetic field exposure: findings from a study of United Kingdom electricity generation and transmission workers, 1973–97. Occup Environ Med 2001;58:307–314.

6. Sorahan T, Nichols L, van Tongeren M, Harrington JM. Occupational exposure to magnetic fields relative to mortality from brain tumours: updated and revised findings from a study of United Kingdom electricity generation and transmission workers, 1973–97. Occup Environ Med 2001;58:626–630.

7. Sorahan T, Nichols L. Mortality from cardiovascular disease in relation to magnetic field exposure: findings from a study of UK electricity generation and transmission workers, 1973–1997. Am J Ind Med 2004;45:93–102.

8. Sorahan T, Kheifets L. Mortality from Alzheimer’s, motor neuron and Parkinson’s disease in relation to magnetic field exposure: findings from the study of UK electricity generation and transmission workers, 1973–2004. Occup Environ Med 2007;64:820–826.

9. Santibáñez M, Bolumar F, García AM. Occupational risk factors in Alzheimer’s disease: a review assessing the quality of published epidemiological studies. Occup Environ Med 2007;64:723–732.

10. National Radiological Protection Board. ELF Electromagnetic Fields and the Risk of Cancer: Report of an Advisory Group on Non-ionising Radiation. Chilton, Oxfordshire: NRPB, 2001.

11. International Agency for Research on Cancer. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Non-ionising Radiation, Part 1: Static and Extremely Low Frequency (ELF) Electric and Magnetic Fields, vol. 80. Lyon: IARC Press, 2002.

12. Kheifets L, Bowman JD, Checkoway H et al. Future needs of occupational epidemiology of extremely low frequency electric and magnetic fields: review and recommendations. Occup Environ Med 2009;66:72–80.

13. Sorahan T. Cancer incidence in UK electricity generation and transmission workers, 1973–2008. Occup Med (Lond) 2012;62:496–505.

14. Renew DC, Cook RF, Ball MC. A method for assessing occupational exposure to power-frequency magnetic fields for electricity generation and transmission workers. J Radiol Prot 2003;23:279–303.

15. Harrington JM, McBride DJ, Sorahan T, Paddle GM, van Tongeren M. Occupational exposure to magnetic fields in relation to mortality from brain cancer among electricity generation and transmission workers. Occup Environ Med 1997;54:7–13.

16. Preston DL, Lubin JH, Pierce DA, McConney ME. Epicure Users Guide. Seattle, USA: Hirosoft International Corp., 1993.

17. Breslow NE, Day NE. Statistical Methods in Cancer Research. Volume II—The Design and Analysis of Cohort Studies. IARC Scientific Publication no. 82. Lyon: IARC Press, 1987.

18. International Agency for Research on Cancer. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Tobacco Smoke and Involuntary Smoking, vol. 83. Lyon: IARC Press, 2004.

19. Rushton L, Hutchings SJ, Fortunato L et al. Occupational cancer burden in Great Britain. Br J Cancer 2012;107(Suppl 1):S3–S7.

20. Chow WH, Linet MS, McLaughlin JK, Hsing AW, Chien HT, Blot WJ. Risk factors for small intestine cancer. Cancer Causes Control 1993;4:163–169.

21. International Agency for Research on Cancer. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. A Review of Human Carcinogens: Arsenic, Metals, Fibres, and Dusts, vol. 100c. Lyon: IARC Press, 2012.

22. Tynes T, Andersen A, Langmark F. Incidence of cancer in Norwegian workers potentially exposed to electromagnetic fields. Am J Epidemiol 1992;136:81–88.

23. Demers PA, Thomas DB, Rosenblatt KA et al. Occupational exposure to electromagnetic fields and breast cancer in men. Am J Epidemiol 1991;134:340–347.

24. Matanoski GM, Breyss PN, Elliott EA. Electromagnetic field exposure and male breast cancer. Lancet 1991;337:737.

25. Pollán M, Gustavsson P, Floderus B. Breast cancer, occupation, and exposure to electromagnetic fields among Swedish men. Am J Ind Med 2001;39:276–285.

26. Shephard RJ. Physical activity and prostate cancer: an updated review. Sports Med 2017;47:1055–1073.