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ORIGINAL ARTICLE

Estimation of quantitative levels of diesel exhaust exposure and the health impact in the contemporary Australian mining industry

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ABSTRACT

Objectives To estimate quantitative levels of exposure to diesel exhaust expressed by elemental carbon (EC) in the contemporary mining industry and to describe the excess risk of lung cancer that may result from those levels.

Methods EC exposure has been monitored in Western Australian miners since 2003. Mixed-effects models were used to estimate EC levels for five surface and five underground occupation groups (as a fixed effect) and specific jobs within each group (as a random effect). Further fixed effects included sampling year and duration, and mineral mined. On the basis of published risk functions, we estimated excess lifetime risk of lung cancer mortality for several employment scenarios.

Results Personal EC measurements (n=8614) were available for 146 different jobs at 124 mine sites. The mean estimated EC exposure level for surface occupations in 2011 was 14 μg/m^3 for 12 hour shifts. Levels for underground occupation groups ranged from 18 to 44 μg/m^3. Underground diesel loader operators had the highest exposed specific job: 59 μg/m^3. A lifetime career (45 years) as a surface worker or underground miner, experiencing exposure levels as estimated for 2011 (14 and 44 μg/m^3 EC), was associated with 5.5 and 38 extra lung cancer deaths per 1000 males, respectively.

Conclusions EC exposure levels in the contemporary Australian mining industry are still substantial, particularly for underground workers. The estimated excess numbers of lung cancer deaths associated with these exposures support the need for implementation of stringent occupational exposure limits for diesel exhaust.

What this paper adds

- Working in the mining industry is characterised by exposure to diesel exhaust (a human carcinogen) due to the wide use of heavy diesel machinery. Previous studies suggest the need for stringent occupational standards, which remain absent in most countries.
- Levels of exposure to diesel exhaust in the contemporary mining industry are still substantial, particularly for underground workers. These levels are associated with a significant excess number of lung cancer deaths.
- Our findings support the need for further occupational exposure control of diesel exhaust in the mining industry.

INTRODUCTION

Diesel exhaust (DE) was classified as a human carcinogen in 2012, with sufficient evidence for lung cancer.[1] Other, more acute health effects of DE include eye, throat and bronchial irritation, and neurophysiological symptoms.[2 3]

Overall, the highest levels of occupational exposure to DE have been reported for underground mining.[4] These high exposure levels result from the use of heavy diesel machinery in enclosed underground work sites. A wide range of diesel-powered equipment is used in mines, including vehicles to transport personnel, haulage trucks, load and dump vehicles, drills, graders and generators.

Elemental carbon (EC) has been used as a specific marker for DE exposure in many occupational environments since the late 1990s.[5] Between 1997 and 2001, a monitoring survey was conducted in seven US non-metal mining facilities to assess quantitative levels of exposure to DE.[6] Arithmetic means (AM) for EC exposure levels among miners who worked their full shift underground ranged from 40 to 384 μg/m^3 across facilities. Average exposures for surface workers at these underground mines were much lower, with levels between 2 and 6 μg/m^3 EC.[6] A review of DE exposure studies reported similar concentrations for mining jobs in the USA, the UK and Estonia.[4] Levels appeared to be particularly high for the underground production workers, who do the drilling, blasting and the loading and haulage of the ore, with AMs ranging from 148 to 637 μg/m^3 EC. Levels were somewhat lower for underground maintenance workers (AM 53–144 μg/m^3).[4] In Australian mines, levels between 10 and 420 μg/m^3 EC for coal and metalliferous mines in the 1990s[7] and mean levels ranging from 11 to 117 μg/m^3 for occupations in underground metal mines in 2005 have been reported.[8]

Although there is currently no national occupational exposure standard for DE in Australia, the Australian Institute of Occupational Hygienists recommends an exposure limit of 100 μg/m^3 EC as a time-weighted average (TWA) over 8 hours,

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primarily to protect workers against irritant effects of DE.[7] In 2011, 5.5% of the total Western Australian (WA) workforce was employed in the mining industry, representing 67 000 workers.[9] WA mines account for over 40% of employment in the Australian mining sector.[9] We aimed to estimate quantitative levels of DE exposure for all mining jobs in WA using a state regulatory exposure database. Then we aimed to estimate the excess risk of lung cancer associated with these current exposure levels.

METHODS

Exposure data

Mining companies in WA are required by the State's Department of Mines and Petroleum to undertake regular risk assessment of all mining hazards including exposure to airborne contaminants. Based on this assessment, each mine is assigned a monitoring quota, defining the minimum number of samples to be collected in each quarterly quota period. The emphasis has been to representatively sample the workforce to indicate exposures. Since 1986, sample results for a wide range of contaminants have been systematically recorded on a computerised system, known as CONTAM.[10] For each result stored in the database, details on employer (including site ID), worker (ID, job title, shift length and pattern, respirator use) and sampling (purpose, date, start and finish time, equipment used, flow rate) have been documented. Identifiable details on companies and workers were excluded before data provision.

EC levels have been monitored for mining occupations since April 2003. Up to January 2015, 8666 EC personal monitoring samples collected in the breathing zone of the worker were available. Sampling was performed using a cyclone sampler (Diesel Particulate Matter, GS-3, aluminium or plastic) with associated single-use diesel particulate matter cassette with a 37 mm quartz filter. Analyses were performed according to the National Institute of Occupational Safety and Health method 5040.[11] The median work-shift length of monitored miners was 12 hours. We excluded four samples of <240 min and nine samples of >840 min from current analyses, as these were considered outliers and unlikely to be representative of the workers' exposure during a full shift. Furthermore, samples collected with an inadequate device (ie, inhalable sampler, n=4), measurements taken during exploration expeditions (n=22) and additional samples requested by an inspector for unknown reasons (n=13) were excluded, leaving 8614 measurements for analysis. Results above the upper limit of EC determination[11] (ie, exceeding the concentration of 0.8 mg/m^3, n=22) were set at 0.8. All EC concentrations in CONTAM were recorded in mg/m^3, which we converted to $\mu g/m^3$ for consistency with previously published studies.

Occupational grouping

When entered into the database, each monitoring result was coded with the job title of the monitored worker. The job codes followed a hierarchical structure, with the following main divisions: 'Management and supervisory'; 'Underground production and services'; 'Mining production and services (surface)'; 'Ore treatment occupations'; 'Railway operations occupations'; 'Metal working processing trades'; 'Electrical or electronic trades'; 'Miscellaneous trades or utilities'; and 'Material handling—store or warehouse occupations'. For modelling purposes, we classified all job titles into occupational groups, without any reference to the measurement data. The grouping was performed to enable accounting for small numbers or no measurements for some of the jobs.

For non-mining surface operations, we applied the same classification as the US Diesel Exhaust in Miners Study, based on the estimated amount of contact with diesel equipment.[6] Surface group 1 (S1) was defined as "occupations with no or very limited contact with diesel equipment". Occupations in S1 included: management and supervisory occupations, sampling/assay/laboratory occupations, metalworking processing trades (except fitters), electrical or electronic trades, power plant operators, water treatment plant operators, gas supply service operators and other utility operators.

The second surface group (S2) consisted of "occupations in which workers drive a diesel forklift indoors <4 hours per shift on average; operate heavy diesel equipment (>75 horse power (HP)) <4 hours per shift on average; drive light diesel equipment (≤75 HP) on a regular basis; or work in close proximity to diesel-powered equipment on a regular basis". These occupations included: processing plant operators, fitters (except diesel), construction trades, conveyor belt occupations and motor trades other than mechanics.

The third surface group (S3) consisted of "occupations in which workers operate heavy diesel equipment ≥4 hours per shift on average; drive a diesel forklift indoors ≥4 hours per shift on average; or repair diesel equipment". Occupations in this group included: mobile plant occupations (ore treatment), final product handling or transport occupations, railway operations occupations, diesel fitters, mechanics, waste disposal equipment operators and material handlers.

Jobs in surface mining production and services, which were not covered in the US Diesel Exhaust in Miners Study, were grouped into a fourth (S4) and fifth (S5) surface occupation group. S4 included drilling and blasting occupations, and open cut service occupations. S5 included excavation equipment operators, mobile plant operators and driving occupations.

Underground occupations were grouped as follows: mining production or development occupations (UG1); drilling and blasting occupations (UG2); loading and transport occupations (UG3); ground or roof support and other service occupations (UG4); and winding and hoisting operators, underground managers and foremen, and other professionals (including mining engineers, geologists, surveyors, industrial hygienists, safety and training officers) in underground mines (UG5).

Statistical analyses

All statistical analyses were carried out in SAS V.9.4 (SAS. Institute, Cary, North Carolina, USA). EC concentrations were summarised as AM, geometric mean (GM) and geometric SD (GSD). Twenty-five per cent of EC measurements were below the limit of detection (LOD). We imputed these concentrations using maximum likelihood estimation, assuming that non-detected values follow the same log-normal probability distribution as the observed data.[12] The non-detected value was substituted by a draw between the average ambient level of 1 $\mu g/m^3$ [13] and the median LOD of 10 $\mu g/m^3$. We repeated the process multiple times to create 25 data sets. These data sets were independently analysed and results were then combined using PROC MIANALYZE to account for imputation error.

The exposure prediction model was developed using the restricted maximum likelihood method with PROC MIXED. The fixed effect terms included year, occupation group, interaction between year and occupation group, mineral mined (gold; nickel; iron; base metals; other) and sampling duration in minutes. Random effects included job title, mine site ID and worker ID. The random effects were assumed to be statistically independent and normally distributed around the mean value of 0. Variance components represent between job, between mine site, between worker and residual variances. Job was included as random effect, aiming to use the best linear unbiased prediction (BLUP) estimates to predict exposure levels for the specific jobs, as has been applied previously.[14–16] BLUP estimates are considered to be similar to fixed effect estimates, unless they are based on small numbers or there is large variability in measurement data, which causes shrinkage of the estimates towards the overall mean.[14]

Model structure:

$$\ln (Y_{adj})_{mjy} = \beta_0 + \beta_Y + \beta_{og} + (\beta_Y \times \beta_{og}) + \beta_M + \beta_S + b_j + b_{ms} + b_w + \varepsilon$$

Where:

$\ln (Y_{adj})_{mjy}$=natural log-transformed EC concentration (adjusted for sampling duration) for the

m^{th} mineral mined, j^{th} job and y^{th} year.

β_0=model intercept.

β_Y=continuous variable for year of measurement (reference 2011).

β_{og}=categorical variable for occupation group ($\beta_{1\text{-}10}$).

$\beta_Y \times \beta_{og}$=interaction term between year of measurement and occupation group.

β_M=categorical variable for mineral mined ($\beta_{1\text{-}5}$).

β_S=continuous variable for sampling duration in minutes (reference 480).

b_j=random effect term for job title ($b_{1\text{-}146}$).

b_{ms}=random effect for mine site ID ($b_{1\text{-}124}$).

b_w=random effect for worker ID ($b_{1\text{-}5365}$).

ε=residual error.

An exposure–response relationship has recently been described to derive the relative risk (RR) between cumulative exposure to EC and lung cancer mortality based on studies among workers in the mining and trucking industries, with an lnRR of 0.00098 for 1 EC $\mu g/m^3$-years (95% CI 0.00055 to 0.00141).[17] An independent panel evaluated the contributing study among miners and the most recent study on truckers for the Health Effects Institute (HEI) and concluded that the results and data from these studies can be usefully applied in quantitative risk assessment.[18] We used this risk function to estimate the excess lifetime risk of lung cancer mortality for different exposure scenarios, based on the EC exposure levels observed in the WA mines. We followed the same method as Vermeulen *et al*,[17] but stratified by sex.

Since our study included both surface and underground operations, we preferred the pooled risk function from the meta-analysis as it reflects a wider application of diesel equipment and is estimated more precisely than an exposure–response relation based on a single study. However, in the HEI report, the miners' study[19] was identified as best addressing the requirements for quantitative risk assessment.[18] We therefore additionally applied the risk function based on the latter study alone (β 0.0012 (95% CI 0.00053 to 0.00187)[17]) for sensitivity analysis.

Population denominator data from the Australian Bureau of Statistics[20] and mortality records from 2010 to 2012 were used to obtain background rates of all-cause mortality in 2011 and subsequently to estimate the probability of surviving each 5-year age interval in WA. Similarly, we estimated lung cancer mortality rates for 2011 to estimate the risk of dying from lung cancer, if not dying from another cause. We then summed the age-specific lung cancer mortality rates to estimate the background lifetime risk of dying from lung cancer up to the age of 80 years. This was performed separately for men and women.

Several scenarios for exposure to DE in the mining industry were defined, with varying exposure levels and employment durations. The levels of DE exposure were based on the modelled levels in 2011 for surface workers (mean S1–5), underground miners (UG1) and for the highest exposed job title (ie, underground diesel loader operator). Durations of employment in the mining jobs were set at 5, 10, 20 or 45 years since the age of 20 years, to represent different employment scenarios. Cumulative EC exposure for each 5-year age group was calculated, assuming a constant exposure over time and lagged 5 years. We performed sensitivity analysis to test the effect of a 15-year lag time instead.

The RR for each cumulative exposure was derived from the aforementioned exposure–response relationship. Background lung cancer mortality rates were multiplied by the RR for each age group and summed to estimate the lifetime risk of dying from lung cancer up to 80 years of age. The excess lifetime risk, expressed as the excess number of lung cancer deaths per 1000 exposed individuals, was then derived using:[17]

$$\text{Excess lifetime risk} = \frac{(\text{Risk}_{\text{exposed}} - \text{Risk}_{\text{unexposed}})}{(1 - \text{Risk}_{\text{unexposed}})}$$

This procedure was carried out for each exposure scenario and for men and women separately.

RESULTS

Measurements of EC concentration (n=8614; table 1) in the breathing zone of workers were collected on 124 mine sites. Within these mines, 5365 individuals were monitored, representing 146 different occupations. Underground workers were monitored most often (representing 79% of the data). The vast majority of measurements came from gold (52%) and nickel (22%) mines.

Measured EC concentrations were higher for underground workers than for surface workers (table 1). Monitored surface workers were exposed to a GM of 9 $\mu g/m^3$ EC overall and levels were comparable across the occupation groups, ranging from 7 to 11 $\mu g/m^3$. The overall GM for underground workers was 42 $\mu g/m^3$. Concentrations among underground workers ranged from 17 $\mu g/m^3$ for UG5 to 59 $\mu g/m^3$ for UG1. Stratified by the mineral mined, the EC exposure levels were lowest for iron ore mines (GMs 6 and 38 $\mu g/m^3$ for surface and underground operations, respectively) and highest for nickel mines (GMs 18 and 48 $\mu g/m^3$).

From the mixed model, fixed effects for occupation group (with S1 as reference) showed that surface workers had the lowest exposure levels, with geometric mean ratios (GMR=exp (β)) between 1.00 for S5 and 1.10 for S3 (table 2). UG1 had the highest levels (GMR 3.30). Compared with gold mines, exposure levels were lower in iron ore (GMR 0.52) and higher in nickel mines (GMR 1.36). The interaction between sampling year and occupation group was statistically significant ($p=0.001$, data not shown), indicating that temporal trends in EC exposure levels differed between the occupation groups. Trends, as obtained from the betas for year of sampling and the interactions presented in table 2, ranged from −1% (S3) to −14% (S4) per year. Analyses excluding the main slope factor (ie, only including the interaction term, not year as a separate fixed effect) indicated that these trends were statistically significant ($p<0.05$) for all except S3 (data not shown). Exposure levels were lower for shorter sampling times, with a slope of 2.6% per hour increase in sampling duration. BLUP estimates for jobs are presented in online supplementary table S1.

Table 1 Occupational exposure to elemental carbon (μg/m^3) in Western Australian mines, summary statistics for data collected between 2003 and 2015

	K*	N† (%)	Per cent <LOD‡	AM§	GM¶	GSD**	5–95th centile
All workers	5365	8614 (100%)	25	68	31	3.90	3–230
Surface workers							
All surface workers	1379	1784 (21%)	66	23	9	3.11	2–86
Occupation group††							
S1	264	319 (3.7%)	60	21	10	3.01	2–70
S2	423	473 (5.5%)	68	26	10	3.28	2–91
S3	356	560 (6.5%)	61	25	11	3.28	2–100
S4	95	98 (1.1%)	76	21	7	2.62	2–33
S5	290	334 (3.9%)	74	18	8	2.72	2–70
Mineral mined							
Gold	341	434 (5.0%)	50	25	13	3.15	2–92
Nickel	142	169 (2.0%)	36	34	18	3.29	2–100
Base metals (Cu-Pb-Zn)	123	146 (1.7%)	60	32	11	3.57	2–110
Iron ore	591	647 (7.5%)	89	13	6	2.23	2–13
Other‡‡	190	388 (4.5%)	61	29	10	3.34	2–120
Underground workers§§							
All underground workers	4043	6830 (79%)	15	80	42	3.45	4–250
Occupation group††							
UG1	602	1018 (12%)	10	104	59	3.35	6–300
UG2	1124	1579 (18%)	15	78	41	3.44	4–240
UG3	1657	2439 (28%)	13	83	44	3.42	5–260
UG4	1087	1364 (16%)	14	72	41	3.25	4–210
UG5	307	430 (5.0%)	36	30	17	3.11	3–94
Mineral mined							
Gold	2509	4085 (47%)	16	76	40	3.48	4–240
Nickel	1087	1688 (20%)	11	89	48	3.35	5–280
Base metals (Cu-Pb-Zn)	488	702 (8.1%)	19	79	41	3.74	4–210
Iron ore	11	12 (0.1%)	33	80	38	4.74	3–210
Other‡‡	236	343 (4.0%)	8.2	70	40	2.83	7–170

*Number of workers.
†Number of samples.
‡Limit of detection.
§Arithmetic mean.
¶Geometric mean.
**Geometric SD.
††S1=Management and supervisory; sampling/assay/laboratory; metalworking processing trades; electrical/electronic trades; power plant operators; water treatment plant operators; gas supply service operators; other utility operators. S2=Processing plant operators; fitters (except diesel); construction trades; conveyor belt; motor trades other than mechanics. S3=Mobile plant; final product handling/transport; railway operations; diesel fitters; mechanics; waste disposal equipment operators; material handlers. S4=Drilling and blasting; open cut service. S5=Excavation equipment operators; mobile plant operators; driving. UG1=Underground mining production or development. UG2=Underground drilling and blasting. UG3=Underground loading and transport. UG4=Underground ground or roof support; other underground service. UG5=Underground winding and hoisting operators; underground managers, foremen and professionals.
‡‡'Other' includes: diamond (n=372), construction materials (n=257), bauxite/alumina (n=48), salt (n=26), heavy mineral sands (n=6), dimension stone (n=4), chromite/platinoids (n=1), manganese ore (n=1) and other/product handling (n=16).
§§Percentage measurements underground per mineral mined: gold 90%; nickel 91%; iron 2%; base metals 83%; other 47%.
AM, arithmetic mean; GM, geometric mean; GSD, geometric SD; LOD, limit of detection.

Fixed effects in the full model, including all variables and the interaction between year and occupation group, explained 82% of the between job variance of the log-transformed EC concentrations, 53% of the between site variance and 10% of the between worker variance (table 2). The null model, that is, the model without fixed effects, indicates that over 50% of the variance was temporal.

Mean estimates of EC exposure levels for each of the occupation groups at a gold mine in reference year 2011 are shown in table 3. Surface groups were exposed to GMs between 13 and 15 μg/m^3 for a 12 hour work shift. Job-specific GMs for surface workers ranged from 10 to 19 μg/m^3. Group GMs for underground workers ranged from 18 to 44 μg/m^3 EC, with job-specific estimates between 14 and 59 μg/m^3. Note that estimated levels are dependent on the mineral mined, for example, estimates are lower for iron ore and higher for nickel mines.

Jobs with the highest exposure levels underground were diesel loader operators, ground or roof support occupations (including shotcreters) and non-contract miners (including miners operating a jumbo or handheld drilling rig), with EC exposure levels (GM) of 59, 55 and 53 μg/m^3 for a 12 hour work shift at a gold mine in 2011, respectively (table 4A). Engineering occupations (19 μg/m^3), motor or engine trades (17 μg/m^3) and mechanical fitters (17 μg/m^3) had the highest exposures to EC on the surface (table 4B).

For average exposures to EC levels of 14 μg/m^3 (mean for surface workers in 2011) over 45 years, we estimated the excess number of lung cancer deaths at 5.5 per 1000 males and 3.2 per 1000 females in WA (table 5). We estimated that there would be 38 and 22 extra lung cancer deaths per 1000 men and women, respectively, if miners spent 45 years working underground with an EC level of 44 μg/m^3. Short careers of 5 years as an underground miner from the age of 20 years would result

Table 2 Fixed effects model parameter estimates and variance components

Model parameters/variance components				
Fixed effects terms	**β***	**SE**	**GMR†**	**p Value**
Intercept	−4.426	0.126	–	–
Occupation group‡				
S1	Ref.	–	1.00	–
S2	0.012	0.150	1.01	0.937
S3	0.095	0.144	1.10	0.511
S4	0.050	0.189	1.05	0.792
S5	−0.0004	0.155	1.00	0.998
UG1	1.194	0.153	3.30	<0.0001
UG2	1.032	0.141	2.81	<0.0001
UG3	1.028	0.145	2.79	<0.0001
UG4	1.041	0.136	2.83	<0.0001
UG5	0.328	0.161	1.39	0.042
Year of sampling				
Continuous (median 2011)	−0.064	0.037	0.94	0.083
Interaction				
S1:Year	Ref.	–	1.00	–
S2:Year	−0.055	0.043	0.95	0.202
S3:Year	0.056	0.046	1.06	0.219
S4:Year	−0.090	0.065	0.91	0.166
S5:Year	−0.042	0.048	0.96	0.378
UG1:Year	0.032	0.041	1.03	0.459
UG2:Year	−0.032	0.039	0.97	0.414
UG3:Year	−0.013	0.038	0.99	0.741
UG4:Year	−0.006	0.039	0.99	0.884
UG5:Year	−0.075	0.047	0.93	0.109
Mineral mined				
Gold	Ref.	–	1.00	–
Nickel	0.308	0.113	1.36	0.007
Iron ore	−0.657	0.133	0.52	<0.0001
Base metals (Cu-Pb-Zn)	0.256	0.173	1.29	0.139
Other	−0.228	0.176	0.80	0.196
Sampling duration				
Continuous—minutes (median 607)	0.0004	0.0001	1.00	<0.0001

	Null model		Final model		
Variance components	**VC§**	**SE**	**VC§**	**SE**	**Per cent¶**
Between job	0.327	0.055	0.057	0.017	82
Between site	0.340	0.061	0.160	0.032	53
Between worker	0.100	0.019	0.091	0.018	10
Residual	1.105	0.026	1.091	0.025	1

*β for fixed effect derived from the mixed model based on the restricted maximum likelihood method.
†Geometric mean ratio.
‡S1=Management and supervisory; sampling/assay/laboratory; metalworking processing trades; electrical/electronic trades; power plant operators; water treatment plant operators; gas supply service operators; other utility operators. S2=Processing plant operators; fitters (except diesel); construction trades; conveyor belt; motor trades other than mechanics. S3=Mobile plant; final product handling/transport; railway operations; diesel fitters; mechanics; waste disposal equipment operators; material handlers. S4=Drilling and blasting; open cut service. S5=Excavation equipment operators; mobile plant operators; driving. UG1=Underground mining production or development. UG2=Underground drilling and blasting. UG3=Underground loading and transport. UG4=Underground ground or roof support; other underground service. UG5=Underground winding and hoisting operators; underground managers, foremen and professionals.
§Variance component.
¶Percentage of variance explained by fixed effects.

in 2 extra lung cancer deaths per 1000 men and 1.2 per 1000 women. When working for 45 years as an underground diesel loader operator (at 59 μg/m^3 EC), the excess number of lung cancer deaths would be 79 and 46 per 1000 men and women, respectively.

The sensitivity analysis showed that application of the risk function based on the US miners' study only, instead of the pooled function, resulted in larger excess numbers of lung cancer deaths (see online supplementary table S2). For example, working as a surface miner (14 μg/m^3 EC) for 45 years resulted in 7.2 extra lung cancer deaths, and 45-year careers as an underground miner at 44 μg/m^3 EC resulted in 62 extra lung cancer deaths per 1000 males.

Using a lag time of 15 years, instead of 5 years, resulted in virtually the same excess number of lung cancer deaths, except for lower numbers for the 45 years employment in mining (see online supplementary table S3). These numbers were reduced to 29 extra lung cancer deaths per 1000 male underground

Table 3 Mean estimate per occupation group (μg/m³ EC prediction for a gold mine in 2011), based on 12 hour shifts

	EC† exposure levels in 2011 (μg/m³)	
Occupation group*	**Group GM‡ (95% CI)**	**Job-specific§ GMs min–max**
Surface workers		
S1	13 (10 to 17)	10–19
S2	13 (8 to 23)	11–17
S3	15 (9 to 25)	11–17
S4	14 (7 to 26)	12–17
S5	13 (8 to 23)	13–15
Underground workers		
UG1	44 (25 to 75)	31–53
UG2	37 (22 to 63)	33–45
UG3	37 (22 to 63)	25–59
UG4	37 (22 to 63)	25–55
UG5	18 (10 to 32)	14–24

*Occupation groups as listed in the Methods section, under 'Occupational grouping'.
†Elemental carbon.
‡Geometric mean.
§Job-specific GMs have been derived using the model function, including the best linear unbiased prediction estimates as presented in online supplementary table S1.
EC, elemental carbon; GM, geometric mean.

Table 4 Predictions of EC exposure levels for 12 hour shifts at a gold mine in 2011

Job title—underground	Occupation group*	EC† exposure level
(A) Underground job titles with the highest level of exposure (μg/m³ EC)		
Diesel loader operator	UG3	59 μg/m³
Ground or roof support occupations (nfs‡)	UG4	55 μg/m³
Non-contract miner	UG1	53 μg/m³
Contract miner	UG1	52 μg/m³
Loading or transport occupations (nfs)	UG3	50 μg/m³
Miner's assistant	UG1	46 μg/m³
Miner (nfs)	UG1	45 μg/m³
Shot firer	UG2	45 μg/m³
Labourer or tool carrier	UG4	44 μg/m³
Hydraulic fill operator	UG4	44 μg/m³
(B) Surface job titles with the highest level of exposure (μg/m³ EC)		
Engineering occupations (nfs‡)	S1	19 μg/m³
Motor or engine trades (nfs)	S3	17 μg/m³
Fitter mechanical (nfs)	S2	17 μg/m³
Diesel motor mechanic	S3	17 μg/m³
Final product packer, loader or dumper operator	S3	17 μg/m³
Fuel and lubrication serviceman	S4	17 μg/m³
Final product warehouse operator	S3	17 μg/m³
Electrical fitter	S1	16 μg/m³
Boilermaker	S1	16 μg/m³
Front end loader operator (mobile plant)	S3	16 μg/m³

*Occupation groups as listed in the Methods section, under 'Occupational grouping'.
†Elemental carbon.
‡Not further specified.
EC, elemental carbon.

miners (at 44 μg/m³ EC), and 17 for female underground miners.

DISCUSSION

Recent measurements of EC (2003–2015) were available for analyses, enabling the estimation of present-day DE exposure levels. Modelling quantitative levels of exposure to EC in the contemporary WA mining industry showed that underground workers had the highest exposure, with levels up to 59 μg/m³ for goldminers in 2011. Surface workers in 2011 experienced lower, but still substantial, exposure (10–19 mg/m³ on average). Lifetime careers (45 years) as surface and underground miners at current levels are associated with 5.5 and 38 extra lung cancer deaths per 1000 men, respectively. The corresponding excess lung cancer deaths are 3.2 and 22 per 1000 women, respectively.

Mean levels in metalliferous underground mining operations in Queensland (2005)[8] showed similar levels when compared with our AMs. For instance, 82 μg/m³ for underground drill operators was reported in the Queensland mines compared with 78 μg/m³ for drilling operations (UG2) in our study, and 48–85 μg/m³ for loading and transport occupations in Queensland compared with 83 μg/m³ in the WA mines (UG3; table 1).

Comparison with international studies indicated that levels in WA mines were of the same order of magnitude as found in the mining industry elsewhere in the world. We observed AMs between 21 and 26 μg/m³ EC and GMs between 10 and 11 μg/m³ for the non-mining surface operations (occupation groups S1–3) in 2003–2015. Personal measurements among surface occupations in a US potash mine in the 1990s showed average concentrations ranging from 12 to 31 μg/m³.[21] In the US Diesel Exhaust in Miners Study, average exposure levels for surface workers were lower, ranging from 2 to 6 μg/m³ across seven non-metal mines in 1998–2001.[6] The median LOD for the measurements in our data set (10 μg/m³) was relatively high for the NIOSH method, which, together with the lower limit of 1 μg/m³ in the imputation process, may partly explain the somewhat higher EC exposure levels for surface workers in our population.

For underground occupation groups, AMs in our study ranged from 30 to 104 μg/m³ EC and GMs from 17 to 59 μg/m³ in 2003–2015. EC concentrations for underground jobs in seven US non-metal mines (1998–2001) varied from 40 to 384 μg/m³.[6] For underground occupations in a US potash mine (1990s), average exposure levels between 53 and 345 μg/m³ were reported.[21] Exposures among underground workers in a US goldmine (1999), where the equipment used had no emission control devices, ranged from 305 to 1165 μg/m³ with the highest exposures observed for drivers of heavy-duty diesel vehicles.[22] The upper level in the latter study exceeded the limit of EC determination,[11] however, above which level samples in our analyses were truncated (n=22). More recently (2006), published EC exposure levels among underground iron ore miners in Sweden varied from 5 to 61 μg/m³.[3,23]

EC exposure levels varied by the mineral mined. Iron ore mines had the lowest levels for both surface (GM 6 μg/m³) and underground operations (GM 38 μg/m³), and nickel mines showed the highest levels (GMs 18 and 48 μg/m³, respectively). These differences remained present in the mixed-effect model, including job type and sampling year. For iron ore mines, which are all open cut in WA, the few measurements of underground occupations represented shaft sinking operations. However, no substantial differences in the technologies used at the different type of hard-rock underground mines in WA are to be expected. The observed differences in exposure levels between the gold, nickel and base metal mines may be explained by the operation sizes, the extent of the overall mine excavation or different companies owning the different mines. Sampling procedures could also differ or maintenance standards may be less stringent or less effective for one industry sector compared to the other. We

Table 5 Excess number of lung cancer deaths for several scenarios of diesel exhaust exposure in mining jobs

Scenarios of typical work histories in mining			Excess number of lung cancer deaths up to 80 years of age (per 1000 workers)	
Job type	**Average exposure**	**Employment duration (years)**	**Males**	**Females**
N (95% CI)	N (95% CI)			
Surface worker	14 μg/m³ EC	5	0.6 (0.3 to 0.9)	0.4 (0.2 to 0.5)
		10	1.2 (0.7 to 1.8)	0.7 (0.4 to 1.1)
		20	2.6 (1.4 to 4.0)	1.6 (0.8 to 2.4)
		45	5.5 (2.7 to 9.2)	3.2 (1.6 to 5.4)
Underground miner (occupation group UG1)	44 μg/m³ EC	5	2.0 (1.1 to 3.0)	1.2 (0.6 to 1.8)
		10	4.4 (2.2 to 7.1)	2.7 (1.4 to 4.2)
		20	11 (5.1 to 20)	6.7 (3.1 to 12)
		45	38 (13 to 97)	22 (7.4 to 57)
Diesel loader operator (underground)	59 μg/m³ EC	5	2.8 (1.4 to 4.2)	1.7 (0.9 to 2.5)
		10	6.4 (3.1 to 11)	3.9 (1.9 to 6.4)
		20	18 (7.5 to 35)	11 (4.5 to 21)
		45	79 (21 to 258)	46 (12 to 151)

EC, elemental carbon; UG1, underground mining production or development.

can only speculate, however, since no data to test any of these hypotheses are available.

The approximate 10-fold range in average exposure levels for underground jobs across facilities as reported by Coble *et al*[6] indicates high variability between facilities. In our study, more than half of the between mine site variability was explained by the occupation group, sampling year and duration, and mineral mined. Residual variance between sites (0.160) suggests that other determinants, such as the use of diesel equipment, maintenance and ventilation efficiencies, may be different between the mine sites, but we had no information on these factors in the database.

In a planned measurement study, one can better specify and control the sampling strategy and the collection of auxiliary information, customised to the research question. The use of administrative exposure databases, on the other hand, has the advantage of generally much larger numbers of monitoring results for a wider range of jobs, locations, agents and a longer period of time. By using the CONTAM data, we had access to more than 8000 EC measurements. Several studies have used existing databases for exposure modelling before,[14 24–26] showing the feasibility of this approach in occupational exposure assessment. However, they also recognised the limitations of using existing data. One of the main limitations is missing information, for example, on exposure circumstances and sampling details. Another potential limitation is the representativeness of the data, as measurements may not cover all jobs and facilities. In WA mines, quotas for monitoring are set based on the risk assessment performed at individual mine sites. As a result, measurements were more often taken in situations where exposure was expected. Selective monitoring may lead to an overestimation of the overall exposure levels, if jobs with no or low exposures to DE have not been monitored at all. Alternatively, since exposure monitoring is not mandatory in WA mines, measurement results in CONTAM may also represent 'best practice' mining companies.

Prediction of exposure levels for individual workers should be considered with appropriate caution. Mean exposure levels were very similar between the three non-mining surface occupation groups, and this was not expected based on the grouping strategy. Workers who drive diesel vehicles for most of their shift (classified as S3) may be protected by air-conditioned cabins, leading to lower exposure levels than expected based on the proportion of their shift spent near diesel machinery. The similar exposure levels between the groups may also indicate bias in measurements taken (as mentioned above), namely that jobs or situations were predominantly measured when exposure to DE was expected. The relatively high exposure level for S1, which included occupations with typically no or very limited contact with diesel equipment, may be explained by such bias. About 45% of all potential surface job titles had been monitored for EC exposures, ranging from 34% for S1 to 70% for S4. Many of the remaining S1 jobs would not involve substantial exposure to DE and could possibly be considered unexposed. In comparison, 71% of all underground job titles were represented by EC monitoring results in CONTAM.

Our findings for underground workers were at the lower end of the exposure ranges reported internationally, particularly for the somewhat older studies. The more recent measurements in our study may reflect changes in diesel engine technology and other efforts to lower exposure levels by the mining industry thus far. Worldwide, DE exposure levels are expected to decrease over time as a result of increasingly stringent emission standards. US and European regulations are driving the conversion from older to newer diesel engine technology.[27] Australia, however, lags behind. Euro1/US1988 engines were implemented in 1995 in Australia, followed by Euro4/US1994 engines in 2007 for on-road vehicles, while traditional diesel engines are still used in off-road heavy duty equipment.[27] These engines in off-road applications, along with many older on-road vehicles still in use, are likely to be responsible for ongoing and substantial emission of DE, adversely affecting the health of exposed workers.

Results from a recent meta-regression on data from studies in the US mining and trucking industries indicate that there is a need for stringent occupational standards for DE.[17] This publication revealed the number of excess lung cancer deaths for different exposure scenarios. An average lifetime occupational exposure (from 20 to 65 years of age) to 25 μg/m³ EC results in an estimated 689 excess lung cancer deaths per 10 000 in the USA in 2009.[17] For exposures to 10 and 1 μg/m³, the excess numbers were estimated to be 200 and 17 per 10 000, respectively.[17] These numbers are all above 1/1000, which is the 'acceptable' level of risk for occupational exposures used by the US Occupational Safety and Health Administration.[28]

Although individual measurements may have exceeded the current recommendation for exposure to DE in occupational settings in Australia, which is set at 100 μg/m³ EC[7], all estimated full-shift exposure levels for mining occupations in 2011 in our study were well below this guideline limit. Nevertheless, based on exposure–response analyses for EC exposure and lung cancer by Vermeulen *et al*,[17] risks of lung cancer are clearly increased for these levels. The excess number of lung cancer deaths associated with the levels of exposure during a lifetime career was estimated at 5.5 per 1000 men for surface workers. For general underground miners, exposure to the current EC levels of 44 $\mu g/m^3$ for 5, 10, 20 or 45 years since the age of 20 years corresponds to excess numbers of lung cancer deaths in WA of 2, 4.4, 11 and 38 per 1000 men, respectively. (Note that lung cancer mortality background rates are higher in the USA than in Australia).[29]

For the calculation of the excess lifetime risk, we assumed an average exposure level for different employment durations based on the levels estimated for 2011. Our data suggested a decreasing temporal trend in EC exposure levels, ranging from −1% to −14% per year, depending on occupation group. The exposure scenarios based on the estimated levels in 2011 will therefore most likely underestimate the actual cumulative exposures experienced by current workers. Hence, the number of excess lung cancer deaths may be higher than we have reported here. On the other hand, for those who recently started working, the number may be overestimated if exposure levels continue to decrease. Another uncertainty is whether the applied risk function is appropriate for female exposed workers, since virtually no women were present in the study populations on which the exposure–response relationship was based and how well the risk function fits cumulative levels of EC beyond 1000 $\mu g/m^3$-years. The latter concerns our excess risk estimates after 45 years in underground mining, which is also indicated by the wide CIs. Furthermore, application of an alternative risk function (ie, from the US miners' study alone) estimation of the excess number of lung cancer deaths would have been higher overall. Despite the inherent uncertainties in the applied risk function due to the assumptions that had to be made in its derivation[17] and the assumptions we had to make, the lung cancer risks are higher than generally acceptable, suggesting that the current DE exposure guideline is not sufficiently stringent.

In summary, our findings show that exposure to DE is still substantial in the contemporary WA mining industry. Exposures are particularly high for underground workers, and may have considerable adverse health effects. Further exposure regulation is therefore warranted. Control of DE exposure could be focused at different stages: replacement of diesel machinery, emission controls (eg, exhaust filters, low-emission engines, regular maintenance of equipment or improved driving habits), transmission controls (eg, ventilation) and exposure controls (eg, enclosed working cabins or respiratory protective equipment). Employee information and training are also important for controlling exposure.

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Contributors SP and RV were responsible for the exposure assessment. SP, NdK and RV were responsible for the data analysis and interpretation. AR, LF and AWM assisted with data interpretation and liaison with data custodians. The paper was drafted by SP and revised with contributions from all authors. All authors have read and approved the manuscript.

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OEM

Estimation of quantitative levels of diesel exhaust exposure and the health impact in the contemporary Australian mining industry

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