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A review of the health effects and exposure-responsible relationship of diesel particulate matter for underground mines

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ABSTRACT

The increasing use of diesel-powered equipment in confined spaces (underground mines) has the potential to over expose underground miners under the threat of diesel particulate matter (DPM). Miners in underground mines can be exposed to DPM concentrations far more than works in other industries. A great number of animal and epidemiological studies have shown that both short-term and long-term DPM exposure have adverse health effect. Based on reviews of related studies, especially some recent evidence, this paper investigated the long and short-term health effects based on animal studies and epidemiological studies. The exposure-response relationship studies were also explored and compared to the current DPM regulation or standards in some countries. This paper found that the DPM health effect studies specifically for miners are not sufficient to draw solid conclusions, and a recommendation limit of DPM concentration can be put in place for better protection of miners from DPM health risk. Current animal studies lack the use of species that have similar lung functions as human for understanding the cancer mode of action in human. And finally, the DPM health hazard will continue to be a challenging topic before the mode of action and reliable exposure-response relationship are established.

1. Introduction

As diesel-powered equipment has good power performance, high economy, efficiency as well as durability, its use has continuously increased in both underground coal and metal/non-metal mines since the 1960s. Various types of diesel-powered equipment are operated in the mining industry. Compared to gasoline equipment, diesel-powered equipment is more efficient and emits less carbon dioxide (a greenhouse gas) per unit of work. Nevertheless, diesel-powered equipment emits much more particulate matter than gasoline equipment during the combustion process. This is a problem in confined spaces, such as underground mines, where it has great potential for miners to be overexposed to diesel particulate matter (DPM). Miners in underground mines can be exposed to far higher DPM concentrations than in other industries. For example, in 1996, the US nationwide average DPM exposure was estimated to be 1.4 $\mu g/m^3$. On the other hand, investigators showed that exposure for the workers in coal mines and noncoal mines ranges from 10 to 1280 $\mu g/m^3$, with environmental equivalent exposure of 2–269 $\mu g/m^3$ [1].

In 1988, based on the results of a series of animal and epidemiologic studies, the National Institute for Occupational Health and Safety (NOISH) in the US recommended that DPM had potential carcinogenic effects on humans [2]. In the following year (1989), International Agency for Research on Cancer (IARC), a part of the World Health Organization (WHO), published a monograph which classified DPM as a probable carcinogen to humans (group 2A) [3]. A number of animal studies have been conducted, which showed that long-term exposure to DPM has the potential to cause lung tumours [4–9]. There are also many epidemiological studies on humans that have suggested the association between health effects and long-term DPM exposure [10–20]. These studies concluded that long-term exposure to high concentrations of DPM could increase the lung cancer risk. In addition, many studies showed that short-term or acute exposure to DPM could also induce negative health effects, such as acute irritation, asthma, cough, light-headedness [1,21–28]. In 2012, based on sufficient evidence of animal and epidemiological studies, IARC classified DPM as carcinogenic to humans (Group 1). For these reasons, health issues associated with DPM exposure are receiving substantial attention from the public, government agencies and academia.

In order to minimize DPM health hazards, the DPM concentration should be maintained below an acceptable standard. Germany, Canada and the USA have already set their limit or

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standard for DPM exposure for mining industries. Germany sets the DPM limit for underground noncoal mines and other surface workplaces at 0.3 and 0.1 mg/m^3, respectively. The Canada Centre for Mineral and Energy Technology sets the standard of DPM at 0.75 mg/m^3 [29]. In the US, the Mine Safety and Health Administration (MSHA) has an exposure standard of DPM for metal/nonmetal mines of 0.16 mg/m^3 (measured as total carbon) [30]. The development of regulations and standards for the DPM exposure in underground mines is still in its early stage in Australia [31]. Currently, the official limit for DPM exposure for underground mines is still not established, and the level of regulation in different states varies. In Australia, many regulatory agencies have considered 0.1 mg/m^3 (measured as elemental carbon, TWA) of DPM as a recommended exposure limit, and this is also recommended by the Australian Institute of Occupational Hygienists (AIOH) [32].

Due to the hazards of DPM, many studies of DPM have been carried out; however, very few detailing the health effects review impacts on mining workers, especially for the underground miners. The aim of this paper is to provide a review of the health effects of DPM on underground miners, especially some recent evidence, and the regulations in some major mineral producing countries with a new trend on what data is more appropriate to reflect the DPM dose. This paper conducted a scientific review of a great number of available literature published over the past three decades. Based on the published animal and epidemiological studies, this paper determined the potential relationship between both long-term and short-term DPM exposure and health effects. This paper also aims to determine whether there was an exposure-response relationship for cancer effects. Available data from animal and human studies have been used to evaluate the exposure cancer unit risk and the cancer mode of action. A recommended exposure limit of DPM for underground mining industry was concluded based on a summary of the published literature and regulation in different countries.

2. Health effects of DPM

2.1. Deposition mechanisms

The main way for DPM to enter the respiratory system is inhalation. It was reported that particles could deposit within the human respiratory tract [1]. Studies showed that the filtering capacity of the nose would be very low when particles' size was less than 0.5 μm [1,34]. When the particle size is less than 1 μm, it is able to deposit in the deepest ranges of lungs. Fig. 1 shows the typical mass-weighted and number-weighted size distributions of diesel particles. As can be seen, more than 90% of the particles' diameters are below 1 μm, which are capable of entering the deepest ranges of the lungs. Many studies have shown that airborne PM, in which DPM is the main component, contributes to the respiratory mortality and morbidity [35,36].

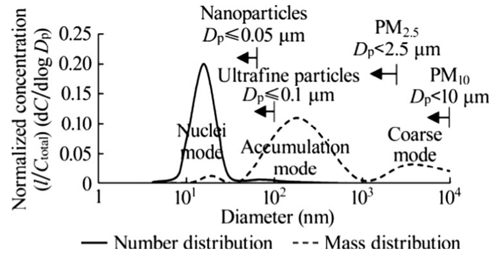

Fig. 1. Diesel particulate matter size distribution (Modified after Kittelson [33]).

2.2. Long-term effects

2.2.1. Laboratory animal studies

A high number of animal studies have been carried out to evaluate the potential health effects of long-term DPM exposure. Many animal studies, including on rats, mice, hamster and monkey, have demonstrated that long-term exposure to high concentrations of DPM contributes to increasing the risk of lung tumour.

Almost all the animal studies have shown a lung tumour response in rats after long-term exposure to a high concentration of DPM (>2.5 mg/m^3). Heinrich et al. conducted a long-term study with rats, mice, and hamsters exposed to unfiltered and filtered DPM to understand its carcinogenicity [4]. All experimental animals were aged 8–10 weeks before the exposure. The exposure was 19 h a day, 5 days a week. The maximum exposure duration for mice, rats and hamsters was 120, 140 and 120 weeks, respectively. The concentrations of unfiltered DPM in this study were about 4 mg/m^3. Each group included 96 animals. There was a clean air exposure chamber for the control groups with equal sample size. A high lung tumour rate in rats (18%, 17/95) had been observed after long-term exposure to DPM compared with the controls (0%, 0/96). Mauderly et al. conducted a carcinogenicity study of rats that were exposed to soot (a primary composition of DPM) at high, intermediate, and low concentrations (0.35, 3.5, 7.0 mg/m^3 respectively) for up to 30 months (7 h/day, 5 days/week) [6]. The result showed that the rate of lung tumour for high and intermediate exposure groups was 13% and 4% respectively, which was higher than that of the control group (1%). Iwai et al. conducted an inhalation study to estimate the relationship between oxidative DNA damage and lung tumour in 48 F344 female rats which were exposed to diesel exhaust at 2.1–4.9 mg/m^3 for up to 12 months (17 h/day, 3 days/week). After 12 months' exposure, the experimental rats were transferred to a clean room and maintained for another 18 months for observation [8]. The results showed that the rate of lung tumours in rats increased gradually with the exposure duration after 6 months and reached the peak at the 9th month; the exposed rats had high rates of death compared with the controls. Many other studies also showed similar results [5,7,9,37]. From the studies above, DPM is considered carcinogenic in rats after long-term exposure. However, a study conducted by Lewis et al. gave an opposite conclusion [38]. In this study, three different animals (monkeys, rats and mice) were exposed to different experimental environments for up to 2 years, including clean air (controls group), 2 mg/m^3 coal dust, 2 mg/m^3 DPM, and 1 mg/m^3 coal dust and 1 mg/m^3 DPM mixture. No significant difference in the rate of lung tumour for rats was found between four exposure groups (2%, 4%, 4% and 4%, respectively). Compared to other studies, this study lacks the post-exposure period for rats, which could be a reason for the different results. It is also noticed that the DPM concentration in this study was lower than other studies, which could also be a limitation for the results.

Some animal studies also selected mice as one of the tested animals. However, discrepant results were achieved in some of those mice studies. Heinrich et al. pointed out that the lung tumour incidence in exposed mice (32%) was about three times that of the controls (11%) [4]. However, a carcinogenic response failed to show in his later study [5]. In this study, mice were exposed to clean air, filtered diesel exhaust (particle free) and unfiltered diesel exhaust (4.5 and 7.0 mg/m^3 DPM) for 13.5 months (18 h/d, 5 d/week). No lung tumour incidence increase was observed in the mice. Although the earlier study provided some evidence for the carcinogens of DPM, no tumorous response was observed in the larger sample size and well-designed later study. Thus, the carcinogenic effect of DPM on mice is inconclusive. The reason for the discrepant results are still not identified.

In contrast to the studies of rats and mice, a lack of significant tumorous response was found in hamsters and monkeys. In Hein-