Contributing Factors in Respirable Dust Lung Deposition in Underground Coal Mines: Short Review

Elham Rahimi, Younes Shekarian, Wei-Chung Su, and Pedram Roghanchi

Abstract

Exposure to respirable dust, particularly in underground mines, significantly affects the worker's health. During the last decades, respirable dust concentrations in surface and underground mines have been significantly reduced. However, the health data shows that the rate of mine workers with respiratory diseases is still high. Significant evidence suggests that respirable dust toxicity is related to particle characteristics, including mineralogy and morphology of the dust particles. This study discusses the respirable coal mine dust (RCMD) deposition in the human lung. Detailed investigation of RCMD particle characteristics, including size, shape, angularity, and composition, as well as bioaccessibility and wettability are required to better understand the RCMD lung deposition. Current mass-concentration-based sampling methods cannot provide sufficient information about the true dose of exposure. Therefore, lung deposition experiments are required to investigate the actual internal exposure dose among underground coal miners.

Keywords

Respirable coal mine dust • Lung deposition • Respiratory system • Dust characterization

E. Rahimi · Y. Shekarian · P. Roghanchi (✉)
Department of Mineral Engineering, New Mexico Institute of Mining and Technology, Socorro, NM, USA
e-mail: pedram.roghanchi@nmt.edu

W.-C. Su
Department of Epidemiology, Human Genetics, and Environmental Sciences in the School of Public Health, University of Texas Health Science Center at Houston, Houston, TX, USA

1 Introduction

The term dust is used for suspended solid particles in the air within a 1–100 µm in diameter. Dust is an inherent byproduct of mining activities that increases notable health and safety concerns. In coal mines, concentrated coal dust is a hazard that can generate easily ignited explosive mixtures, and inhalation of smaller particles can negatively affect both internal and external organs, including the lung, kidney, and cardiovascular system. Inhalation and lung deposition of coal dust does not only depend on a particle's size but also its aerodynamic diameter. Respirable dust generally refers to particles having an aerodynamic diameter <10 µm and a median cut point (d_{50}) of 4 µm (World Health Organization, 1999).

Respirable coal mine dust (RCMD) is a mixture of more than 50 elements and their oxides. RCMD may contain pyrite, traces of other minerals, quartz, illite, kaolinite, and feldspars that can be found in the host rocks (Jing et al., 2010; Sarver et al., 2019). The main sources of respirable coal mine dust (RCMD) include coal seam and surrounded rock strata, intake air, diesel exhaust, mining operations, and rock dusting (National Academies of Sciences, 2018).

Current RCMD sampling methods rely on the total mass of the respirable coal dust and its quartz mass content. However, the efficacy of the mass-concentration-based monitoring system as an indicator of the actual dose of exposure is questionable. Therefore, RCMD lung deposition and its relationship with the RCMD particle characteristics should be comprehensively investigated in order to estimate the true exposure dose while working underground. This paper discusses the RCMD lung deposition mechanisms and the authors' attempt to understand the RCMD lung deposition through experimental studies.

A. Kallel et al. (eds.), *Selected Studies in Environmental Geosciences and Hydrogeosciences*, Advances in Science, Technology & Innovation, https://doi.org/10.1007/978-3-031-43803-5_25

2 RCMD Lung Deposition

There are a variety of mechanisms for particle deposition in the respiratory system, some depending on size. These mechanisms include inertia impaction, gravitational sedimentation, and Brownian diffusion (Marin & Ostrowski, 2016). RCMD has a size of 10^{-3}–10 µm in diameter, which potentially deposits in different parts of a respiratory system. The dominant deposition mechanism of the coarse RCMD particles is inertia impaction due to their relatively large mass (Islam et al., 2020). In contrast, after being inhaled, the fine dust particle with a small particle mass can easily follow the inhaled air and deposit deep into the lung through the Brownian diffusion mechanism (Hofmann, 2011).

To illustrate lung deposition based on particle size, the human respiratory system is simplified into three regions: head region, tracheobronchial region (TB), and alveolar region (gas exchange region) (Fig. 1). Particles with an aerodynamic size of fewer than 10 µm could be inhaled through the nasal and oral cavities in the head region, which, based on the condition, may trap in different parts of the airways (International Commission on Radiological Protection: Human respiratory tract model for radiological protection, 1994). Since the smallest particles have little inertia, all move along with the air when inhaled and enter the respiratory tract. Most of these particles deposit with only a tiny percentage being breathed back out. Medium-sized particles also tend to move along with the air and are inhaled. However, the majority of them fail to deposit in the respiratory tract and are exhaled back out. Large particles may not follow air streamlines as the air turns to be inhaled; some of them will fail to be inhaled at all (Hinds, 1999; Saber & Heydari, 2012). Most of those inhaled deposits within the respiratory tract, but some will leave with the exhaled air. If a particle makes it deep into the lungs, there are alveolar macrophages that can gobble it up and then physically move up to the conducting bronchioles. However, very fine particles may find their way into the bloodstream with oxygen. At the blood-gas barrier, carbon dioxide diffuses out from the deoxygenated blood and into the air of the alveoli, which then gets breathed out, and with each breath in, oxygen enters the alveoli and freely diffuses into the blood (International Commission on Radiological Protection: Human respiratory tract model for radiological protection, 1994). In the case of an underground coal miner, that freshly oxygenated blood is prone to contain RCMD particles, which head off to the pulmonary veins, the heart, and then to the body tissues. Associated particles in the bloodstream potentially precipitate in different parts of a respiratory system or other organs incur a broad spectrum of health hazards (Hinds, 1999). These RCMD particles may include a considerable amount of fine or ultrafine particles according to technical mining factors used and the most damaging particles are probably those that are small enough to penetrate deep into the lungs. In light of this, diesel particulate matter (DPM) with a diameter of less than 1 µm is considered a concern for underground workers (National Academies of Sciences, 2018). Submicron particles are not cleared as efficiently as larger particles and have mobility within the respiratory system or beyond via translocation to blood (Ahookhosh et al., 2020).

Based on particle size, roughly 20% of the 10-nm (nm), 4% of the 300-nm, and nearly all of 10-µm (µm) particles end up depositing in the head region. Overall, deposition in the tracheobronchial region is relatively low, about 25% of 10 nm, less than 1% of 300 nm, and only about 1.5% of 10 µm particles will deposit. The deposition of particles larger than 3 µm and smaller than 10 nm can be higher if not already deposited in the head region. Approximately, 42% of the 10 nm, less than 6% of the 300 nm, and around 2% of 10 µm particles depositing in the alveolar region. The deposition of the 10 µm particles is negligible since very few of these particles reach the alveoli region. This shows that for equivalent masses, ultrafine particles (UFP) appear to result in a more severe lung response. (Heyder & Rudolf, 1984; Hinds, 1999; International Commission on Radiological Protection: Human respiratory tract model for radiological protection, 1994).

3 Discussion

Considerable research and analyses have been conducted to investigate the causes of rising lung diseases among coal miners despite the significant reduction in RCMD mass concentration in underground working areas (Blackley et al., 2014). In a recent study, a realistic estimate for respirable and thoracic fraction was provided based on experimental data and a mathematical model of oral and nasal inhalation concerning age, gender, activity, and smoking (Brown et al., 2002; Qian et al., 2016). Based on the defined thoracic and respirable fractions, the aerodynamic size of particles that can penetrate the respiratory tract might change by increasing the rate of activity with both nasal and oral inhalations. The remarkable results might help in the interpretation of health effect evidence and in designing experimental studies.

In the current experimental study at the New Mexico Tech with a partnership of UTHealth, the human airway system has been simplified using an innovative Mobile Aerosol Lung Deposition Apparatus (MALDA) to estimate RCMD lung deposition in a near-real situation. This system consists of head-airways, both realistic human nasal and oral cavities, a delicate and physiology-based human TB airway,

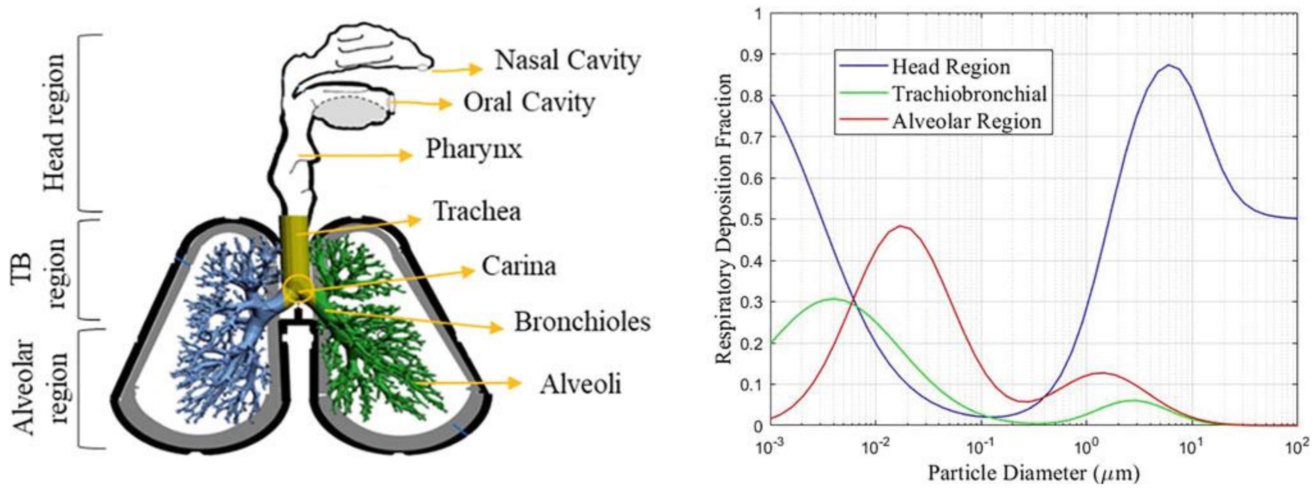

Fig. 1 Simplified human respiratory system included the main three regions (left) based on fractions of particle deposition (right)

the inner surface coated with silicon oil to mimic the sticky and wet nature of airways, and extended airways down to the 11th airway generation as a representative for the alveolar region. The flow rate distribution is adjustable by selecting conductive tubing with different inner diameters and the number of particles depositing is measured by a wide-range aerosol spectrometer (Rahimi, 2020; Su et al., 2019).

In a respiratory deposition of dust particles, in addition to the size of the particles, the shape, in other words, angularity and sphericality, will significantly affect the deposition. Specifically, non-spherical particles may easily halt in the path along the respiratory airways (Sellaro et al., 2015). Mass of particle can also affect the particle deposition, whether the mass is low and precipitates in diffusion mechanism of deposition, or when the mass of the particles is high and inertia is the dominant mechanism of deposition (Huang et al., 2005; Islam et al., 2020). Not all of the RCMD inhaled into a miner's respiratory tract will deposit in the lung to become the RCMD dose. A portion of the inhaled RCMD could be exhaled out of the respiratory tract during exhalation without deposition. This phenomenon is especially significant for nanosize dust particles or UFP (Brown et al., 2002; Su et al., 2019).

The true dose of environmental and internal exposure is necessary to be assessed and compared with the data from the mass-concentration-based sampling method. Currently, the mine health-related RCMD personal sampling is based on the mass concentration which may not correctly represent the true RCMD dose received by a coal miner, especially for RCMD less than 4 μm. Therefore, the total amount of RCMD inhaled may not be representative of the RCMD actual exposure dose. The number-concentration-based RCMD samples could be an alternative and ideal index for RCMD dose estimations (Rahimi, 2020; Shekarian, 2020).

4 Conclusions

A comprehensive investigation of RCMD characterization is essential to achieve a better understanding of the probable reasons for the rising RCMD exposure and lung diseases. It is also crucial to investigate the actual dose of exposure, both externally and internally, in order to understand the main causes of respiratory diseases. Therefore, the relationship between respirable dust particles characterizations and lung deposition is particularly needed to be understood. Furthermore, detailed studies of morphological properties, including particle size, angularity, mass, shape, and elemental composition as critical parameters, are essential to categorize dust particle deposition better. Other environmental factors may affect the process of particle lung deposition; hence, other detailed studies should be conducted to explore any involved factors contributing to particle deposition.

Acknowledgements This study is funded by the National Institute for Occupational Safety and Health (NIOSH) [75D30119C06390].

References

Ahookhosh, K., Pourmehran, O., Aminfara, H., Mohammadpourfard, M., Sarafraz, M. M., & Hamishehkar, H. (2020). Development of human respiratory airway models: a review. *European Journal Pharmaceutical Sciences* (145), 105233.

Blackley, D. J., Halldin, C. N., Wang, M. L., & Laney, A. S. (2014). Small mine size is associated with lung function abnormality and pneumoconiosis among underground coal miners in Kentucky, Virginia and West Virginia. *Occupational Environment Medicine, 71*, 690–694.

Brown, J. S., Zeman, K. L., & Bennett, W. D. (2002). Ultrafine particle deposition and clearance in the healthy and obstructed lung.

American Journal Respiratory Critical Care Medicine, 166, 1240–1247.

Heyder, J., & Rudolf, G. (1984). Mathematical models of particle deposition in the human respiratory tract. *Journal Aerosol Science, 15*(6), 697–707.

Hinds, W. (1999). Aerosol Technology: properties, behavior, and measurement of airborne particles. Chapter 11, University of Virginia Library, VA, USA.

Hofmann, W. (2011). Modelling inhaled particle deposition in the human lung-a review. *Journal Aerosol Science., 42*(10), 693–724.

Huang, X., Li, W., Attfield, M. D., Nadas, A., Frenkel, K., & Finkelman, R. B. (2005). Mapping and prediction of coal workers' pneumoconiosis with bioavailable iron content in the bituminous coals. *Environmental Health Perspectives, 113*(8), 964–968.

International Commission on Radiological Protection:. (1994). Human respiratory tract model for radiological protection. 24. ISN: 0146–6453.

Islam, M. S., Paul, G., Ong, H. X., Young, P. M., Gu, Y. T. & Saha, S. C. (2020). A review of respiratory anatomical development, air flow characterization and particle deposition. *International Journal Environmental Research Public Health*. 17, 380.

Jing, Y., Xiukun, W., Jianguang, G., & Gaiping, L. (2010). Surface characteristics and wetting mechanism of respirable coal dust. *Mining Science Technology, 20*, 0365–0371.

Marin, X. B., & Ostrowski, L. E. (2016). Cilia and Mucociliary Clearance. *Cold Spring Harbor Perspectives Biology* 9(4)

National Academies of Sciences. (2018). *Engineering and Medicine: Monitoring and sampling approaches to assess underground coal mine dust exposures* (pp. 1–150). The National Academies Press. Washington DC.

Qian, Q. Z., Cao, X. K., Shen, F. H., & Wang, Q. (2016). Correlations of smoking with cumulative total dust exposure and cumulative abnormal rate of pulmonary function in coal-mine workers. *Experimental Therapeutic Medicine, 12*(5), 2942–2948.

Rahimi, E. (2020). Investigation of Respirable Coal Mine Dust (RCMD) and Respirable Crystalline Silica (RCS) in the U.S. Underground and Surface Coal Mines. Order No. 28156748, New Mexico Institute of Mining and Technology. In PROQUESTMS ProQuest Dissertations & Theses A&I. Retrieved from http://libproxy.uoregon.edu/login?url=https://www.proquest.com/dissertations-theses/investigation-respirable-coal-mine-dust-rcmd/docview/2468128535/se-2?accountid=14698

Saber, E. M., & Heydari, G. (2012). Flow pattern sand deposition fraction of particles in the range of 0.1–10 mm at trachea and the first third generation sunder different breathing conditions. *Computers Biology Medicine* 42, 631–638.

Sarver, E., Kelesa, C., & Rezaee, M. (2019). Beyond conventional metrics: Comprehensive characterization of respirable coal mine dust. *International Journal Coal Geology, 207*, 84–95.

Sellaro, R., Sarver, E., & Baxter, D. (2015). A standard characterization methodology for respirable coal mine dust using SEM-EDX. *Resources, 4*(4), 939–957.

Shekarian, Y. (2020). An Investigation of the Effects of Mining Parameters on the Prevalence of Coal Worker's Pneumoconiosis (CWP) Risks among the US Coal Miners. Order No. 28156223, New Mexico Institute of Mining and Technology. In PROQUESTMS ProQuest Dissertations & Theses A&I. Retrieved from http://libproxy.uoregon.edu/login?url=https://www.proquest.com/dissertations-theses/investigation-effects-mining-parameters-on/docview/2467855260/se-2?accountid=14698. https://doi.org/10.13140/RG.2.2.22358.27205.

Su, W. C., Chen, Y., & Xi, J. (2019). A new approach to estimate ultrafine particle respiratory deposition. *Inhalation Toxicology, International Forum Respiratory Research, 1*(31), 1091–7691.

World Health Organization (1999). Hazard prevention and control in the work environment: Airborne dust. Occupational and environmental health, Department of the protection of the human environment, Geneva.

Advances in Science, Technology & Innovation
IEREK Interdisciplinary Series for Sustainable Development

Amjad Kallel · Maurizio Barbieri · Jesús Rodrigo-Comino · Helder I. Chaminé · Broder Merkel · Haroun Chenchouni · Jasper Knight · Sandeep Panda · Nabil Khélifi · Ali Cemal Benim · Stefan Grab · Hesham El-Askary · Santanu Banerjee · Riheb Hadji · Mehdi Eshagh *Editors*

Selected Studies in Environmental Geosciences and Hydrogeosciences

Proceedings of the 3rd Conference of the Arabian Journal of Geosciences (CAJG-3)

IEREK
RESEARCH & KNOWLEDGE ENRICHMENT

Springer

Advances in Science, Technology & Innovation

IEREK Interdisciplinary Series for Sustainable Development

Amjad Kallel · Maurizio Barbieri ·
Jesús Rodrigo-Comino · Helder I. Chaminé ·
Broder Merkel · Haroun Chenchouni ·
Jasper Knight · Sandeep Panda ·
Nabil Khélifi · Ali Cemal Benim ·
Stefan Grab · Hesham El-Askary ·
Santanu Banerjee · Riheb Hadji ·
Mehdi Eshagh
Editors

Selected Studies in Environmental Geosciences and Hydrogeosciences

Proceedings of the 3rd Conference of the Arabian Journal of Geosciences (CAJG-3)

Springer

Editors
Amjad Kallel
ENIS, University of Sfax
Sfax, Tunisia

Jesús Rodrigo-Comino
Departamento de Análisis Geográfico Regional
y Geografía Física
Facultad de Filosofía y Letras
Campus Universitario de Cartuja
University of Granada
Granada, Spain

Broder Merkel
Freiberg, Germany

Jasper Knight
University of the Witwatersrand
Johannesburg, South Africa

Nabil Khélifi
Springer, a part of Springer Nature
Heidelberg, Germany

Stefan Grab
School of Geography, Archaeology and
Environmental Studies
University of the Witwatersrand
Johannesburg, South Africa

Santanu Banerjee
Indian Institute of Technology Bombay
Mumbai, India

Mehdi Eshagh
New Technologies Information Society (NTIS)
University of West Bohemia
Pilsen, Czech Republic

Maurizio Barbieri
Department of Chemical Engineering Materials
Environment
Faculty of Engineering
Sapienza University of Rome
Rome, Italy

Helder I. Chaminé
Polytechnic of Porto
School of Engineering (ISEP)
Porto, Portugal

Haroun Chenchouni
Higher National School of Forests
Khenchela, Algeria

Sandeep Panda
Gujarat Biotechnology University
Gandhinagar, Gujarat, India

Ali Cemal Benim
Düsseldorf University of Applied Sciences
Düsseldorf, Germany

Hesham El-Askary
Chapman University
Orange, USA

Riheb Hadji
Laboratory of Applied Research in Engineering
Geology, Geotechnics, Water Sciences, and
Environment
University of Farhat Abbas
Setif, Algeria

ISSN 2522-8714 ISSN 2522-8722 (electronic)
Advances in Science, Technology & Innovation
IEREK Interdisciplinary Series for Sustainable Development
ISBN 978-3-031-43802-8 ISBN 978-3-031-43803-5 (eBook)
https://doi.org/10.1007/978-3-031-43803-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.