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Perspective

Emerging concern on air pollution and health: Trade-off between air pollution exposure and physical activity

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ABSTRACT

Air pollution is a major contributor to the global disease burden, especially affecting respiratory and cardiovascular health. However, physical activity is associated with improved lung function, a slower decline in lung function, and lower mortality. The public is more likely to be exposed to air pollution during outdoor physical activity. However, studies on how long-term and short-term exposure to air pollution interacts with physical activity yield inconsistent results, and the thresholds for air pollution and physical activity remain unclear. Thus, more studies are needed to provide sufficient evidence to guide the public to safely engage in outdoor physical activity when exposed to air pollution.

1. Introduction

Air pollution is one of the major environmental risk factors that can result in significant health and economic losses. Currently, 91% of the global population still lives in areas with annual average $PM_{2.5}$ concentrations above 10 μg/m^3 (especially in Asia, the Middle East, and Africa) [1]. The Global Burden of Disease (GBD) study shows that air pollution has ascended from the 13th leading factor for attributable disability-adjusted life years (DALY) in 1990 to the 7th in 2019, resulting in 6.67 million air pollution attributable deaths worldwide [2]. Numerous studies have found that air pollution increases the risk of diseases involving the respiratory, cardiovascular, neurological, endocrine, and reproductive systems [3]. Furthermore, air pollution exposure leads to adverse birth outcomes, pregnancy disorders, and neurodevelopmental impairment [4].

Inadequate physical activity is also considered to be one of the major factors contributing to the burden of disease, which can result in a variety of adverse health outcomes [2,5]. Previous studies have suggested that a minimum of 150 min of moderate-intensity exercise or 75 min of vigorous-intensity exercise per week is required for health benefits [6–9]. Despite international efforts to implement a range of policies to encourage physical activity, 80% of adolescents and 27% of adults fall short of the World Health Organization's (WHO) recommendations [10]. It is well known that proper physical activity can improve human health [11], reducing the risk of respiratory disease and premature death [12]. Physical activity is associated with better lung function, a slower decline in lung function, and lower mortality, as well as a positive protective effect for those with chronic lung disease [13]. The respiratory benefits of physical activity are related to deep inspiration and smooth muscle activation, which can further reduce systemic and bronchial inflammation and increase maximal oxygen uptake [14].

Several studies using laboratory cardiopulmonary exercise test have found that physical activity elevates minute ventilation and the air-exchange function of lung tissues [15–18], thereby increasing the amount of air breathed in and, consequently, the exposure to pollutants that cause more serious health hazards [19]. For instance, cycling increases the minute ventilation and total number of deposited particles by 4.5 times compared to resting [20] and by 4.3 times compared to car passengers [21]. Zoladz et al. found that PM_{10} deposition in marathon runners was 6–10 times higher than those at rest [22]. Therefore, the public is more likely to be exposed to air pollution during outdoor physical activity. A number of human and animal studies have begun to

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Table 1
Summary of the interaction between long-term exposure to air pollution and physical activity.

Author	Design	Population	Location	Physical activity	Exposure	Outcome	Main findings
Yu et al. [30]	Cross-sectional study	821 children, aged 8–12 years	Hong Kong, China	Habitual exercise (sports, free play, running, ball games, cycling)	SO_2; NO_2; PM_{10}	VO_2 max	Children who exercised in high-pollution areas had a lower VO_2 max than children who exercised in low-pollution areas [27.9 vs. 29.8 mL/(kg·min)].
Andersen et al. [34]	Cohort	57,000 adults, aged 50–65 years	Diet, Cancer and Health Cohort, Denmark	Sport cycling, walking, and gardening	NO_2	Mortality; CVD; respiratory; cancer; diabetes	Benefits of cycling, participating in sports, and gardening on all-cause and cause specific mortality are similar in both low and high NO_2 areas.
Zhang et al. [35]	Cohort	359,067 adults, age ≥18 years	Taiwan, China	Habitual PA (light, moderate, medium-vigorous, high-vigorous)	$PM_{2.5}$	White blood cell	Effects of PA and $PM_{2.5}$ exposure on systemic inflammation are independent.
Sun et al. [31]	Cohort	66,820 adults, age ≥18 years	Elderly Health Service Cohort, Hong Kong, China	Habitual PA (walking, stretching, TCE, and aerobic)	$PM_{2.5}$	Mortality; CVD; respiratory	No interaction between PA and $PM_{2.5}$; the beneficial effects of habitual PA outweighed the detrimental effects of long-term exposure to $PM_{2.5}$ on mortality.
Guo et al. [32]	Cohort	140,072 adults, age ≥18 years	Taiwan, China	Habitual PA (light, moderate, medium-vigorous, high-vigorous)	$PM_{2.5}$	Hypertension incidence	The negative association between PA and hypertension remained stable in people exposed to various levels of $PM_{2.5}$, and the positive association between $PM_{2.5}$ and hypertension was not modified by PA.
Elliott et al. [33]	Cohort	104,990 female adults	Nurses' Health Study, USA	Leisure-time (low, moderate, vigorous)	$PM_{2.5}$	CVD and overall mortality	No multiplicative interaction between long-term $PM_{2.5}$ exposure and physical activity.
Tu et al. [27]	Cross-sectional study	31,162 adults, aged 50–65 years	Henan Rural Cohort Study, China	Habitual PA	PM_{10}; $PM_{2.5}$; PM_1; NO_2	ASCVD	Exposure to high levels of air pollutants was related to an increasingly high 10-year ASCVD risk, and these associations were attenuated by PA.

SO_2, sulfur dioxide; NO_2, nitrogen dioxide; PM_{10}, thoracic particulate matter; $PM_{2.5}$, fine particulate matter; PM_1, particulate matter less than 1 μm; VO_2 max, maximum oxygen intake; CVD, cardiovascular diseases; ASCVD, atherosclerotic cardiovascular diseases; PA, physical activity.

focus on the health effects of physical activity and air pollution. However, the trade-off between the risks of air pollution and the benefits of outdoor physical activity remains unclear.

2. Effects of air pollution and physical activity on human health

The effects of air pollution and physical activity on human health are evaluated through two primary types of studies: short-term studies, which measure health outcomes a few hours or days after exposure, and long-term studies, which track health outcomes over many years [23,24].

In terms of long-term exposure to air pollution and physical activity (Table 1), it has been found that regular physical activity ameliorates or attenuates the effects of long-term exposure to air pollution on the respiratory system [25], cardiovascular system [26–28], and obesity [29]. However, a notable study by McConnell et al. [25] in 1993 recruited a cohort of 3,535 children in Southern California and followed them up for 5 years, revealing that air pollution combined with outdoor exercise may contribute to the development of asthma in children. Furthermore, a cohort study has indicated that high $PM_{2.5}$ exposure can counteract the benefits of regular physical activity in reducing hypertension [28]. On the other hand, several cross-sectional studies have found that regular physical activity can ameliorate the effects of air pollution on cardiopulmonary fitness [30], blood pressure [26], and atherosclerotic cardiovascular disease [27]. However, some cohort studies have found no interactions between long-term exposure to air pollution and regular physical activity concerning the cardiovascular system and mortality [31–34]. In addition, Zhang et al. [35] found an independent effect of regular physical activity and $PM_{2.5}$ exposure on systemic inflammation. There was still a lack of consistent evidence on the interaction between long-term exposure to air pollution and physical activity.

Studies regarding the short-term exposure to air pollution and physical activity (Table 2) have also found that physical activity in polluted environments can lead to acute health effects such as deteriorated lung function [36–38], increased levels of inflammatory markers [36,39], and reduced vasodilation [40]. Jacobs et al. examined the advisability of cycling to work in polluted urban environments. Through an intervention study, they found that exposure to traffic-related particulate matter during exercise resulted in an increase in the distribution of inflammatory blood cells in healthy volunteers [41], while the interaction between physical activity and air pollution remained unclear. A study conducted in London found that short-term exposure to traffic pollution prevents the beneficial cardiorespiratory effects of walking in people with chronic obstructive pulmonary disease, ischemic heart disease, or even those without chronic cardiopulmonary conditions [38]. Another study found that short-term exposure to air pollution from walking had a greater effect on moderate asthmatics than on mild asthmatics [37]. Similarly, adverse effects of physical activity under air pollution conditions on the respiratory system were found in panel studies [42,43]. However, several crossover studies have found that physical activity reduces the adverse effects of air pollution on the respiratory system [44–46], cardiovascular system [47], and heart rate variability [48]. For example, a study in a highly polluted area found that physical activity can prevent $PM_{2.5}$-related arteriosclerosis, despite exacerbating airway inflammation [49]. Research on this topic, primarily conducted in developed countries, presents inconsistent findings across study designs, such as crossover studies, panel studies, and cross-sectional studies.

3. Effects of air pollution and physical activity from animal studies

Some studies of the effects of air pollution and physical activity on human health have been limited by ethical constraints. Thus, animal models have become indispensable for studying the health effects and mechanisms of air pollution and physical activity. The study found that

Table 2
Summary of the interaction between short-term exposure to air pollution and physical activity.

Author	Design	Population	Location	Exposure length	Physical activity	Exposure	Outcome	Main findings
Kubesch et al. [47]	Cross-over	28 healthy adults	Barcelona, Spain	2-h exposure in high and low TRAP environment	15 min intervals alternating rest and cycling on a stationary bicycle	BC; UFP; NOx; PM_{10}; $PM_{2.5}$; PMcoarse	SBP	Evidence of an interaction between PA and PM_{10} and PM coarse increasing SBP.
Cole-Hunter et al. [48]	Cross-over	28 healthy adults	Barcelona, Spain	2-h exposure in high and low TRAP environment	15 min intervals alternating rest and cycling on a stationary bicycle	UFP; BC; $PM_{2.5}$	HRV	PA reduced the negative impact of TRAP on heart rate variability at high TRAP site.
Matt et al. [46]	Cross-over	29 healthy adults	Barcelona, Spain	2-h exposure in high and low TRAP environment	15 min intervals alternating rest and cycling on a stationary bicycle	BC; UFP; NOx; PM_{10}; $PM_{2.5}$; PMcoarse	Respiratory function	PA reduced the negative impact of TRAP on respiratory function.
Sinharay et al. [38]	Cross-over	>60 years adults	London, United Kingdom	2-h	Walk	BC; NO_2; PM_{10}; $PM_{2.5}$; UFP	Cardiovascular and respiratory outcomes	Short-term exposure to traffic pollution prevents the beneficial cardiopulmonary effects of walking for healthy individuals and individuals with ischemic heart diseases and COPD.
Lovinsky-Desir et al. [45]	Cross-sectional study	129 children, aged 9–14 years	New York City, United States	6 days	Moderate-to-vigorous physical activity	BC	FeNO	Active children had less airway inflammation than nonactive children, but primarily among children with lower personal BC exposure.
Laeremans et al. [42]	Panel	122 healthy adults	Antwerp, Belgium; Barcelona, Spain; London, United Kingdom	24 h	Physical activity energy expenditure (MET-hours)	BC	HRV; Retinal vesse diameters; FeNO; Lung function	No evidence of heart rate variability responses to physical activity, BC exposure, or interaction was observed. FeNO and peak expiratory flow were detrimentally affected by BC, regardless of PA levels.
Laeremans et al. [44]	Panel	115 healthy adults	Antwerp, Belgium, Barcelona, Spain; London, United Kingdom	7 days	Physical activity energy expenditure (MET-hours)	BC	Lung function	Physical activity was associated with improved pulmonary function at low BC concentrations, but benefits decreased when BC concentrations increased.
Chen et al. [49]	Panel	20 healthy male adults	Beijing, China	7 visits (14 days/visit)	Habitual PA	BC; $PM_{2.5}$; UFP	EBC; FeNO; BP	In highly polluted areas, frequent exercise might protect against $PM_{2.5}$-associated arterial stiffness but exacerbate airway inflammation.
Kocot et al. [43]	Panel	30 male adults, aged 18–30 years	Katowice, Poland	2 separate 15-min exercise	Submaximal exercise trials on a cycle ergometer	PM_{10}; $PM_{2.5}$; NOx; SO_2	HRV; BP; SpO_2; FeNO; Lung function	Exposure to ambient air pollution during short-term submaximal exercise is associated with a decrease in airflow (FEV_1/FVC), and the decrease is more apparent when the exercise takes place under particularly high exposure conditions.

BC, black carbon; UFP, ultrafine particle; PMcoarse, PM with aerodynamic diameter 2.5–10 μm ($PM_{2.5–10}$); TRAP, traffic-related air pollution; SBP, systolic blood pressure; BP, blood pressure; HRV, heart rate variability; COPD, chronic obstructive pulmonary disease; FeNO, fractional exhaled nitric oxide; EBC, exhaled breath condensat; SpO_2, pulse oxygen saturation; FEV_1, forced expiratory volume in 1 s; FVC, sorced vital capacity.

physical activity in a polluted environment altered airway permeability [50,51] and suppressed particulate-matter-induced lung inflammation and systemic inflammation in mouse models [52,53]. Moreover, some studies have observed that exercise can protect mice from $PM_{2.5}$-induced cardiovascular damage [54] and improve heart rate variability [55]. Another study found that mice exposed to low levels of $PM_{2.5}$ had a reduced ratio of intracellular to extracellular levels of the inflammatory marker heat shock protein 70 (HSP70) in the moderate- or high-intensity exercise groups [56]. However, inconsistent results also exist in some studies. One study exposing rats to particulate matter found no changes in the expression of the superoxide dismutase (SOD) and catalase (CAT) in heart and lung tissue, with or without exercise [57]. Additionally, physical activity did not alter the negative effects of air pollution on cognitive function in mice [58].

4. Thresholds for health effects of air pollution and physical activity

The threshold of air pollution levels below which outdoor physical activity can be safely undertaken remains a critical question. Wu et al. found that the $PM_{2.5}$ threshold concentration was about 31 μg/m^3 for the 2,000 m jogging in a randomized controlled study [59]. Guo et al. found

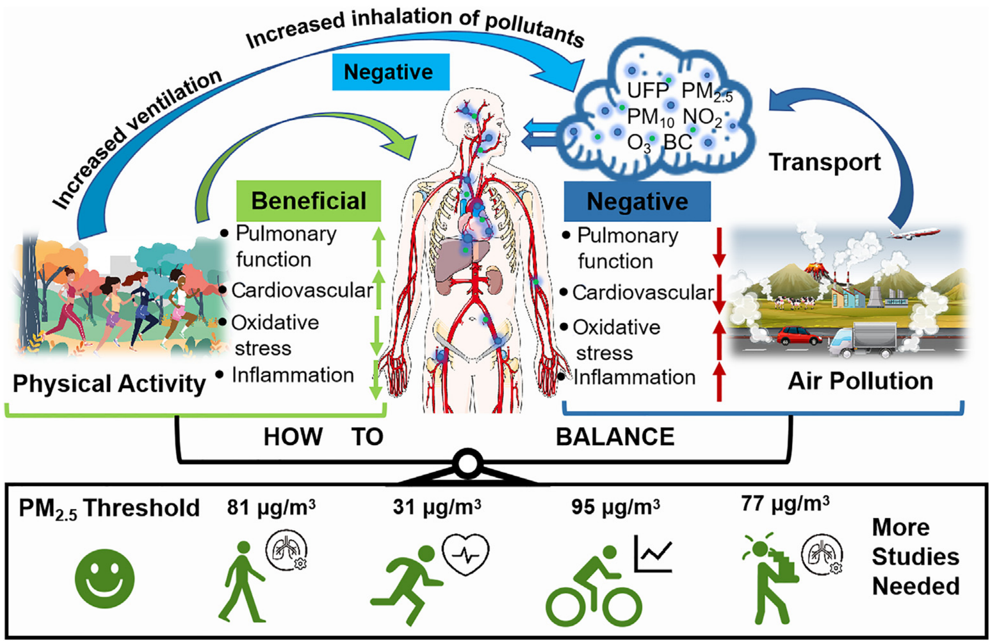

Fig. 1. Interaction between air pollution and physical activity affects human health. Walking and vigorous activity show the thresholds for the effects of air pollution and walking or vigorous activity on lung function [60], jogging shows the threshold for the effects of air pollution and jogging on blood pressure [59], and cycling shows the threshold for the effects of air pollution and cycling on all-cause mortality [62].

that $PM_{2.5}$ exposure levels above a certain value eliminated the beneficial effects of physical activity on lung function, with thresholds of about 77 μg/m^3 (95% CI: 39.7, 102) in the high-intensity physical activity group and about 81 μg/m^3 (95% CI: 58.9, 111) in the walking group through a cohort study of 13,032 [60]. Researchers have also found that physical activity of less than 1,000 MET-min/week at high levels of air pollution resulted in (net) health benefits, while physical activity of more than 1,000 MET-min/week at low to moderate levels of air pollution resulted in (net) health benefits [61]. Taino et al. explored the relationship between $PM_{2.5}$ concentration and cycling time, establishing the tipping point curve and break-even point curve. At a certain $PM_{2.5}$ concentration, when the cycling time reaches the tipping point curve, the health gain will no longer increase, and when the break-even point curve is exceeded, the health damage will be suffered [62]. Differences in research methods and health outcomes result in wide variations in thresholds for air pollutants (Fig. 1). Thresholds for air pollution and physical activity on human health require fine-grained studies, aiming to provide practical tools to guide the public on performing outdoor physical activity in polluted ambient air.

5. Other factors

Climate change can affect both air pollution and physical activity, especially during heat waves. Heat waves, affecting nearly half the world's population and exposing more than 1 billion workers to high temperatures [63], can cause increased mortality [64], affect the cardiorespiratory system [65], and impact mental health [66]. Heat waves exacerbate air pollution [67,68] and produce synergistic effects on health when combined with air pollution [69,70]. In addition, heat waves can reduce physical activity capacity and motor cognition [63]. During heat waves, however, the specific health effects of air pollution and physical activity remain unclear.

6. Perspectives

There are significant inconsistencies in the current literature regarding the interaction between air pollution and physical activity on health. More studies are needed to provide sufficient evidence to guide the public toward practicing outdoor physical activity. In the future, more in-depth research should be encouraged from the following perspectives:

a) Regional differences in air pollution by concentration and composition. Many developing countries in Asia and Africa still suffer from high levels of air pollution, whereas existing research has been mainly performed in developed countries with lower levels of air pollution. There is a lack of panel or crossover studies on the interaction between air pollution and physical activity in developing countries.

b) Outdoor physical activity exposes individuals to a mix of air pollutants, with particulate matter comprising various harmful components, some of which have significant adverse health effects on people. The health effects of simultaneous exposure to multiple air pollutants and physical activity are not yet fully understood.

c) Insufficient previous studies on the interaction between air pollution and physical activity in potentially vulnerable individuals or populations. Studies should examine people who are regularly engaged in outdoor physical activity and those with underlying medical conditions that need more protection, such as those working outdoors (traffic policemen, sanitation workers, etc.), those undertaking heavy physical labor (athletes, construction workers, etc.), and susceptible populations (children, the elderly, patients with respiratory diseases, etc.).

d) Animal experiments have the advantages of easy handling and controlled experimental conditions. Subsequent investigations should delve into the inherent mechanisms underlying the health impacts of air pollution and physical activity via animal experiments. Additionally, future research endeavors could focus on examining intervention approaches targeting the adverse health consequences associated with air pollution and physical activity, employing animal experiment models.

e) A lack of research on the thresholds for the interaction between air pollution and physical activity, and there is a lack of clear thresholds for different people in different physical activities. Currently, research has only been conducted in individual scenarios such as walking, jogging, and cycling [59,60,62], which fail to provide a basis for air pollution control and the formulation of public health protection policies, nor can it provide a basis for the public's daily physical activity. More precise thresholds for the health effects of air pollution and physical activity should be established based on crossover studies and panel studies.

f) In the context of global climate change, heat waves are becoming more frequent and more intense. Similarly, heat waves can adversely affect health and even cause death in the public [63,64]. However, the effect of heat waves on the interaction of air pollution and physical activity remains unclear. Further research is needed on how to avoid heat waves and reduce air pollution exposure while increasing physical activity.

g) Effective guidance for the public to be physically active in polluted conditions is important. The Air Quality Index (AQI) and Air Quality Health Index (AQHI) currently used in many countries are insufficient to provide individual/personalized physical activity advice to the general public. Further research on air pollution and physical activity indices should be conducted to guide public physical activity behavior. Furthermore, with the popularity of smart wearable devices, it is also possible to monitor the environmental conditions and physical activity of the public to create a feedback system for personalized health management.

CrediT authorship contribution statement

P.P.W.: visualization, writing–original draft. Q.G., J.F.(J.) Z.: writing–review & editing. Y.C.Z., M.Y.B., S.Z.C.: review & editing. X.L.D.: conceptualization, writing–review & editing, supervision. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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