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SHORT REPORT

Is diesel equipment in the workplace safe or not?

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ABSTRACT

Objectives Recently, diesel motor exhaust (DME) has been classified as a known human carcinogen. We used data from epidemiological studies of diesel exposures to perform a quantitative risk assessment to calculate DME exposure levels, expressed as elemental carbon (EC), corresponding to acceptable risk (AR) and maximum tolerable risk (MTR) levels of 4 to 10^{-5} and 4 to 10^{-3} for the lifetime excess probability of dying from lung cancer.
Methods Previously published slope estimates (n=14) of the exposure–response curve (ERC) for EC exposure and lung cancer were used in life-table analyses to calculate EC exposure levels corresponding to the specified AR and MTR levels.
Results Considered ERC slope factors ranged from 0.00060 to 0.0012 natural logarithm of the relative rate (lnRR) per $\mu g/m^3$ years based on different selections of studies and study-specific risk estimates. Exposure limits based on these slope factors were between 0.009–0.017 and 0.85–1.67 $\mu g/m^3$ EC for the AR and MTR, respectively.
Conclusions Derived exposure limits based on the AR and MTR are around or well below 1 $\mu g/m^3$ EC. Such limits are below current occupational exposure levels, and in some instances even below environmental exposure levels. Although uncertainties exist in the exact slope factors, these results indicate that an acceptable excess lung cancer mortality risk can only be achieved at very low DME exposure levels, suggesting that diesel engines using older technologies should be removed from the workplace when possible or emissions strictly controlled.

What this paper adds

- Diesel motor exhaust (DME) has been classified as a human carcinogen but no quantitative risk assessment (QRA) has been performed to date to derive occupational exposure limits.
- On the basis of a survey carried out in 15 European Union countries in 1990–1993, diesel exhaust is the fourth most common carcinogenic agent in workplaces, with 3 million regularly exposed workers.
- We performed a QRA to calculate DME exposure levels, expressed as elemental carbon (EC), corresponding to acceptable risk (AR) and maximum tolerable risk (MTR) levels corresponding to a lifetime excess probability of 4 to 10^{-5} and 4 to 10^{-3} of dying of lung cancer.
- Results show that AR and MTR levels are respectively in the 0.01 and 1.0 $\mu g/m^3$ EC exposure range, which are (well) below contemporary occupational exposure situations.
- The derived risk levels are hardly achievable in occupational workplaces using older technology diesel engines.

INTRODUCTION

Diesel engines are widely used in many industrial settings and forms of transportation such as mining, construction, agriculture, forestry, shipping and other activities where diesel-powered vehicles and tools are used. It has been estimated that 1.4 million workers in the USA and 3 million workers in Europe are occupationally exposed to diesel motor exhaust (DME).[1] At the same time, exposure to DME has been linked to several acute and chronic adverse health effects, including lung cancer.[2] In 2012, a working group of the International Agency for Research on Cancer (IARC) concluded that there was sufficient evidence in humans and experimental animals to classify DME as a group 1 (carcinogenic to humans).[1] After this hazard classification, Vermeulen *et al*[3] published an exposure–response curve (ERC), based on available studies that quantified the lung cancer rate by DME exposure using elemental carbon (EC) as a proxy. We argued then that this ERC could be used for quantitative risk assessment (QRA).

Subsequently, several reviews of the literature and underlying studies were published.[2 4–6] Most recently, a panel of the Health Effects Institute (HEI) reviewed two of the main studies contributing to the IARC evaluation and reflected on the ERC derived by Vermeulen *et al.* The HEI panel concluded that underlying studies could be usefully applied in QRA but noted that a systematic characterisation of the ERC and associated uncertainties should be addressed.[2]

We present results of a QRA based on the ERC published by Vermeulen *et al* with additional sensitivity analyses based on alternative (published) ERCs to estimate acceptable exposure levels.

MATERIAL AND METHODS

Contributing studies and meta-regression

As described previously, three epidemiological studies, two from the trucking industry and one among non-metal miners, were available with detailed quantitative reconstruction of historical exposure levels, using EC as the exposure metric.[7–9] For the primary meta-regression, we used rate estimates presented by the original authors as their primary analyses. In further sensitivity analyses, suggested by us and others,[4 10] different rate estimates were used to determine the sensitivity of the derived ERC to the selection of estimates from alternative risk models from the contributing studies. We did not include a fourth study on occupational EC and lung cancer risk[11] because of methodological considerations.[10]

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ERCs were estimated using a meta-analytic log-linear regression model in which the natural logarithms of the reported rate estimates were inversely weighted by their variance, and the correlation of rate estimates within a single study was accommodated using the method of Greenland and Longnecker.[12] For further details of the meta-regression method used see Vermeulen *et al*.[3]

Life-table analysis

Life tables were used to estimate the excess risk of dying from lung cancer due to DME, contrasting lung cancer mortality in a hypothetical population with no or only background exposure to that in a population where everybody was exposed according to a specific DME scenario. Information on the average population size and number of deaths from all causes and lung cancer in 5-year age categories for the Dutch population during 2000–2014 was obtained from Statistics Netherlands. A Generalized Additive Model was used to obtain risks estimates for each single year and age from this data, using the midpoint of age categories and single smooth terms for year and age. Estimated probabilities of death for each age in the most recent year (2014) were converted into age-specific mortality rates.

For the exposed population, age-specific lung cancer mortality rates at age t ($q_{c1}(t)$) were calculated from the baseline lung cancer rate ($q_{c0}(t)$) and the age-specific (cumulative) exposure as implied from the exposure scenarios as follows: $q_{c1}(t) = q_{c0}(t) \times \exp(\beta \times \text{exposure}[t])$, with β the exposure slope coefficient from the risk model. The difference was then added to the baseline all-cause mortality rate to calculate the all-cause mortality rate in the exposed population.

Starting with hypothetical birth cohorts of 10 000 participants, we then calculated the size of the population at risk for each cohort and age up to 120 years. Age-specific probabilities of death from all-causes were calculated from the corresponding rates by assuming that these were constant over the year. The number of deaths of lung cancer in each cohort and at each age was estimated in proportion to the ratio of lung cancer deaths and all-cause mortality rates at that age. The cumulative risk of lung cancer at each age was then calculated as the cumulative number of lung cancer deaths divided by the original cohort size, and the excess risk as the difference in cumulative risk between the exposed and unexposed cohorts.

Risk models

All models under consideration were relative rate models based on (lagged) cumulative exposure, expressing the incidence rate (λ) at age t and cumulative exposure x as a multiplicative function of a possibly time-varying baseline rate, that is, $\lambda(x,t) = \lambda_0(t) \times \exp(\beta \times x)$. Risks were calculated from rates by assuming that these were constant during a year. Slope factors (β) for the different models are listed in table 1, and cumulative exposures were calculated from the exposure scenarios using a 10-year lag.

We calculated the EC exposure levels corresponding to the acceptable risk (AR) and maximum tolerable risk (MTR) levels, assuming an exposure duration of 40 years (age 20–60). AR and MTR are defined as the lifetime excess cumulative risks of dying from lung cancer due to (occupational) exposure at 10^{-6} or 10^{-4} per exposure year and are used in both Europe and the US. Assuming a 40-year tenure these correspond to lifetime excess risks of 4 to 10^{-5} and 4 to 10^{-3}, respectively. Excess risk calculations were truncated at the age of 100 assuming that deaths occurring beyond this age are unlikely to be related to the exposure of interest. In a sensitivity analyses we repeated the calculations and calculated the AR and MTR at age 80.

RESULTS

The slope factor (β) of the previously published primary meta-regression model was 0.00098 (lnRR per μg/m³ years)[10]

Table 1 ERC meta-analytic slope factors based on primary selected risk estimates and alternative risk and study selections and EC exposure levels corresponding to acceptable and MTR levels

Serial number	Contributing studies and selected analyses: Garshick *et al*	Silverman *et al*	Steenland *et al*	ERC slope factor (lnRR per μg/m³ years)	Acceptable risk (4 to 10^{-5}) EC (μg/m³)	MTR (4 to 10^{-3}) EC (μg/m³)
1	*5 years lag; excl mechanics*	*15 years lag*	*5 years lag*	0.000982	0.011	1.03
2	0 year lag; excl mechanics	15 years lag	5 years lag	0.000909	0.011	1.11
3	10 years lag; excl mechanics	15 years lag	5 years lag	0.001021	0.010	0.99
4	5 years lag; incl mechanics	15 years lag	5 years lag	0.000936	0.011	1.08
5	5 years lag; excl mechanics	0 year lag	5 years lag	0.000608	0.017	1.66
6	5 years lag; excl mechanics	15 years lag; excluding highest risk estimate	5 years lag	0.001060	0.010	0.95
7	5 years lag; excl mechanics	15 years lag	0 year lag	0.000927	0.011	1.09
8	5 years lag; excl mechanics	15 years lag	5 years lag	0.000646	0.016	1.56
9	5 years lag; excl mechanics	15 years lag	5 years lag	0.000713	0.015	1.42
10	5 year lag; unadjusted for tenure	15 years lag	5 years lag	0.000774	0.013	1.30
11		15 years lag	5 years lag	0.001066	0.010	0.95
12		15 years lag		0.001181	0.009	0.85
13			5 years lag	0.000959	0.011	1.05
14	5 years lag; excl mechanics			0.000605	0.017	1.67
	Calculated ERC slope based on a fixed MTR (4 to 10–3)			0.00101		1
				0.0001		10
				0.00005		20
				0.00001		100

Italics indicate the choice of study specific risk estimates as published by the respective authors as the primary analyses (model 1).
EC, elemental carbon; ERC, exposure–response curve; excl, excluding; incl, including; MTR, maximum tolerable risk.

(table 1). Slopes based on alternative study and risk estimate selections varied between 0.00060 and 0.0012. Life-table analyses for AR and MTR excess lung cancer risk levels, based on the primary ERC, corresponded to EC exposure levels of 0.01 and 1.03 μg/m^3, respectively. These results varied between 0.009–0.017 and 0.85–1.67 μg/m^3 EC for the AR and MTR based on alternative ERCs, respectively.

Additional sensitivity analyses counting deaths only to the age of 80 instead of 100 resulted in a 47% increase in AR and MTR associated EC levels. Using multistate European Union or US mortality data resulted in the AR and MTR associated EC levels to be 21% higher and −10% lower on average than using the Dutch mortality data (data not shown).

We further calculated the slope factors that would correspond to an MTR based limit of 100, 20, 10, or 1 μg/m^3 EC. Based on these analyses, EC levels above 10 μg/m^3 would only be permissible if the slope factor was <10% of the primary slope factor of 0.00098.

DISCUSSION

DME has been classified as a known human carcinogen. The data contributing to this classification relates predominantly to exposure from diesel engine technologies being used between the 1960s and the early 2000s. For non-road engines, that are most relevant in occupational settings, the emission limits in Europe have declined from between 0.54 and 0.85 g/kWh in 1999–0.025 g/kWh in 2011–2014. For non-road engines under 37 kW, particle emission is allowed at 0.6 g/kWh, and for the smallest engines (<19 kW) the emissions are not regulated at all.[13] As such much of the contemporary and near future occupational DME exposures will be related to the so-called traditional or transitional diesel engine technology (<2007) on which the IARC evaluation and QRA presented in this paper are based. After 2007, new diesel technologies have become available, characterised by the integration of wall-flow diesel particulate filters and diesel oxidation catalysts. These newer technologies reduce particulate matter and EC emissions by more than 99% on a per-km or per-kWh basis.[14] Although human data allowing the direct comparison of the carcinogenic potential of these newer and older technologies are not available, the significant reduction in emissions can be expected to reduce the lung cancer risk (per-kWh).

Our QRA analyses indicated that, based on the derived ERCs, exposure limits based on the AR should be well below 0.1 μg/m^3 EC, while exposure limits based on the MTR would be around 1.0 μg/m^3 EC. Customary exposures to EC at the workplace vary from 1 (parking attendants), 2–5 (professional drivers), 5–10 (construction and mechanics), to >100 μg/m^3 in underground mining which are all in the range or well above the MTR level.[15] Median ambient air EC levels between 0.5 and 2 μg/m^3 have been reported for metropolitan areas in Europe and the US.[16 17]

In our analyses we entertained several sensitivity analyses which have been proposed by ourselves and others.[3 4] We did not include the sensitivity analyses proposed by Morfeld and Spallek[4] where risk estimates from the DEMS study were adjusted for radon exposure. As indicated by the HEI panel, radon is not a major confounder in the DEMS study, and adjustment is likely to lead to biased results instead.[2]

Although several regulatory agencies are considering implementing new regulation for DME at the workplace, current occupational regulations for DME vary from ~100[18] to 20 μg/m^3 EC.[19] Such limits would correspond to a hypothetical slope factor that is 20–90 times lower than our derived primary slope factor based on the studies available to date. Such slope factors fall well outside the CIs of the primary slope factor and were not observed in any of the sensitivity analyses.

Our QRA analyses indicate that exposure limits for DME at the workplace based on the AR are well below current occupational exposure levels and even below current environmental EC levels. Controlling risk at the MTR level would correspond to exposure levels that are at the lower end of the occupational exposure range for DME. These results would indicate that older technology diesel equipment cannot be safely used in many occupational settings. It may therefore not be practical to set occupational exposure limits for DME but rather to move towards an expedited process of removal of these diesel engines from the workplace and/or to implement strict control measures.

Contributors RV conceived the idea for the analyses presented. LP and RV conducted the statistical analyses. RV and LP interpreted the results and wrote the manuscript. Both authors read and approved the final manuscript.

Competing interests None declared.

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