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REVIEW ARTICLE

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Occupational exposure to inhaled nanoparticles: Are young workers being left in the dust?

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Abstract

Objectives: Occupational exposure to inhaled nanoparticles (NPs) represents a significant concern for worker health. Adolescent workers may face unique risks for exposure and resulting health effects when compared with adult workers.

Methods: This manuscript discusses key differences in risks for occupational exposures to inhaled NPs and resulting health effects between young workers and adult workers via an examination of both physiological and occupational setting factors.

Results: Previous studies document how adolescents often face distinct and unique exposure scenarios to occupational hazards when compared to adults. Moreover, they also face different and unpredictable health effects because biological functions such as detoxification pathways and neurological mechanisms are still developing well into late adolescence. Early exposure also increases the chances of developing long-latency disease earlier in life.

Taken together, adolescents' rapid growth and development encompasses highly dynamic and complex processes. An aggravating factor is that these processes do not necessarily fall in line with legal classifications of adulthood, nor with occupational exposure limits created for adult workers.

Conclusions: The differences in exposures and health consequences from NPs on young workers are insufficiently understood. Research is needed to better understand what adolescent-specific mitigation strategies may be most suitable to address these risk factors.

KEYWORDS
adolescent, airborne particles, inhaled exposure, vulnerable workers

1 | INTRODUCTION

Worldwide more than 37 million adolescents between 15 and 17 years of age are engaged in hazardous work—defined as work in an unhealthy environment which may result in exposures to hazardous substances, agents, or processes that are damaging to health.[1] Adolescents exposed to hazards at the workplace can become ill or can be injured—even fatally—if safety and health standards and working arrangements are not correctly defined and implemented. Furthermore, many of the health problems resulting from unhealthy working conditions during adolescence may not develop until adulthood.

For centuries, workers have been exposed to incidental ultra fine particles (UFPs; diameter ˂100 nm) in trades such as welding, brazing, and mining among others. For more than a decade, epidemiological studies have demonstrated an association between exposure to increased concentrations of fine and UFPs and adverse health effects, namely pulmonary and cardiovascular morbidity.[2,3] Particles in the nano-range are of particular concern as they may translocate and be transported by mechanisms such as macrophage-mediated clearance,[4,5] interstitial-lymphatic clearance[6] and the blood circulation to distant sites and organs.[7-9] Recently, the increase in the production and application of engineered nanomaterials (ENMs) has raised concern about occupational exposures and resulting health effects. Workers exposed repeatedly to high levels of either engineered or incidental nanoparticles (NPs) are at particular risk.[10] While research on occupational exposure to ENMs has gained increased attention, there has been a lack of focused research efforts on young workers specifically, who may be at particular risk for exposure to, and for health effects following exposures. This situation has left thousands of young workers unprotected and ill prepared for novel exposure scenarios, begging the question: are young workers being left in the dust?

2 | DISCUSSION

Workplace exposures to inhaled particles are of considerable concern due to their association with occupational lung diseases, as well as a wide range of non-respiratory illnesses.[11] Young workers represent a vulnerable population due to their heightened potential for hazardous exposures or damage to physiological development. Occupational safety and health (OSH) for youth faces many challenges not found for adults. Among these challenges are the inadequacy of personal protective equipment, prolonged latency following exposure, ongoing organ development, and biological maturation.

2.1 | Differences between adolescent and adult workers

Two main concepts must be distinguished: first, the time windows for exposure are longer for adolescents. By being exposed early in life, the total work time exposure will be longer and also the life expectancy will be longer, which increases the chance for the manifestation of delayed outcomes. Second, unique developmental differences may render adolescent workers more vulnerable to exposures, and may additionally increase their risk for adverse health effects.[12,13] Adolescents are not simply small workers: they often face distinct and unique exposure scenarios to occupational hazards when compared to adults and may also face different and unpredictable resulting health effects, as biological functions such as detoxification pathways and neurological mechanisms are still developing into late adolescence and beyond.[13]

2.2 | Physiological factors

2.2.1 | Lung development

The post-natal period is one of rapid pulmonary development with the proliferation of more than 40 different cell types and the development of more than 80% of alveoli.[14] More than 25 000 terminal bronchi develop, giving rise to more than 300 million alveoli. This intense process of lung proliferation is not complete until late adolescence,[14,15] and most indices of pulmonary function reach their maximum levels in early adulthood.[16] The continuum of lung development results in discrete windows of vulnerability, during which hazardous exposures may have the potential to affect the growth and function of the respiratory system.[14,17] Respiratory vulnerability and adverse health effects resulting from inhaled exposures have been demonstrated in children exposed to second hand smoke[13] and ambient air pollution.[18-20]

2.2.2 | Inhaled dose

Even in similar workplace exposure scenarios, developmental differences of the pulmonary system between the adult and young worker may result in different inhalation patterns. The characteristics of the air drawn into the lungs is greatly influenced by the morphometry of the respiratory tract, which causes numerous changes in pressure, flow rate, and direction as air moves into and out of the system.[21] Pulmonary morphometry, in particular differences in upper respiratory tract structure and branching patterns of the lower regions are highly age-related. Such differences may result in distinct patterns of gas transport due to the effect of geometric variations on airflow patterns.

On average, adolescents breathe more air per kilogram of body weight than adults,[22] leading to an elevated whole-body dose of inhaled particles. Ginsberg et al[23] demonstrated that in the deep (alveolar air exchange) region of the lung, particle dose could be two to four-fold higher among children than adults, due to differences in ventilation rate per unit surface area (V/SA) in the deep lung region. Thus, similar exposure levels to particles may result in higher deposited dose per lung surface area in adolescent workers compared to adult workers. It should also be considered that adolescents may have narrower airways than those of adults, indicating the potential for increased airway obstruction in situations of inflammation.[24] Furthermore, the breathing zone of an adolescent may vary, but is likely to be lower and potentially closer to working surfaces and sources of contaminants than for an adult worker. Adolescents may therefore be more likely to be exposed to freshly released particles during work tasks.

As the nose is effective at filtering nano-sized particles by diffusive deposition,[25] oral versus nasal breathing represents another determinant of NP dose to the lungs. Children are more likely to breathe through their mouths than adults[26] increasing their risk of pulmonary exposure to NP that would otherwise be filtered out in the nose. The size of nasal passageways also increases with age,[26] indicating a larger particle filter in adults when compared with adolescents. A study that compared nasal filter efficiency of particles for children and adults found the average nasal deposition percentages were lower in children than in adults, both at rest and during exercise.[25] Another study[27] determined nasal deposition efficiency (NDE) and found children to have significantly decreased NDE of particles compared to adults.

2.2.3 | Deposition and absorption

The mechanisms, the pattern and the efficiency of particle deposition in the lungs largely depend on the aerodynamic and thermodynamic diameters of the respiratory tract. Deposition occurs when particles carried to the alveoli come into proximity with the epithelial surface. Research has shown that acinar flow and mixing may be highly complex due to the intricacy of the acinar geometry, which changes during the course of lung development.[28] Notably, because the depth and size of alveoli increases with age, there is a difference in acinar airflow patterns between saccular airways (smooth flow with no rotational components) and airways with fully formed alveoli (largely rotational and potentially irreversible). During critical stages of lung development, it therefore can be hypothesized that a shift in acinar flow patterns may result in differences in particle deposition on the alveolar walls between young workers and their adult counterparts.

The Human Respiratory Tract Model of the International Commission of Radiological Protection (ICRP) provides particle deposition data for adults at different breathing patterns and activities. Data are given for the extrathoracic, the bronchiolar and the alveolar regions for adolescents (15 years old) and adults. However, the deposition data given for adolescents is derived solely by applying numerical scaling factors from adult data.[29] Taken together, it becomes clear there is a considerable lack of knowledge on the deposition rate of inhaled particles for adolescents, making it difficult to adequately predict how the deposition may differ from adult workers.

2.2.4 | Metabolism and clearance

The predominant mechanism for particle clearance from the peripheral lungs is uptake by lung surface macrophages and transport to the larynx.[30] Inter-species differences have been observed for particle clearance and have been attributed to the number of generations of respiratory bronchioles.[30] However, whether this route of uptake and subsequent clearance differs in different phases of lung development is unclear and should be further investigated to allow for improved risk assessments of particle translocation in developing adolescents.

Pharmacokinetic handling of xenobiotics is likely to differ in adolescents compared to adults with respect to metabolism, clearance, protein binding, and volume of distribution.[31-33] Adolescents exhibit maturing metabolic detoxification pathways, which may increase the duration of residence and amount of any given internal dose. Pharmaceutical drug metabolism research has provided a body of evidence on the developmental differences for metabolic pathways and subsequent elimination between adolescents and adults.[34] Important metabolic pathways, such as cytochrome P450 systems and glutathione conjugation are significantly less efficient than later in life. Furthermore, maturational changes accounting for differences in the glomerular filtration rate and tubular secretions may be present between adolescents and adults.[35] Thus, toxic substances taken up with the particles will have a longer residence time in the body and thereby have a longer window of opportunity to cause damage and to accumulate to higher internal levels if the exposure is sufficiently long or repetitive.

2.2.5 | Neuro-cognitive factors

In addition to physiologic vulnerability, adolescents may also face a higher risk due to neuro-cognitive factors. Adolescents seem to be more affected than adults by exciting or stressful situations when making decisions.[36] Compared with adults who have reached full cognitive maturation, adolescents may be more likely to make unreasonable and potentially dangerous decisions due to these described "risk-taking" behaviors when faced with fast-paced, exciting or stressful situations in the workplace.

2.3 | Occupational settings factors

2.3.1 | Personal protective equipment

The special risks faced by young workers is not only limited to their developing physiologies, but also to external, occupationally relevant factors. Most important is the use and efficiency of personal protective equipment (PPE) at the workplace, notably respiratory protective devices (RPDs). PPE, including RPDs, are designed to meet the needs and physical specifications of adult workers' faces and respiration patterns, not those of adolescents. While filter respirators for smaller faces do exist, their existence is not widely known and many companies do not have them in stock. Regular sized RPDs may not fit properly and increase the chances for leaks due to improper face-to-face piece seal, this is the reason why authorities such as the US Food and Drug Administration warn the public that respirators are not effective to protect children against diseases transmitted by aerosols.[37] RPDs that do not fit properly may increase the chance for leaks due to improper face-to-face piece seal.[38,39]

2.3.2 | Lack of experience

Young workers often have little control over the pace of work and may be less informed about the occupational risks compared to their adult peers. As young workers often are employed on a limited, part-time basis, employers may be less willing to dedicate time and resources to comprehensive OSH training. Young workers employed on temporary contracts are less likely to participate in long-term competence development, have less control over the pace of work and may be less informed about the occupational risks present. Moreover, young workers will face limited bargaining power with employers when it comes to negotiating adverse workplace situations, and lack the mechanisms for widely voicing their concerns. These issues are not unique to young workers but are likely more pronounced due to elevated risk-taking behaviors.

3 | CONCLUSIONS AND RECOMMENDATIONS

While OSH research on adult workers has provided evidence toward the development of prevention strategies for many hazardous exposures, such research does not take into account the developmental differences of adolescents and their vulnerability during critical windows of growth and maturation. Existing OSH guidelines for adults fail to recognize that adolescents may face greater risk for acute and long-term harm from inhaled occupational exposures. As such, it is important that targeted OSH research is developed for this unique worker population.

Dose remains a critical concept in toxicology. In nanotoxicology, effective calculations of dosimetry and the biologically effective dose have proven elusive. Tissue burdens, including mass balance toxicokinetics, are necessary to properly characterize particles, especially the dose of translocated NPs that reach beyond the portal of entry and what mechanism and consequences result from this dose. However, the unique timing of exposure to inhaled NPs during adolescence remains a parameter that may be overlooked. This is especially important to consider given the limited knowledge on NP biokinetics within the developing lung in regard to maturation of the alveolar microvasculature and phases of late alveolarization. For young workers exposed to airborne NP, it may be the "dose and the timing" that effectively makes the poison. It is well known that children are susceptible to the adverse developmental effects of toxins.[40] It is equally clear that adolescents and young adults are susceptible to adverse effects of toxins,[41] as organ development continues in the lung[42] and the brain.[43]

To address this issue of windows of vulnerability, the first step is to develop more precise computational tools that allow the calculation of inhaled NP dose to advise risk assessment at all ages where exposure may occur. The ICRP's Human Respiratory Tract Model is limited in calculating inhaled particle dose as the deposition data given for adolescents is derived by applying numerical scaling factors from adult data. It is recommended that research be carried out to develop and validate more precise particle dosimetry models for adolescent exposure scenarios. Secondly, special consideration of adolescent physiology should be applied for the implementation of regulatory guidelines for occupational exposure limits.

To achieve this, targeted research studies must be designed that assess the interaction of developmental characteristics of adolescents to risks in the workplace. Specifically, the implementation of longitudinal studies is recommended to assess the potential chronic health effects related to occupational NP exposures in young workers. Tailored longitudinal studies would provide clarity of temporal sequences between exposure and adverse health effects, allow calculation of incidence of adverse health effects, and facilitate the study of specific occupational particle exposures, such as in welding or in mining.

Finally, OSH training needs to be adapted to the psychology and low-power position of adolescents in companies.[44,45] An apprenticeship-partnership model between companies, schools and governmental bodies that includes clear rules about safety and health as part of becoming a professional craftsperson may help counter many of the above-mentioned issues. In this concept, companies recognise young workers as future assets and thus are more likely to give them access to training and to include them in their long-term competence development programs.

More accurate dosimetry models that take adolescent respiratory parameters into consideration, matched with increased research into the fate and potential health effects of inhaled particles for developing youth are necessary toward the development of regulatory policies aimed at protecting the health of young workers worldwide. As young workers represent one fourth of the global working age population, ensuring adequate workplace protection measures through informed policy actions is critical for their long-term health, safety, and productivity. In turn, protecting the future productivity of adolescents directly impacts the economic well being of societies, enforcing the point that we simply cannot afford to leave young workers in the dust.

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DISCLOSURE

Approval of the research protocol: N/A. *Informed consent*: N/A. *Registry and registration no. of the study/trial*: N/A. *Animal studies*: N/A. *Conflict of interest*: The authors declare they have no actual or potential competing financial interests.

AUTHOR CONTRIBUTIONS

The authors discussed the topic together and reviewed the literature. HG drafted the first manuscript, both refined the structure and contributed to the discussion.

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