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Review

Exposure to Occupational Carcinogens in Great Britain

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Introduction: This paper describes the available exposure information for carcinogens in Great Britain and discusses some of the issues involved in using such data to inform an assessment of the attributable occupational cancer burden.

Methods: Carcinogenic agents or occupations/industries such as hairdressers were identified from the list of International Agency for Research on Cancer groups 1 and 2a evaluations and estimates of exposure prevalence for 1990–1993 were obtained for a subset of these agents/ circumstances from the CARcinogen EXposure (CAREX) database, compiled as part of the Europe Against Cancer programme. Estimated prevalence of exposure was added for some carcinogenic exposure circumstances not covered by CAREX. Information about the level of exposure to chemical agents was obtained from the Health and Safety Executive's (HSE) National Exposure Database. Other information was obtained from relevant databases such as the Central Index of Dose Information for ionizing radiation or published sources.

Results: In total, there were 64 carcinogenic agents/circumstances identified with almost seven million people exposed in Great Britain. The top 30 entries covered 99.5% of the estimated exposed population. The CAREX data were generally higher than the comparable data on the numbers of people exposed to those agents available from the HSE, although in some individual cases there was considerable over- or underestimation of the exposure prevalence when using the CAREX database. The level of exposure varied greatly between substances and between workplaces. For some agents, e.g. radon and sunlight, there are important regional differences in exposure within the country. Exposure to carcinogenic agents in Great Britain was different from that in other countries: in some cases higher and in others lower. Exposure levels in the past in Britain were mostly greater than today.

Conclusions: Generalizing risk estimates from epidemiological studies in different countries or the past to estimate the fraction of cancers attributable to work must be done with care, particularly in the case of population-based case–control studies where exposure estimates are generally crude. Better estimates of the distribution of levels and the prevalence of occupational exposure to carcinogenic substances in Great Britain are needed and systems should be put in place to track this information in the future. With commitment from all stakeholders, it is possible that by 2025 exposure to known occupational chemical carcinogens could be essentially eliminated in Great Britain.

Keywords: attributable fraction; carcinogen; exposure

INTRODUCTION

The UK Health and Safety Executive's (HSE) Disease Reduction Programme (DRP) is part of the wider 'Fit for work, fit for life, fit for tomorrow' initiative, also known as FIT3. The aim of the DRP is to achieve a reduction in the incidence rate of work-related ill health caused by exposure to hazardous agents, and part of this programme focuses on the risks from occupational carcinogens. Another objective of the programme is, to the extent that the data will allow, to subdivide any headline estimates into exposure–cancer combinations that can be set alongside other intelligence in order to determine possible priorities for workplace interventions. Part of the

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initial work in the cancer theme of the DRP has been to obtain the best estimate of the current and future burden of occupational cancer in Great Britain, expressed as the attributable fraction (AF) of all cancers. To achieve this, HSE has convened two workshops to discuss how this objective may be best approached (see http://www.hse.gov.uk/research/hsl_pdf/2005/hsl0554.pdf, for a report from the first workshop and http://www.hse.gov.uk/research/hsl_pdf/2007/hsl0732.pdf, for a report of the second workshop). This paper has developed from discussions of what exposure information is necessary to undertake an assessment of the attributable occupational cancer burden.

Steenland and Armstrong (2006) define the AF as the proportion of cases of disease that is related to a specific exposure or alternatively the fraction of disease in a population that may be avoided by reducing or eliminating exposure to a causal hazardous agent. AF can be estimated using the following formulae:

$$\mathrm{AF} = \frac{P(E)(\mathrm{RR} - 1)}{1 + P(E)(\mathrm{RR} - 1)}, \qquad (1)$$

where $P(E)$ is the proportion of the population exposed to agent E and RR is the relative risk of a specific cancer death arising for someone 'exposed' compared with those who are unexposed. Both of these parameters may be obtained from a population-based case–control study or cohort studies can be used to obtain information about RR, with estimates of the proportion exposed being obtained from other information sources.

In most population-based case–control studies exposure is categorized, often as 'exposed' or 'unexposed'. The information available to construct these categorizations may be quite crude and generally relies on job title and industry as the main determinants of the assignment. There is clearly considerable potential for recall bias and misclassification in making these assessments, and there will be systematic differences in the categorization of whether subjects are exposed between studies, possibly even within studies for different agents. Exposure assessments in cohort studies are generally better than population-based epidemiological studies, although many cohort studies exclude female workers and/or people with short periods of employment. However, the main issue in this situation is how best to identify the prevalence of exposure in the population that is appropriate for the relative risk estimates. For example, it would clearly be inappropriate to associate a relative risk obtained from a cohort of asbestos insulators who had sustained high exposures to the population where estimates of exposure prevalence were based on self-reports of ever having had contact with asbestos. Quantitative estimates of the exposure of workers are not strictly necessary to assess cancer burden, but it is clearly important in judging whether data from epidemiological studies being used to assess AF are relevant to the British population as a whole.

Exposure to hazardous agents varies in time, within and between workers, between worksites and from one country to another. It is difficult to be sure that epidemiological data collected in one country is relevant to others because of the likely differences in technology, working conditions and attitudes about the health risk of the material. Similarly, there is uncertainty about whether modern exposure data are relevant to past conditions and about data from specific worksites being relevant to all other sites operating that process. There are periodic surveys of exposure within sectors of British industry carried out by HSE or as part of specific research projects, and these data can provide some insight into exposure across a wide range of circumstances. However, there are no routine systems to track the prevalence and/or intensity of such carcinogenic exposures in Great Britain or in most other countries.

The main aim of this paper is to identify the exposure information that is available in Great Britain to support an assessment of the number of cancers attributable to occupational causes, to discuss the methodological issues behind using the information in such an assessment and to make recommendations for data collection to support this type of exercise in the future. We also try to identify how far it may be possible to reduce exposure to occupational carcinogens in the future.

IDENTIFICATION OF THE MOST IMPORTANT CARCINOGENIC EXPOSURES

Our starting point has been to identify what we believe are the most important carcinogenic exposures in Great Britain. We have mainly focussed on historic exposures that are responsible for currently producing cases of cancer, but we also discuss changes in exposure that will impact on future risks. Agents have been identified on the basis of the following criteria:

- there was sufficient good-quality information to decide that the agent has the potential to cause cancer;
- the vast majority of people exposed to carcinogens in Great Britain would be included in the evaluation; and
- there was the possibility for poorly controlled exposure and hence an expectation that there was a risk.

The International Agency for Research on Cancer (IARC) and a number of other authorities compile lists of carcinogens. These assessments are mainly based on an evaluation of the potential for an agent or some other exposure circumstance to cause cancer (i.e. the hazard) and mostly do not evaluate the risks associated with the exposure. However, they are sufficient for the first part of our selection criteria.

Since 1971, IARC have evaluated >900 agents and of these ∼400 have been identified as carcinogenic or potentially carcinogenic to humans. The evaluation is categorized according to the strength of evidence as either:

Group 1: The agent is carcinogenic to humans, where there is sufficient evidence of a causal relationship between exposure and cancer in humans.

Group 2a: The agent is probably carcinogenic to humans, where there is limited evidence of carcinogenicity in humans and sufficient evidence of carcinogenicity in experimental animals.

Group 2b: The agent is possibly carcinogenic to humans, which is generally assigned in cases where there is limited evidence of carcinogenicity in humans and less than sufficient evidence of carcinogenicity in experimental animals. However, it has also been used where there is inadequate evidence of carcinogenicity in humans and sufficient evidence of carcinogenicity in experimental animals, or other situations where it is believed it is possible that the agent is carcinogenic in humans.

Group 3: The agent is not classifiable as to its carcinogenicity to humans, where commonly the evidence for carcinogenicity is inadequate.

Group 4: The agent is probably not carcinogenic to humans, where there is evidence of a lack of carcinogenicity in humans and in experimental animals.

A full description of the IARC systems for categorizing carcinogenic agents may be found on their website (http://monographs.iarc.fr/ENG/Preamble/index.php).

For the purposes of this paper, all of the agents and circumstances identified as a Group 1 or 2a carcinogen were selected for further consideration, based on our view that exposure was more likely for these agents and that exposure data were more likely to be available for them. It is a matter of judgement which agents should be included in this type of assessment. The criteria for classification of an agent in IARC Group 1 are high and only including these agents or circumstances would probably underestimate the true extent of exposure to occupational carcinogens. The evidence for the carcinogenicity of agents in Group 2b is clearly more uncertain than for Group 1. On balance, we believe that the inclusion of IARC 1 and 2a agents in our analysis will provide a fairly reliable view of exposure to occupational carcinogens in Great Britain. There were 100 agents or exposure circumstances included in Group 1 and a further 68 in Group 2a (in 2007). The list includes some situations where many people are likely to have been exposed, such as in work environments where there was environmental tobacco smoke (ETS), others where only relatively few people were exposed, such as where vinyl chloride monomer was used, and some where occupational exposure is unlikely, e.g. human papillomavirus.

To obtain estimates of the numbers of people exposed, we have relied on a project to establish a database of the number of workers in Europe exposed to carcinogens, known as the CARcinogen EXposure (CAREX) (Kauppinen *et al.*, 2000). CAREX contains data on 139 carcinogens, including all substances that were in IARC groups 1 and 2a when the database was compiled. Information about this project can be accessed on the Internet (http://www.ttl.fi/Internet/English/Organization/Collaboration/Carex/default.htm), and we have shown in Table 1 the British data for the agents and/or circumstances

Table 1. Estimates of the number of people exposed to carcinogenic agents at work based on data from CAREX

Agent/process	Number exposed
Involuntary ETS exposure	1 310 000
Solar radiation	1 270 000
Silica, crystalline	590 000
Radon-222 and its decay products	562 000
Diesel engine exhaust	473 000
Wood dust	434 000
Benzene	298 000
Ethylene dibromide	283 000
Lead compounds, inorganic	249 000
Hairdresser or barber (occupational exposure as a . . .)	191 000
Painter (occupational exposure as a . . .)	150 000
Chromium [VI] compounds	130 000
Tetrachloroethylene	119 000
Coal-tars plus other PAH sources	106 000
Iron and steel founding	100 000
Asbestos	95 000
Formaldehyde	94 000
Nickel compounds	85 000
Strong inorganic acid mists containing sulphuric acid	42 000
Cadmium and cadmium compounds	36 000
Cobalt metal with tungsten carbide	36 000
Arsenic and arsenic compounds	25 000
X-rays and gamma radiation	22 000
Styrene-7,8-oxide	18 000
Trichloroethylene	16 000
Rubber industry	12 000
Beryllium and beryllium compounds	11 000
Cyclophosphamide	8000
Cisplatin	4000
Vinyl chloride	4000

with the greatest number of people exposed at work. The entries in the table comprise 99.5% of the people identified by CAREX as having occupational exposure to carcinogens. These data refer to employment during the period 1990–1993; nothing more recent is available. Note it is likely that some people will have been exposed to more than one agent, e.g. many construction workers will have had exposure to both asbestos and crystalline silica, but the CAREX data do not allow for any estimate of this type of overlap.

Estimates of prevalence were also available for a small number of carcinogens from HSE reviews of hazardous substances or other official sources. These data are compared with the corresponding CAREX data in Fig. 1. The CAREX data generally provided higher estimates of exposure prevalence (on average ∼2.5 times higher), although there was a moderate correlation between CAREX estimates and other sources of data ($r^2 = 0.61$ on the log-transformed data). In some cases, the CAREX estimate of prevalence appeared to be low even when there was no comparative data. For example, CAREX has only 22 000 persons exposed to X-rays or gamma rays whereas HSE estimates that there were ∼60 000 radiation workers in 1990 (HSE, 1998). In other cases, the CAREX estimates appear too high, for example, 249 000 people exposed to inorganic lead or lead compounds (HSE estimate 15 500). Part of the difference between the CAREX estimates and those from official sources may be temporal changes in the prevalence of exposure, although differences are more likely due to difference in the definition of an exposed person, for example, everyone in a particular industry compared with only the most highly exposed workers. Ideally, when estimating the occupational cancer burden, the exposure prevalence data should be based on the same exposure definition that was used to classify subjects in the epidemiological studies, e.g. the prevalence data should be representative of more highly exposed industrial workers if the risk estimates come from industry cohort studies.

The CAREX data were obtained from detailed information from Finland and the US and adapted by expert judgement to reflect the British circumstances (Kauppinen *et al.*, 2000). It is likely that they provide prevalence data intermediate between identifying just the most heavily exposed workers and including everyone that might potentially be exposed. In this sense, they may be quite comparable to the assignment of exposure that is typically made in population-based case–control studies. Despite the various reservations about the sources of exposure prevalence data, we believe that the CAREX data currently provide the most comprehensive estimate of exposure prevalence information for Great Britain.

No comprehensive estimates of differences in exposure prevalence were available for the past, although it seems likely that, as the proportion of people employed in industrial jobs was higher 30 or 40 years ago, more people would have been exposed to occupational carcinogens in the past. Information about the number of people employed in some relevant industries are available from historic employment statistics (Business Statistics Office, 1978). For example, Fig. 2 shows data for industrial workers from the coke industry, iron and steel manufacturing, leather tanning and the rubber industry (the gap indicates the period for which data were not available) with the CAREX data being shown at 1993. For leather tanning and coke production, there has been a fairly steady decline in the number of operatives since the 1940s, while for the other industries the number of operatives appears to peak during the 1950s or 1960s and then decline. For other agents, such as the antineoplastic drug cisplatin, the number of people exposed has probably increased over the last few decades. Currently, in Great

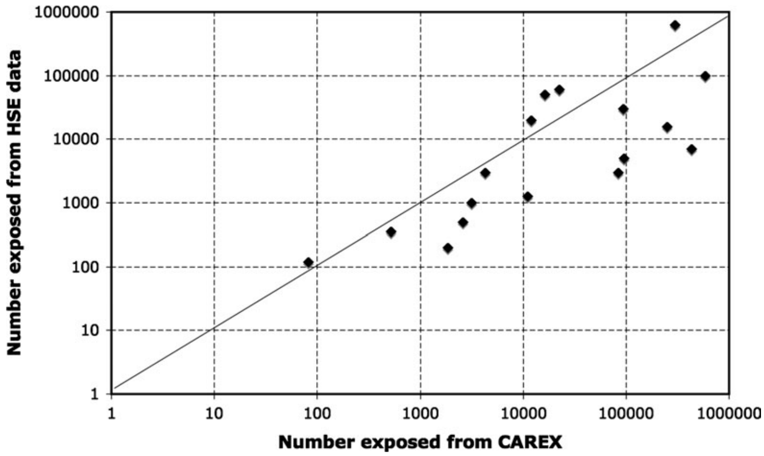

Fig. 1. Comparison of estimates of the number of people exposed to specific carcinogens from CAREX and HSE data.

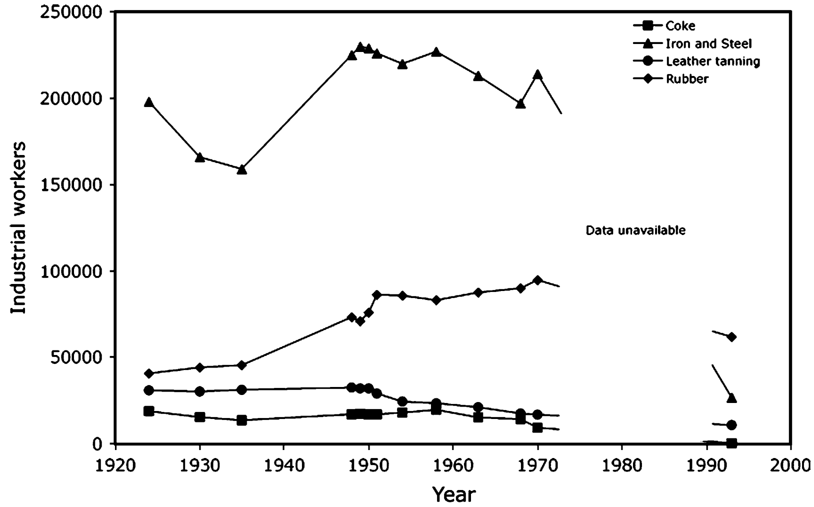

Fig. 2. Changes over time in the numbers of industrial workers in four industries with known carcinogenic risks (note the gap in data between 1970 and 2005).

Britain there are about four million prescriptions for antineoplastic drugs dispensed each year (C. Waugh, ISD Scotland, personal communication) and there must be several hundred thousand health care workers potentially exposed to these agents.

SOURCES OF INFORMATION ABOUT OCCUPATIONAL EXPOSURE IN GREAT BRITAIN

We have restricted our discussion of exposure information to the top 30 carcinogens in terms of the prevalence estimates from CAREX. For chemicals, there is information available in the HSEs National Exposure Database (NEDB), which was set up in 1986 (Burns and Beaumont, 1989). The NEDB data are not in the public domain, although we have obtained information on the data for this paper. About 80 000 exposure samples were gathered between 1986 and 2001, along with 12 000 abstracts of occupational hygiene visit reports prepared by HSE staff from 1983 to 2001 (J. Tickner, personal communication). Most of the data were collected for HSE inspection purposes, although some data were gathered from HSE-sponsored industry-wide surveys, from exposure measurement method development surveys or from industrial sources (Cherrie *et al.*, 2001). There is no guarantee that the data in NEDB are representative of industry because of the variety of purposes for which they were collected, but this is probably the most comprehensive collection of good-quality exposure data in Great Britain.

The quantity of exposure data for each substance varies considerably, from >6000 samples for quartz to less than five measurements for each of ~70 substances. The most frequently occurring measurements in NEDB are for quartz, total dust (~4500 samples), toluene (~3200) and styrene (~3000). In recent years, the number of measurements added to NEDB has decreased markedly. For example, Fig. 3 shows the number of respirable quartz measurements in NEDB by the year of collection. The peak years for obtaining data were 1986–1990 and thereafter the numbers have decreased to <100 measurements made in each of the last 6 years for which data were available. It should be noted that NEDB does not include any measurements of ETS exposures, the main occupational carcinogens identified in CAREX, or for any physical agents.

Figure 4 shows information about the average (bar) and maximum (triangle) exposure levels for the chemical exposures in the top 30 agents based on data from NEDB, with the data normalized to the current British occupational exposure limit (OEL) [workplace exposure limit (WEL)], or where there is no WEL (coal tar and diesel exhaust) to the relevant American Conference of Governmental Industrial Hygienists Threshold Limit Value. There are no British exposure data for ethylene dibromide in NEDB or for styrene oxide, but in this latter case we have shown the available information for styrene as an indicator of the relative exposure. For 12 of the 19 datasets, the average exposure level was above the OEL and for each of the substances the maximum exposure measurement recorded in NEDB was higher than the limit, in some cases by more than three orders of magnitude. As we have highlighted, one must be cautious about interpreting these information because the data in NEDB have been collected for different purposes and from a non-random sample of workplaces.

Clearly, the comparison of the exposures with the exposure limit is potentially misleading because the

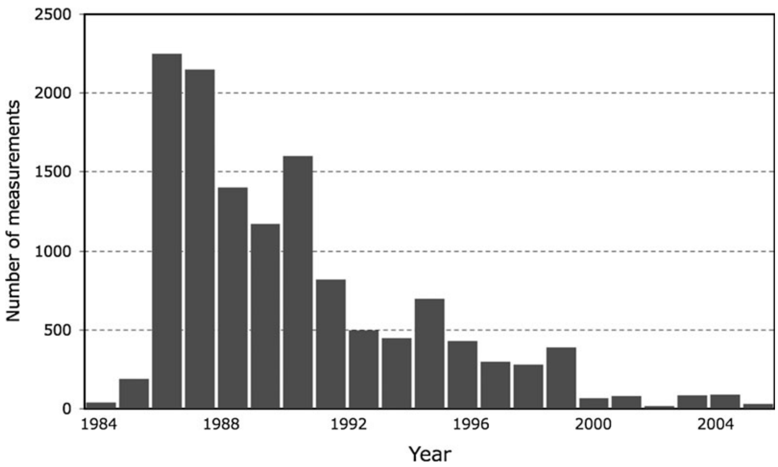

Fig. 3. The number of measurements of crystalline silica stored in NEDB by year collected.

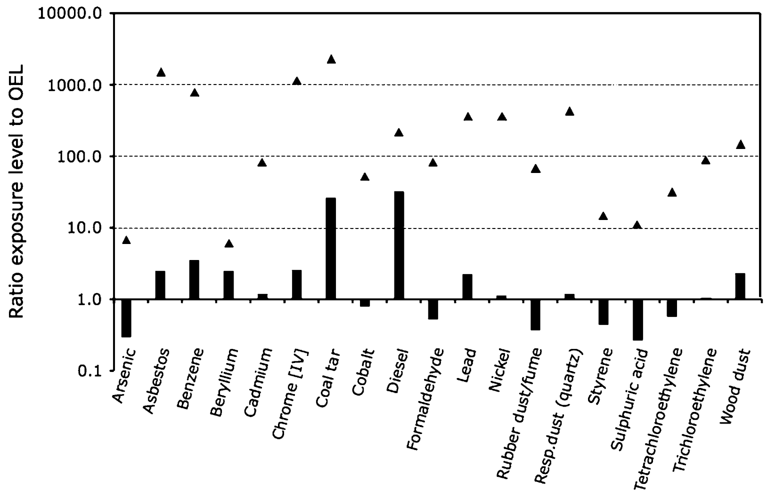

Fig. 4. The ratio of the mean and maximum exposure level to the OEL for 20 chemical agents in NEDB (the bar represents the mean exposure divided by the appropriate OEL and the triangle represents the maximum data point).

limits have not been derived on a common basis. In Britain, in the past most carcinogens were assigned a maximum exposure limit, which was set not to eliminate risk but on the basis of practicability and socio-economic considerations. Some of these substances also have relatively small amounts of data associated with them, e.g. 62 measurements of diesel exhaust, while others had less reliability because of limitations on the measurement methodology, e.g. all of the measurements of beryllium were below the limit of detection for the analysis (although the limit of detection was quite high in relation to the beryllium exposure limit). However, despite these limitations these data indicate that for many substances the historic exposure levels represented by NEDB data were higher than would be considered acceptable today and that in some cases people were exposed to very high levels.

Other sources of information on chemicals include a number of European Union risk assessment reports (RARs), many compiled by HSE scientists using information obtained from their own enquiries and from industry. These data can be accessed on the European Chemical Bureau website (http://ecb.jrc.it/existing-chemicals/). For example, the RAR for trichloroethylene summarizes data from 837 samples collected in a UK plant manufacturing this chemical, 298 samples from an associated packing plant, along with several hundred measurements in various user industries (http://ecb.jrc.it/DOCUMENTS/Existing-Chemicals/RISK_ASSESSMENT/REPORT/trichloroethylenereport018.pdf). Other information on specific industries can be found in the peer-reviewed scientific literature or in reports prepared by industry or others. For example, Sorahan and Esmen (2004) summarize the results of >2000 measurements of airborne cadmium concentrations in the UK nickel–cadmium battery industry obtained between 1957 and 1992.

Increasingly, information about exposure of workers is available from biological monitoring studies of metabolites of the agent or the original chemical in blood, urine or other body fluids. For example, Unwin *et al.* (2006) summarize data on 1-hydroxypyrene (1-OHP) levels in urine for workers exposed to polycyclic aromatic hydrocarbons (PAHs) in a cross-section of UK industry along with data from personal airborne exposure monitoring. These authors showed a strong linear correlation between various inhalation exposure measures, e.g. benz(a)pyrene (BaP) and 4–6 ring PAHs ($r^2 = 0.94$), and good correlation between BaP and 1-OHP ($r^2 = 0.77$). Biological monitoring data can provide useful measures of exposure to assess whether specific epidemiological studies are suitable to estimate risks for the wider population and may provide information about temporal changes in exposure level, although some have argued against the use of biomonitoring data in some circumstances because they may not properly reflect the exposure-disease process (Petry *et al.*, 1996).

Information on exposure to ionizing radiation is available from the HSE's Central Index of Dose Information database, which contains details about radiation doses received by all classified radiation workers. The database has information about both the number of persons classified and their doses. Information about radon levels in workplaces is available from a number of published sources. For example, Dixon *et al.* (1988) estimated that there were ~3500 people in the UK exposed to >15 mSv/year. Watson *et al.* (2005) provide a comprehensive review of exposure of the UK population to ionizing radiation, which shows that incidental exposure to radon is currently the most prevalent source of occupational exposure to ionizing radiation in the UK with ~5000 exposed >10 mSv year^{-1}.

Ultraviolet (UV) levels are continuously monitored at several fixed outdoor sites throughout Great Britain. The annual level varies from year to year, and there are important differences between the north and south of Britain (AGNIR, 2002). So far as we are aware, there are no systematic measurements of personal exposure to UV radiation of workers in the UK. Thieden *et al.* (2005) have measured exposure of gardeners in Ireland and Denmark during the summer months. They found that the personal exposure was only a small fraction (4–7%) of the total ambient solar radiation, but still comparable to the ACGIH limit for UV exposure for outdoor workers (~90 and 140% of the limit for Irish and Danish gardeners, respectively). The exposures were very dependent on the behaviour of the individuals and the pattern of work, including the time of day that lunch breaks were taken, which were generally spent indoors. 'Risk behaviour', such as the worker removing his shirt, on average more than doubled the exposure of the individual.

ETS exposure in the workplace has been the most common occupational carcinogen according to the CAREX database. Work by Brennan *et al.* (2004) has indicated that the additional lifetime risk of lung cancer among individuals who had never smoked but were exposed to 'average' levels of ETS is 16–18% and may be as high as 32% for those exposed to combined spousal, workplace and social sources. Hole (2004) arbitrarily set the increased risk figure to 25% for the Scottish population and calculated that the attributable number of lung cancer deaths among non-smokers was 44 per annum. Extrapolating this up to the British population would suggest that between 400 and 500 non-smokers may currently die every year as a result of past exposure to ETS. Clearly, only a fraction of this exposure was received in the workplace but a recent survey of >2000 of the UK working population showed that 60% of employees worked in premises where smoking was permitted (Malam *et al.*, 2004). Jamrozik (2005) carried out an analysis of the probable numbers of workers in the UK who die as a result of their exposure to ETS at work. He concluded that some 617 deaths per annum could be attributed to ETS, with ~54 of these in the highly exposed hospitality sector. These 617 deaths per annum estimate are further broken down to include lung cancer (160), stroke (182) and ischaemic heart disease (274).

Recent smoke-free legislation in Scotland, England, Wales and Northern Ireland will have a marked effect on the numbers of workers exposed to ETS at work and will reduce the number of cancer deaths from ETS exposure in subsequent years. Based on the CAREX data, these regulatory actions will probably reduce the number of workers occupationally exposed to carcinogens by about a fifth.

DIFFERENCES IN EXPOSURE BETWEEN COUNTRIES OR REGIONS WITHIN COUNTRIES

Occupational exposure to carcinogens varies between countries and even between different regions within the UK. This geographical variation in exposure is important because if risk estimates for AF assessment are based on epidemiological studies from a specific situation that differs markedly from the general pattern in Britain then the extrapolated attributable cancer burden may be biased. Differences in exposure between countries may arise because of differences in legislation, differences in technology, differences in social class, culture and attitude to risks or for geographic reasons such as climate or geology. For example, from the ExAsRub study in the rubber industry, where the researchers have analysed data from NEDB, industry and other sources, exposure to airborne dust during the 1960s was ~15 mg m^{-3}

in mixing and compounding departments of Polish plants, ~5 mg m^{-3} in the corresponding areas of the UK industry and ~1 mg m^{-3} in the Dutch plants (H. Kromhout, personal communication).

In US coke ovens in the early 1970s, the exposure levels on oven tops were higher than in Britain. Davies *et al.* (1986) summarized the benzene soluble inhalable aerosol concentrations from 12 British coke ovens, where the average levels for each job category ranged from 0.5 to 2.2 mg m^{-3}, with the highest exposure for Valvemen working on the tops of the ovens. They also quote corresponding data for 10 coke plants in the US where the levels ranged from 0.9 to 3.2 mg m^{-1}, with the highest exposure again received by the Valvemen. Within the UK data, there were substantial differences between sites, with the highest plant average exposures on the oven tops being between 2 and 6 mg m^{-3} and the lowest being between 0.4 and 0.6 mg m^{-3}. These differences were mostly related to the effectiveness of the seals on the side doors and lids of the ovens.

Radon contributes about half of all exposure to radioactivity in the UK. It is well known that radon exposures differ widely between regions within Britain because of differences in geology. Green *et al.* (2002) summarize the information available to the UK National Radiological Protection Board on the distribution of radon levels in homes in England and Wales, which showed that the highest levels were found in Cornwall (average 162 Bq m^{-3}) where almost 40% of the British properties above the 200 Bq m^{-3} action level were located. In contrast, 33 of the 41 counties in England and Wales each had <1% of the homes above the action level. Radon levels in workplaces are expected to show similar variation throughout the country (Watson *et al.*, 2005). It is estimated that ~50 000 people are exposed radon at work with an average exposure of 5.3 mSv per annum, probably mostly in south-west England.

There is also likely to have been inequality in terms of exposure to ETS at work depending on work type, social class and geographical area. For example, Edwards *et al.* (2006) measured $PM_{2.5}$ (particulate matter with average diameter <2.5 μm, as a marker of ETS exposure levels) concentration in pubs in areas classified as deprived and affluent within Manchester. Their study indicated that hospitality workers in deprived areas were exposed to airborne $PM_{2.5}$ concentrations that were on average twice those measured in pubs in affluent areas. Work in Scotland examining the effect of recent legislation to prohibit smoking in enclosed public places has shown that exposure to ETS, as $PM_{2.5}$, reduced from a mean value of 246 μg m^{-3} before the ban to 20 μg m^{-3} in the period after the ban (Semple *et al.*, 2007). From July 2007, public health legislation across the British Isles has prevented exposure to ETS in almost all occupational settings.

One must be cautious about interpreting the reasons for apparent differences in exposure between countries since differences in sampling technique or sampling strategy may give rise to apparent differences that are due to the measurement methodology. For example, measurements of asbestos in the past have been problematic because of the subjective nature of the microscopic analysis technique. During the 1970s, laboratories were reporting concentration estimates on the same samples that on average could differ by almost 10 times (Beckett and Attfield, 1974) and that systematic differences of 2- to 3-fold could arise from the use or not of an eyepiece graticule in the microscopic evaluation of samples (Beckett *et al.*, 1976). In the case of exposure in coke ovens, Davies *et al.* (1986) noted that the analysis method used for these evaluations in Britain had changed on safety grounds from using benzene as an extraction solvent to cyclohexane. He identifies that the change had reduced the quantity of material extracted and had therefore reduced the reported exposures (~30% lower according to Harrison and Thomas, 1987). However, the comparison between the British and American data does not take account of these differences in analytical method.

WHICH EXPOSURES SHOULD BE INCLUDED IN AN ASSESSMENT OF CANCER BURDEN?

We have seen that the top 30 IARC 1 and 2a carcinogens or circumstances cover 99.5% of those occupationally exposed to carcinogenic agents. The data from NEDB and from other sources described above suggest that some of these do not necessarily need to be considered in assessing AF because it is likely that even in the past exposure to these agents was generally well controlled. From Fig. 4, it is clear that there were always some measurements made that exceeded the current exposure limits but we believe there is still a reasonable case to be made for excluding several of these agents on the grounds of good control measures being in place. For example, the available data for ionizing radiation, excluding radon, show that occupational exposures were closely monitored and very tightly controlled and have been so for >30 years. Similarly, vinyl chloride, beryllium and arsenic have been recognized as toxic for many decades and have been subject to great care in use. The data for beryllium in Fig. 4 suggest that there were high exposures but in reality the levels were generally not detectable. Patel and Parsons (2003) describe the results from monitoring the exposure of 1200 beryllium workers on the Joint European Taurus project where 95% of all airborne beryllium measurements were less than the detection limit of 0.03 μg and 99.98% of measurements were <2 μg m^{-3} once the effect of respiratory protection was allowed for.

Based on our judgement about the potential for relatively uncontrolled exposure during the late 1980s and early 1990s, and the numbers of people exposed at work, we have identified what we believe were the top carcinogenic occupational exposures in Britain (Table 2) and these agents should be included in any assessment of cancer burden. Other agents could also be included but we doubt that they will contribute importantly to the overall assessment. The agents identified in Table 2 are probably also the most important targets for control interventions to reduce future risks.

There are a number of agents where there is potential occupational exposure that are not included in our list because the currently available evidence for human carcinogenicity is not strong, i.e. they are not classified as either IARC category 1 or 2a. These agents include materials that are widely used or circumstances where relatively large numbers are employed. For example, according to the CAREX database there are 15 000 people in Britain exposed to dichloromethane and 140 000 exposed to glass wool (classified as IARC 2b and 3, respectively). Several tens of thousands of people may be exposed to bitumen for which there is limited evidence of carcinogenicity in humans, although it is known that these materials contain carcinogenic PAHs. Finally, circumstances such as shift working are extremely common and recent evidence has suggested there may be potential cancer risks associated with this type of work pattern (Megdal *et al.*, 2005). If there is a cancer risk associated with shift work, then there would be many hundreds of thousands of workers in Britain at risk. It is unrealistic to attempt to include these types of exposure in any assessment because of the uncertainty about the risk, although further research may change the importance of specific agents in terms of AF.

Table 2. Key carcinogenic occupational exposures during the early 1990s

Exposure	Comments on the potential for exposure in recent times
Involuntary ETS exposure	General ventilation in bars and restaurants generally poor
Solar radiation	Little protection available to outdoor workers, plus poor awareness of risks
Silica, crystalline	Exposures still high in construction-related industries
Radon	Difficult to control and levels affected by the drive to increase energy efficiency of buildings
Diesel engine exhaust	Poor controls outside garages
Wood dust	Local ventilation available, but often not maintained well
Lead compounds, inorganic	Controls in place although not particularly focussed on cancer risk
Chromium [VI] compounds	Exposure has often been poorly controlled
Coal-tars plus other PAH sources	Poor controls in many industrial sectors
Iron and steel founding	Generally poor control in these environments
Asbestos	Exposure situations often not recognized and so controls may be inadequate

TEMPORAL CHANGES IN EXPOSURE LEVEL

Differences in exposure over time are also of interest in assessing the occupational AF for cancer and particularly in estimating future cancer burden. If exposure changes with time, then there is no guarantee that the time period covered by the source epidemiological study or studies is relevant to the period for which the AF is calculated. There are good *a priori* reasons to believe that exposure should either stay the same or decrease over time because of general improvements in technology, but clearly an industry in decline where there is no investment in new equipment may see exposure levels rise if there are no remedial actions taken to control exposures.

Symanski *et al.* (1998) analysed 696 exposure datasets from many industries throughout the world and showed that there was a median annual decline in exposure level of 6% (inter-quartile range 1–11%). Subsequent studies from several industries and countries have shown average decline in exposure within the above range. These reductions have been attributed to many small improvements, particularly in reducing the number of emission sources in plants and the introduction of engineering controls at sources of emission of hazardous substances into the work environment. Creely *et al.* (2006) extracted data from the NEDB for rubber dust, rubber fume, toluene, wood dust and flour dust to investigate whether there were corresponding time trends evident in Britain. They showed that for the rubber industry, the annual mean exposure change ranged from −8.2 to −12% in mixing and processing and from −0.5 to −3.4% in curing, −11% for toluene exposure and −8% for wood dust exposure. The data for flour dust showed no changes over the period 1985–2003. Data available from British industry sources were broadly comparable with the data from NEDB. In addition, data from measurements made in British quarries showed annual average respirable dust levels changing by −6% and corresponding quartz levels by −1.2%. There are no historical data on ETS exposures but improvements in ventilation technology and a decline in smoking prevalence from 45% of all men and women in the early 1980s to ∼25% in 2002 would tend to suggest that ETS exposures in the hospitality trade are likely to have substantially reduced (Rickards *et al.*, 2004) and as we have seen the recently introduced smoking bans have almost eliminated occupational exposure to ETS in the UK (Semple *et al.*, 2007).

Analyses of large datasets are unlikely to identify the underlying causes for changes in exposure levels. Creely *et al.* (2006) carried out separate investigations to attempt to determine the factors causing the reduction in exposures by revisiting a number of workplaces where exposure measurements had originally been made ~10 years earlier. The information obtained suggested that technological changes in production processes, availability and introduction of improved equipment, response to new legislation and follow-up inspections together with global economic trends were some of the main drivers in reducing exposure levels.

In summary, occupational exposure levels in Great Britain have generally been declining over time. This must be one of the more reassuring aspects in relation to the risks from established carcinogens. From our analysis, we cannot detect any reason why exposure to carcinogenic agents would change differently from non-carcinogens; it is probably other factors such as technological innovation and the attitudes of managers in an industry that dictate change. We therefore believe that the exposure level to the key carcinogens identified in this paper and the numbers exposed will have decreased. It seems likely that since the early 1990s, the exposure levels in British workplaces will have decreased to ~30% of their original levels (assuming a 6% reduction per year). Assuming a continued reduction at this rate, by 2025 the intensity of these exposures could be ~2% of the levels measured in the 1990s.

DISCUSSION

One of the main problems in assessing the burden of occupational cancer in Britain and how it is changing over time is the absence of any reliable information about occupational exposure to carcinogens. The HSE's NEDB provides a valuable repository of intelligence about occupational exposure levels for most chemical carcinogens, but this information was mostly obtained during the 1980s and early 1990s and currently there is very little exposure data collected systematically by government agencies. There may be data collected by industry and we have seen that in some cases this can provide a good picture of exposures in specific sectors. However, these data are not being systematically collated and archived and it is likely that much of the historic data are not retained.

In addition to exposure measurements, it is valuable to collect contextual information about exposures in industry. For example for hazardous substances, details of the materials used, the way that they are handled, the size of the work rooms, the type of local control measures and personal protective equipment used provide a valuable insight into exposures. Currently, there are several exposure modelling techniques that are available to take this type of information and provide semi-quantitative estimates of exposure (e.g. Cherrie, 1999; Cherrie and Schneider, 1999). Combined with some exposure measurement data, these models can produce fairly reliable quantitative estimates of exposure and this could be very valuable in assessing the risks from carcinogens in Britain.

Also, there is no proactive collection of survey information about the prevalence of exposure to occupational carcinogens. Regular collection of such data, say every 5 years, for the key carcinogens in the main industrial sectors would provide a valuable set of information on which to judge changing patterns of exposure and whether national interventions were actually having an impact on the numbers of people in Britain exposed to occupational cancer risks.

We firmly believe that it should be a national priority to regularly collect intelligence data on exposure for all of the key occupational carcinogens we have identified, i.e. those listed in Table 2. As a starting point, it would be helpful to collate results of occupational exposure assessments from the existing population-based case–control studies, such as the UK Adult Brain Cancer study (van Tongeren *et al.*, 2004), which might be developed into a British cancer Job Exposure Matrix (JEM) similar to the Finnish JEM (Kauppinen *et al.*, 1998). In addition, there should be a nation-wide collection of data on the number of people exposed and the circumstances of the exposure such as the method of handling the chemical, etc., which could be achieved by a scheme of voluntary reporting of data by occupational hygiene professionals. This contextual information should be supplemented with targeted collection of quantitative exposure data, which in combination with exposure modelling using the contextual information would allow a reliable assessment of the national occupational exposure to carcinogens. These data should be published and used as an indicator of progress towards elimination of occupational cancer in Great Britain.

Alongside the collection of exposure data, it is important to put in place appropriate national interventions with the aim of further reducing both the number of people exposed and the intensity of exposure to carcinogens. There are many initiatives already in place that will help sustain the reduction in exposure to carcinogens at work. For example, the recent bans on cigarette smoking in enclosed public places throughout Britain has ensured that ETS is eliminated as a cause of occupational cancer. The introduction of the European Registration, Evaluation, Authorisation and Restriction of Chemical Substances (REACH) regulations for chemicals and the requirement for industry to seek out possible substitutes for carcinogens will see the further elimination

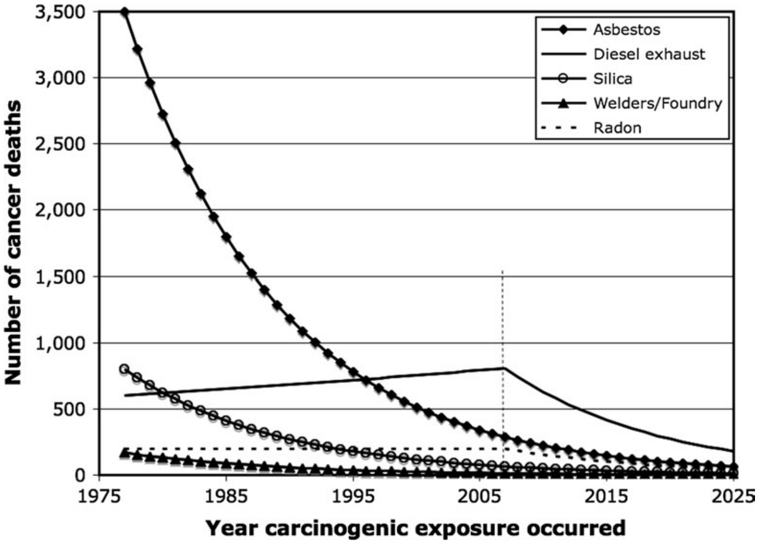

Fig. 5. Hypothetical changes in cancer mortality for five occupational carcinogens based on projected changes in exposure over time.

of carcinogens from many products used in the workplace. The much tighter management of asbestos that is being introduced in Britain should also further reduce exposures of workers who encounter asbestos in buildings. However, there is a need for further action to reduce exposure, particularly in relation to exposure to solar radiation, radon, crystalline silica, diesel exhaust particulate and other process-generated occupational carcinogens.

Figure 5 shows a hypothetical change in occupational cancer deaths for five of the agents identified in this paper in relation to the year that the 'causal' exposures were assumed to have occurred. For example, we assume there are 3500 deaths currently from mesothelioma and lung cancer due to asbestos exposure and that for simplicity the exposure that caused these occurred in 1977. The predicted exposures were assumed to drop by 8% per year (combination of reduced exposure and/or reduced prevalence of exposure) and with a direct (and linear) relation between exposure and cancer risk there would be ~300 cancer deaths in the future predicted from exposures in 2007 (i.e. at the vertical dotted line on the figure). Exposure to asbestos in 2025 is predicted to result in ~60 asbestos-related cancer deaths in the following decades. For two of the substances (radon and diesel exhaust particulate) in Fig. 5, we do not believe that effective steps have previously been taken to control exposure to these agents and we have therefore assumed that between the 1970s and the present that exposures stayed the same (radon) or even slowly increased (diesel exhaust particulate). However, we have assumed that from 2007 steps will progressively be taken to reduce these exposures. For the five agents in the example, the predicted number of deaths from exposure in 2025 reduces to ~6% of the deaths resulting from exposure in the 1970s. Of course, these figures are highly dependent on the assumptions that we have made, but they serve to illustrate the possibility to substantially reduce the occupational cancer burden in the future.

By 2025, we believe that it should be possible to reduce the level and prevalence of exposure to known occupational chemical carcinogens in Britain so that these exposures will contribute very much <1% of all cancers in the future. This is a challenging target that will require a consistent effort on the part of industry and the HSE if we are to achieve it.

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