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Diesel engine exhaust exposures in two underground mines

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ABSTRACT

Exposure to diesel engine exhaust (DE) is a major concern in underground mines. It has been linked to cardiopulmonary diseases and is classified as a human carcinogen. The goal of this study is to assess DE exposures in workers at two underground gold mines, to compare exposure levels within and between the mines, and to compare different methods of measuring DE exposures, namely respirable combustible dust (RCD), elemental carbon (EC) and total carbon (TC). Ambient and personal breathing zone (PBZ) measurements were taken. Side-by-side monitoring of RCD and of the respirable fraction of EC and TC (EC_R and TC_R) was carried out in the workers' breathing zone during full-shift work. Regarding ambient measurements, in addition to EC_R, TC_R and RCD, a submicron aerosol fraction (less than 1 μm) of EC and TC was also sampled (EC_1 and TC_1). Average ambient results of 240 μg/m^3 in RCD, 150 μg/m^3 in EC_R and 210 μg/m^3 in TC_R are obtained. Average PBZ results of 190 μg/m^3 in RCD, 84 μg/m^3 in EC_R and 150 μg/m^3 in TC_R are obtained. Very good correlation is found between EC_R and EC_1 with a Pearson correlation coefficient of 0.99 ($p < 0.01$) calculated between the two log-transformed concentrations. No differences are reported between EC_R and EC_1, nor between TC_R and TC_1, since ratios are equal to 1.04, close to 1, in both cases. Highest exposures are reported for load-haul-dump (LHD) and jumbo drill operators and conventional miners. Significant exposure differences are reported between mines for truck and LHD operators ($p < 0.01$). The average TC_R/EC_R ratio is 1.6 for PBZ results, and 1.3 for ambient results. The variability observed in the TC_R/EC_R ratio shows that interferences from non-diesel related organic carbon can skew the interpretation of results when relying only on TC data.

1. Introduction

Exposure to diesel engine exhaust (DE) has been linked to increased cancer risk and cardiopulmonary diseases. DE has been classified as a human carcinogen (group 1) by the International Agency for Research on Cancer and has become a contaminant of primary interest at the international level [1]. Vermeulen et al. reported that 6% of deaths from lung cancers could be linked to occupational exposures to DE [2]. Peters et al. estimated a lifetime career (45 years) extra lung cancer deaths per 1000 males of 5.5 and 38 for miners experiencing exposure levels of 14 and 44 μg/m^3 of elemental carbon (EC), respectively [3]. In addition, acute exposures to DE have been associated with respiratory irritation and inflammation, and cardiovascular effects [4–9].

DE refers to the complex mixture of chemical substances found in solid, liquid or gaseous states resulting from the incomplete combustion of diesel fuel. The type of engine, fuel, oil, and operations are some of the factors that can affect the composition of DE. Carbon oxides (CO and CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), water vapor, sulfur compounds, low molecular weight hydrocarbons (e.g. benzene, 1,3-butadiene), and oxygenated compounds (e.g. aldehydes) can all be found in the mixture. Diesel particulate matter is composed of EC onto which organic carbon (OC) compounds and other particles (unburnt fuel, lubricant droplets, metallic additives, etc.) are adsorbed. The majority of the particles are within the respirable fraction (fraction corresponding to particles with aerodynamic

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diameter lower than 10 μm with 50% efficiency cut-off at 4 μm) and most are ultrafine particles (100 nm in diameter or less) [10].

Occupational exposure limits (OEL) for DE vary between and within countries. In the province of Quebec, Canada, a limit value of 600 μg/m^3 of respirable combustible dust (RCD) was implemented in the mining industry until 2016. Since 2016, the OEL has been established at 400 μg/m^3 of total carbon (TC) [11]. The Canadian province of Ontario has a regulatory time-weighted limit value of 400 μg/m^3 of TC transposable to EC via a conversion factor of 1.3 (i.e. about 310 μg/m^3 for EC) for the mining industry [12]. Both monitoring strategies imply a size selective sampler to collect the respirable fraction (less than 4 μm). The U.S. Mine Safety and Health Administration has prescribed an 8 h OEL of 160 μg/m^3 of TC based on recommendations and methods of the National Institute for Occupational Safety and Health (NIOSH) [13]. In this case, the monitoring strategy requires a size-selective sampler to collect the submicron range (less than 1 μm). There is currently no time-weighted average threshold limit value proposed by the American Conference of Governmental Industrial Hygienists (ACGIH).

Underground mines pose great occupational health and safety challenges due to their very unique work environments. The presence of off-road, diesel-powered mobile machinery is one of these challenges. The goal of this study is to assess diesel engine exhaust exposures in workers of two underground mines, to compare exposure levels within and between the mines, and to compare several methods of measuring diesel engine exhaust exposures.

2. Materials and methods

Two filter-based methods for assessing DE are compared: the NIOSH 5040 method used for sampling the carbonaceous fraction (EC and TC), and the RCD method [14,15]. For the NIOSH 5040 method, nylon cyclones were used with 25 mm quartz filter cassettes and GilAir pumps (Sensidyne, LP, St. Petersburg, FL, USA) set at a flow rate of 1.7 L/min. For the RCD method, nylon cyclones were used with 25-mm silver membrane cassettes and GilAir pumps (Sensidyne, LP, St. Petersburg, FL, USA) set at a flow rate of 1.7 L/min.

Side-by-side personal RCD and respirable EC (EC_R and TC_R) samples were taken in the workers' breathing zone during their full shift (between 10 and 12 h). Ambient RCD and EC_R (TC_R) samples were taken simultaneously in main circulation routes (i.e. bypasses and ramps) over periods ranging from 4 to 6 h. Air was sampled at a height of about 1–1.5 m in order to correspond to the shared breathing zone of workers. For ambient measurements, in addition to the respirable fraction of EC and RCD, a submicron fraction (less than 1 μm) of EC (EC_1 and TC_1) was selected using a prefilter which consists of a cassette with a jeweled submicron impactor (Airtech, Flir System Inc., Wilsonville, OR, USA). For sampling this submicron aerosol fraction, GilAir pumps (Sensidyne, LP, St. Petersburg, FL, USA) set at a flow rate of 1.7 L/min were used.

Sampling was carried out during two separate periods of two weeks each. For all measurements, pumps were calibrated before and after every sampling period using a DryCal volumetric flow meter (Mesa Labs Inc., Lakewood, CO, USA). Field observations were noted throughout the sampling periods. Carbonaceous fractions (RCD, EC, TC) were analysed by the laboratories of the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST) (Montreal, Canada).

Statistical analyses were performed with the SPSS software (Statistics 21, IBM Corporation, Armonk, NY, USA). The geometric mean (GM) and geometric standard deviation (GSD) were used for describing the exposure profiles. The estimated arithmetic mean (AM) and the corresponding 90% confidence limits were used for comparing personal exposure levels to exposure limits and for evaluating the cumulative damage from exposure to diesel exhaust. Similar exposure groups (SEG) were based on job titles. Pearson correlation coefficients and bilateral t tests were calculated on the log-transformed concentrations to compare exposure levels within and between the mines.

3. Results

3.1. Ambient measurements

Ambient RCD, EC and TC concentrations are presented in Table 1. Average EC_R, EC_1, TC_R and TC_1 are 193, 191, 256, and 247 μg/m^3, respectively. The highest ambient concentrations ($EC_R = 580$ and $TC_R = 1000$ μg/m^3) are observed in the ventilation exhaust section of the mine. Average TC_R/EC_R and TC_1/EC_1 ratios are both equal to 1.3. Concentrations of TC_R and TC_1 are lower than the regulation in force in Quebec and Ontario (400 μg/m^3) but higher than the one in force in the USA (160 μg/m^3). Concentrations of EC_R and EC_1 are lower than the Ontario regulation ($EC \times 1.3 \leq 400$ μg/m^3; approximately 310 μg/m^3), and concentrations of RCD are lower than the former Quebec regulation of 600 μg/m^3.

Fig. 1 presents the relationship between respirable EC_R and EC_1 concentrations. A very good correlation is found between both parameters. Pearson correlation coefficient of 0.99 ($p < 0.01$) is calculated between the two log-transformed concentrations. The ratio between EC_R/EC_1 and TC_R/TC_1 are both equal to 1.04, close to 1. These results indicate that around 96% of the diesel particulates are within the submicron range, less than 1 μm.

3.2. Personal measurements

Descriptive statistics for personal RCD, EC and TC concentrations are summarized in Table 2. Average personal TC concentration is 150 μg/m^3, less than half the Quebec OEL of 400 μg/m^3.

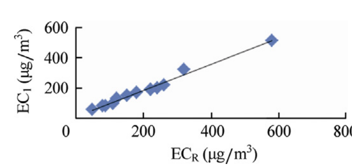

Fig. 1. Relationship between EC_R concentrations and EC_1 concentrations.

Table 1
Summary of ambient RCD, EC and TC measurements.

	RCD (μg/m^3)	EC_R (μg/m^3)	TC_R (μg/m^3)	EC_1 (μg/m^3)	TC_1 (μg/m^3)
AM	289	193	256	191	247
90% CL	226–421	145–283	202–348	143–283	196–333
GM	240	150	210	160	200
GSD	1.9	2	1.8	1.9	1.8
n	17	17	17	13	13

Note: AM means the estimated arithmetic mean; 90% CL means 90% confidence limits; GM means the geometric mean; GSD means the geometric standard deviation; and n means the number of samples.