Original article

Engagement in outdoor physical activity under ambient fine particulate matter pollution: A risk-benefit analysis

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Abstract

Background: Outdoor physical activity (PA) brings important health benefits, but exposure to polluted air increases health risks. This study aimed to quantify the tradeoff of PA under fine particulate matter ($PM_{2.5}$) air pollution by estimating the optimal PA duration under various pollution levels.

Methods: A risk-benefit analysis was performed to estimate the optimal outdoor moderate-intensity PA (MPA) duration under varying $PM_{2.5}$ concentrations.

Results: An inverse nonlinear relationship was identified between optimal MPA duration and background $PM_{2.5}$ concentration levels. When background $PM_{2.5}$ concentration increased to 186 $\mu g/m^3$, the optimal outdoor MPA duration decreased to 2.5 h/week, the minimum level recommended by current PA guidelines. When background $PM_{2.5}$ concentration further increased to 235 $\mu g/m^3$, the optimal outdoor MPA duration decreased to 1 h/week. The relationship between optimal MPA duration and background $PM_{2.5}$ concentration levels was stronger when exercising at a location closer to a source of air pollution. Compared to the general adult population, adults aged 60 years and older had substantially steeper curves—the optimal outdoor MPA duration decreased to 2.5 h/week when background $PM_{2.5}$ concentration reached 45 $\mu g/m^3$.

Conclusion: The health benefit of outdoor MPA by far outweighs the health risk of $PM_{2.5}$ pollution for the global average urban background concentration (22 $\mu g/m^3$). This modeling study examined a single type of air pollutant and suffered from measurement errors and estimation uncertainties. Future research should examine other air pollutants and indoor PA, incorporate short- and mid-term health effects of MPA and air pollution into the risk-benefit analysis, and provide estimates specific for high-risk subgroups.

Keywords: Air pollution; Exercise; Physical activity; $PM_{2.5}$; Risk-benefit analysis

1. Introduction

Physical activity (PA) is a key strategy for combatting the worldwide disease burden.[1,2] Regular engagement in PA confers important health benefits beyond controlling risk factors for diabetes, cardiovascular disease, dementia, and certain types of cancer and can improve mood, physical functioning, and overall quality of life.[3,4] Both the World Health Organization (WHO) and U.S. physical activity guidelines recommend at least 2.5 h of moderate-intensity physical activity (MPA) throughout the week.[5,6] Time spent outdoors is positively associated with MPA and improves cardiorespiratory fitness.[7,8] PA in natural settings offers non-invasive, low-cost solutions to public health problems, such as mental illness and obesity.[9] Increasing time spent outdoors may be a simple and effective strategy for promoting PA and fitness in the population.[10]

However, PA and outdoor air pollution may be an unhealthful combination. Currently, 91% of the world's population live in places where air pollution levels exceed the limits established by the WHO air-quality guidelines.[11] Fine particulate matters ($PM_{2.5}$), particles that are less than 2.5 mm in diameter, are among the main existing air pollutants.[12] $PM_{2.5}$ is a mixture of solid and liquid particles suspended in the air, most of which come from the combustion of fossil fuels in the process of heating, power generation, and operating motor

vehicles.[13] $PM_{2.5}$ can be inhaled and deposited in the airway and alveolar surfaces, causing local and systemic inflammation.[14] Short- and long-term exposure to $PM_{2.5}$ has been linked to elevated blood pressure, myocardial infarction and stroke, and respiratory diseases, such as asthma and bronchitis.[15−17] $PM_{2.5}$ pollution is considered a significant environmental risk factor for all-cause and disease-specific mortality.[18,19] $PM_{2.5}$ pollution is particularly relevant to outdoor PA due to higher air-pollutant inhalation during exercise.[20]

Carlisle and Sharp[21] assessed the adverse impact of 6 major air pollutants, including $PM_{2.5}$, on athletic performances in the United Kingdom and recommended that athletes and exercisers avoid exercising near the roadside where ambient air pollution levels are high. Some large, heavily polluted cities, such as New Delhi and Beijing, have taken measures to reduce air pollution and have issued warnings to discourage outdoor activities based on air quality index readings.[22,23] On a global scale, climate change may have a profound impact on people's PA patterns.[24,25] The interaction between global warming and air pollution may create complex dynamics that jointly influence people's PA engagement.

In the world's most polluted cities and regions, residents often need to make day-to-day decisions about whether they should exercise outdoors and for how long. The challenge of making such decisions, aided by alerts of high pollution levels, may deter people from exercising outdoors altogether, despite evidence suggesting that the benefits of exercise outweigh the health risks of air pollution in most urban environments.[26,27] A large cohort study in Denmark found that long-term exposure to high levels of traffic-related air pollution did not attenuate the benefits of PA on premature mortality.[26] Two studies concluded that the benefits of active commuting (i.e., cycling or walking) and outdoor PA outweigh the risk of mortality due to air pollution and traffic accidents.[27,28] More recently, Giallouros et al.[29] estimated the impacts of cycling and walking during high air pollution days on all-cause mortality. They concluded that, in general, the health benefits of cycling and walking outweighed the mortality risks induced by the exposure to outdoor air pollution.

Built upon previous studies,[27,29] our study aimed to estimate when the health benefits of PA get washed out or even reversed by the health risks of air pollution. Specifically, we conducted a risk-benefit analysis to determine the optimal outdoor MPA duration in $PM_{2.5}$ pollution. In order to be inclusive of diverse populations, we included all types of outdoor MPA rather than focusing on a specific activity such as active commuting. We further estimated the optimal MPA duration in response to $PM_{2.5}$ pollution by PA locations. Finally, we assessed the optimal MPA duration among adults aged 60 years and older.

2. Methods

Risk-benefit analysis is a set of quantitative methods, drawn from different disciplines, used to evaluate and estimate comprehensively the risks and benefits of an existing or prospective action (e.g., behavior, policy, or intervention).[30] As a result, a risk-benefit ratio is often calculated to quantify the tradeoffs of risks and benefits that can be used to inform decision making.

In this study, we conducted a risk-benefit analysis to estimate the optimal outdoor MPA duration under different $PM_{2.5}$ concentration levels $(\mu g/m^3)$. The risk of outdoor MPA pertains to the elevated all-cause mortality risk resulting from ambient $PM_{2.5}$ pollution. In contrast, benefit pertains to the reduction in all-cause mortality risk attributable to increased PA levels. We estimated the outdoor MPA duration (h/week) that optimized the combined risks and benefits (i.e., minimized the overall mortality risk ratio) across the range $(200−500 \ \mu g/m^3)$ of $PM_{2.5}$ concentration levels.

The PA exposure variable is expressed as metabolic equivalent (MET) h per week computed as the MET intensity multiplied by hour per week of a specific activity. The MET is computed as the activity-specific metabolic rate divided by the resting metabolic rate. One MET is the metabolic energy expended while sitting quietly, roughly equal to 3.5 mL/kg/min. MPA $(3.0−5.9$ METs) increases the metabolic rate $3.0−5.9$ times over resting, and vigorous-intensity PA $(\geq 6.0$ METs) increases the resting metabolic rate 6 times or more over resting metabolic values. In our study, the PA exposure assessed is MPA. We assume a PA level of 3.0 METs, which is at the lower range of MPA $(3.0−5.9$ METs). This assumption intends to relate the PA exposure durations to casual exercises at slower paces (e.g., dog walking, walking for pleasure, or bicycling for leisure or to work). These activities could be more realistic for the average adult exerciser and fall into the daily PA recommended by PA guidelines.[6]

2.1. Risk of outdoor MPA

The risk of outdoor MPA was calculated based on the changes in the inhalation rate under ambient $PM_{2.5}$ pollution in comparison to the alternative of not spending time in outdoor MPA. Therefore, the risk calculation considers the incremental risk of outdoor MPA but not the overall risk of $PM_{2.5}$ pollution.

Based on the U.S. Environmental Protection Agency's Exposure Factors Handbook,[31] the following inhalation rates among U.S. adults were adopted in the risk-benefit analysis: 0.3 m^3/h (0.2 m^3/h for women and 0.4 m^3/h for men) during sleep, 0.6 m^3/h (0.5 m^3/h for women and 0.7 m^3/h for men) during rest (including light-intersity PA), and 3.0 m^3/h (2.5 m^3/h for women and 3.5 m^3/h for men) during MPA. Given a total of 168 h in a week, we assumed 8 h of sleep in a day or 56 h of sleep in a week, and people made their decisions about how they allocated the remaining 112 h in a week between MPA and rest. Therefore, the MPA duration per week equals 112 h subtracted by the rest duration per week (Eq. (1)).

MPA duration per week

$$= 112 \ h − rest \ duration \ per \ week \qquad \text{Eq.(1)}$$

We differentiated between background $PM_{2.5}$ concentration and exposure to $PM_{2.5}$ pollution during outdoor MPA. Background $PM_{2.5}$ concentration refers to the ambient average $PM_{2.5}$ concentration in a neighborhood. Empirical research

shows that exposure to PM$_{2.5}$ pollution during outdoor PA (e.g., running and cycling on or near city roads) is generally higher than background PM$_{2.5}$ concentration.[22] We defined the concentration factor (CF) as the ratio of exposure to PM$_{2.5}$ pollution over background PM$_{2.5}$ concentration. In Tainio et al.,[27] the mode-specific exposure concentrations were estimated by multiplying background PM$_{2.5}$ concentration by 2.0 for cycling or 1.1 for walking. In this study, we assumed CF = 1.5 in the main risk-benefit analysis and a range between 1 and 2.5 in the subgroup analysis. Therefore, exposure to PM$_{2.5}$ pollution is the product of CF and background PM$_{2.5}$ concentration (Eq. (2)).

Exposure to PM$_{2.5}$ pollution

$$= CF \times background\ PM_{2.5}\ concentration \qquad Eq.(2)$$

To estimate the increase in exposure to PM$_{2.5}$ pollution due to outdoor MPA, the inhaled dose of the PM$_{2.5}$ with and without outdoor MPA (i.e., spending the time in rest instead) was calculated by taking into account changes in exposure concentrations, inhalation rates, and duration. The inhaled dose without outdoor MPA (μg/week) was calculated as the sum of 2 parts—the inhaled dose during sleeping and the inhaled dose during rest (Eq. (3)). The inhaled dose during sleep (or rest) is the product of the inhalation rate during sleep (or rest), the time spent per week in sleep (or rest), and the background PM$_{2.5}$ concentration.

Inhaled dose without outdoor MPA

$$= inhalation\ rate\ during\ sleep \times 56\ h$$
$$\times\ background\ PM_{2.5}\ concentration$$
$$+\ inhalation\ rate\ during\ rest \times\ 112\ h$$
$$\times\ background\ PM_{2.5}\ concentration \qquad Eq.(3)$$

The inhaled dose with outdoor MPA (μg/week) was calculated as the sum of 3 parts—the inhaled dose during sleeping, rest, and MPA (Eq. (4)). In particular, the inhaled dose during MPA is the product of the inhalation rate during MPA, the duration of MPA per week, and the exposure to PM$_{2.5}$ pollution when exercising.

Inhaled dose with outdoor MPA

$$= inhalation\ rate\ during\ sleep \times 56\ h$$
$$+\ background\ PM_{2.5}\ concentration$$
$$+\ inhalation\ rate\ during\ rest \times (112\ h - MPA\ duration)$$
$$\times\ background\ PM_{2.5}\ concentration$$
$$+\ inhalation\ rate\ during\ MPA \times MPA\ duration$$
$$\times\ exposure\ to\ PM_{2.5}\ pollution$$
$$\qquad Eq.(4)$$

We further calculated the increase in exposure to PM$_{2.5}$ pollution due to outdoor MPA relative to the baseline without any MPA in a week. Precisely, the increase in exposure to PM$_{2.5}$

pollution is defined as a proportional increase in background PM$_{2.5}$ concentration due to outdoor MPA (Eq. (5)).

Increase in exposure to PM$_{2.5}$ pollution =

$$\left(inhaled\ dose\ with\ outdoor \frac{MPA}{inhaled}\ dose\ without\ outdoor\ MPA -1 \right)$$
$$\times\ background\ PM_{2.5}\ concentration \qquad Eq.(5)$$

Burnett et al.[32] estimated the impact of long-term exposure to outdoor PM$_{2.5}$ pollution on mortality at the global scale using data from 41 cohort studies conducted in 16 countries. Using data reported in Supplementary Table 1 of their study, we performed a meta-analysis to estimate the pooled effect size of the all-cause mortality risk ratio in response to a 10 μg/m^3 change in background PM$_{2.5}$ concentration to be 1.089 (95% confidence interval (95%CI): 1.071−1.106). We adopted this point estimate in the primary analysis and the lower and upper boundaries of the 95%CI in the sensitivity analysis. We calculated the change in the all-cause mortality risk ratio resulting from exposure to PM$_{2.5}$ pollution during MPA in Eq. (6).

Mortality risk ratio in response to PM$_{2.5}$ pollution

$$= e^{\ln(1.089)\times(increase\ in\ exposure\ to\ PM_{2.5}\ pollution/10)}$$
$$\qquad Eq.(6)$$

2.2. Benefit of outdoor MPA

The benefit of outdoor MPA was calculated based on the reduction in all-cause mortality risk ratio attributable to the increase in weekly MPA duration. Arem et al.[33] pooled data from multiple population-based prospective cohorts conducted in the US and Europe with a total of 661,137 adults, 116,686 deaths, and a median follow-up period of 14.2 years. Cox proportional hazards regression was performed to estimate the multivariable-adjusted mortality risk ratios in response to MPA duration per week (0 weekly MPA duration as the baseline, with a mortality risk ratio of 1).[33] Based on their estimates, we performed an ordinary least squares regression in which the natural logarithmic-transformed mortality risk ratio served as the dependent variable, and the third-degree polynomials of weekly MPA duration served as the independent variables (Eq. (7)). The adjusted R-squared of the estimated ordinary least squares was above 0.99. Fig. 1 shows the estimated regression curve. We used the estimated Eq. 7 to calculate the change in the all-cause mortality risk ratio in response to variations in weekly MPA duration. The specific values for the intercept and coefficients are reported in Table 1.

$$\ln(mortality\ risk\ ratio\ in\ reponse\ to\ MPA\ duration)$$

$$= \beta_0 + \beta_1 MPA\ duration + \beta_2 (MPA\ duration)^2$$

$$+ \beta_3 (MPA\ duration)^3$$

$$\qquad Eq.(7)$$

Table 1
Parameter values adopted in primary and subgroup risk-benefit analysis.

Parameter	Primary analysis	Subgroup analysis by location	Analysis of adults aged 60 years and older
Inhalation rate of sleep (m^3/h)	0.3	0.3	0.3
Inhalation rate of rest (m^3/h)	0.6	0.6	0.6
Inhalation rate of MPA (m^3/h)	3.0	3.0	3.0
Weekly sleep duration (h)	56	56	56
Concentration factor	1.5	1.0, 1.5, 2.0, and 2.5	1.5
Background $PM_{2.5}$ concentration ($\mu g/m^3$)	2−500	2−500	2−500
Mortality risk ratio in response to a 10-$\mu g/m^3$ increase in $PM_{2.5}$ concentration	1.089	1.089	1.440
β_0 in Eq. (7)	0.0009438848	0.0009438848	0.0009438848
β_1 in Eq. (7)	−0.0357964234	−0.0357964234	−0.0357964234
β_2 in Eq. (7)	0.0008082915	0.0008082915	0.0008082915
β_3 in Eq. (7)	−0.0000055871	−0.0000055871	−0.0000055871

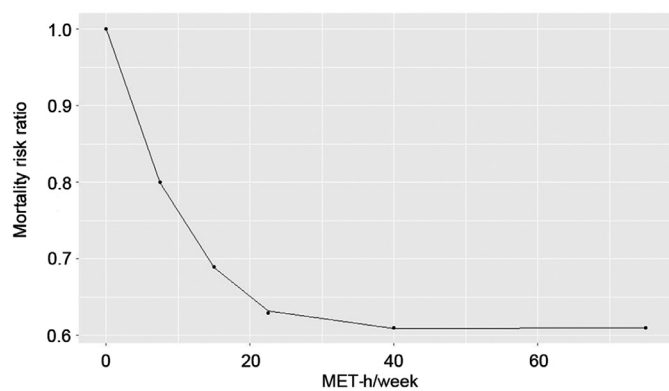Abbreviations: MPA = moderate-intensity phsical activity; $PM_{2.5}$ = fine particulate matter.

Fig. 1. Regression-estimated natural logarithmic mortality risk ratio by weekly moderate physical activity duration in metabolic equivalent (MET)-h.

2.3. Combining risk and benefit of MPA

The overall all-cause mortality risk ratio, defined as the product of the mortality risk ratio in response to MPA duration, calculated from Eq. (6), and the mortality risk ratio in response to $PM_{2.5}$ pollution, calculated from Eq. (7), is shown in Eq. (8). We estimated the optimal weekly MPA duration that minimized the overall mortality risk ratio at each background $PM_{2.5}$ concentration level (from 2 $\mu g/m^3$ to 500 $\mu g/m^3$ in an increment of 1 $\mu g/m^3$ in each iteration). Following the method used by Burnett et al.,[32] we adopted 2 $\mu g/m^3$ as the starting point for the background $PM_{2.5}$ concentration level because that was the minimum $PM_{2.5}$ concentration level observed in the cohort studies. The equations were solved using the built-in function "optimize" in *R*, Version 4.0 (The R Core Team, Vienna, Austria).

Overall mortality risk ratio

$= mortality\ risk\ ratio\ in\ reponse\ to\ MPA\ duration$

$\times motality\ risk\ ratio\ in\ response\ to\ PM_{2.5}\ pollution$

Eq.(8)

2.4. Sensitivity analysis

We used the lower (i.e., 1.071) and upper (i.e., 1.106) boundary of the 95%CI for the all-cause mortality risk ratio in response to a 10 $\mu g/m^3$ change in background $PM_{2.5}$ concentration to estimate the optimal weekly MPA duration.[32] This sensitivity analysis offered insights into the level of uncertainty associated with the findings from the primary analysis.

2.5. Subgroup analysis

Along with the primary risk-benefit analysis, we performed 2 subgroup analyses. First, we varied the value of CF from 1 to 2.5 (e.g., outdoor MPA in the backyard *vs.* near or on busy roads).[27] This analysis provided a range of estimates specific to exercise locations where $PM_{2.5}$ concentration deviates from the background average. Second, given the increasing vulnerability of older adults to elevated air pollution levels, we estimated the optimal weekly MPA duration specific to the older population. Burnett et al.[32] reported the mortality risk ratio in response to a 10-$\mu g/m^3$ change in background $PM_{2.5}$ concentration to be 1.440 among adults aged 60 years and older. This estimate was used for the analysis that was specific to older adults. Parameter values used in the primary and subgroup analysis are summarized in Table 1.

3. Results

Fig. 2A shows the estimated optimal outdoor MPA duration in response to differing $PM_{2.5}$ concentration levels. An inverse nonlinear relationship is revealed; the optimal outdoor MPA duration per week decreases as background $PM_{2.5}$ concentration increases. Under a background $PM_{2.5}$ concentration of 100 $\mu g/m^3$, the optimal outdoor MPA duration is 17.0 MET-h (or 5.7 h) per week. The optimal outdoor MPA duration decreases to 7.5 MET-h (or 2.5 h) per week (i.e., the minimum weekly MPA duration recommended by the PA guidelines) when background $PM_{2.5}$ concentration increases to 186 $\mu g/m^3$,[27] and it further decreases to 3 MET-h (or 1 h) per week when the background $PM_{2.5}$ concentration reaches 235 $\mu g/m^3$.

Fig. 2B shows the relationship between the estimated optimal outdoor MPA duration and background $PM_{2.5}$ concentration levels under differing mortality risk ratios in response to
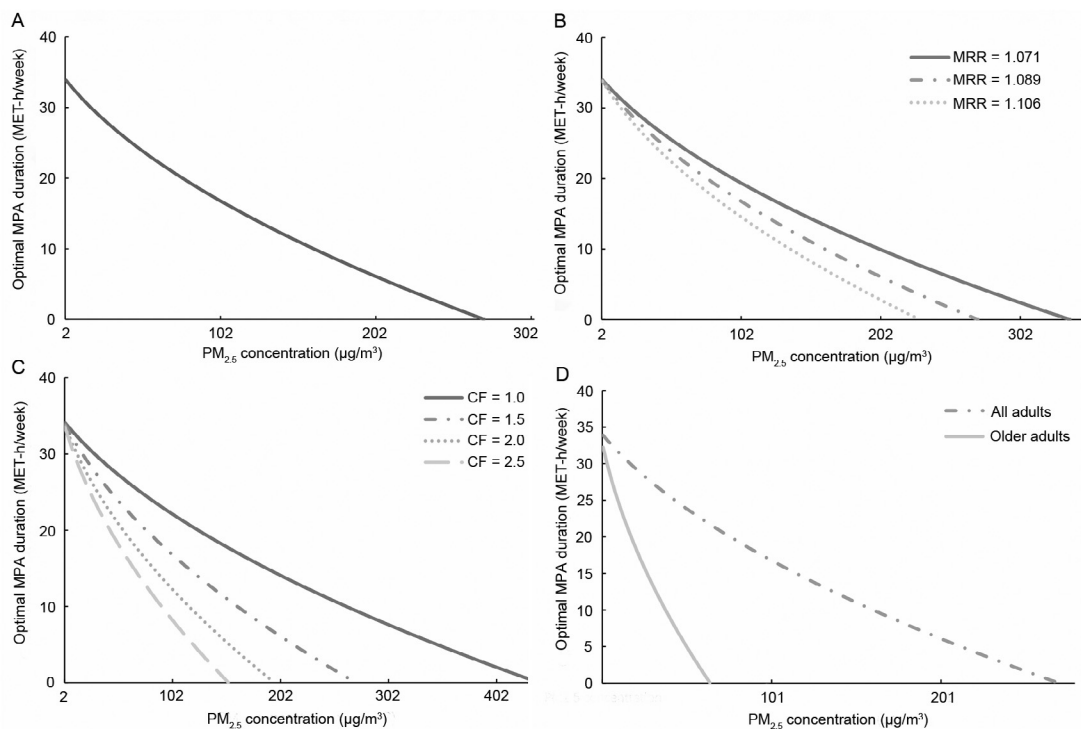
Fig. 2. Estimated optimal MPA duration at varying background PM$_{2.5}$ concentrations, (A) Main analysis, (B) Sensitivity analysis of alternative MRR, (C) Subgroup analysis by physical activity locations denoted by CFs, and (D) Subgroup analysis by age groups. CF = concentration factor; MPA = moderate-intensity physical activity; MRR = mortality risk ratios; PM$_{2.5}$ = fine particulate matter.

PM$_{2.5}$ pollution. As the mortality risk ratio increases from the lower boundary to the upper boundary of its 95%CI, the optimal outdoor MPA duration decreases for each background PM$_{2.5}$ concentration level. For instance, given a background PM$_{2.5}$ concentration level of 100 μg/m^3, the optimal outdoor MPA duration decreases from 19.5 MET-h (or 6.5 h) to 17.0 MET-h (or 5.6 h) and further to 14.8 MET-h (or 4.9 h) per week under the mortality risk ratio of 1.071, 1.089, and 1.106, respectively.

Fig. 2C shows the heterogeneous relationship between the estimated optimal outdoor MPA duration and background PM$_{2.5}$ concentration levels across alternative CF values. When CF or the ratio of exposure to PM$_{2.5}$ pollution over background PM$_{2.5}$ concentration increases from 1.0 to 2.5 in an increment of 0.5, the rate of decrease in the optimal outdoor MPA duration under elevated background PM$_{2.5}$ concentration levels accelerates. For instance, in a background PM$_{2.5}$ concentration of 100 μg/m^3, the optimal outdoor MPA duration, given a CF of 1.0, 1.5, 2.0, and 2.5, is 22.3 MET-h (or 7.4 h), 17.0 MET-h (or 5.7 h), 12.4 MET-h (or 4.1 h), and 8.4 MET-h (or 2.8 h) per week, respectively. Given a CF of 1.0, 1.5, 2.0, and 2.5, the optimal outdoor MPA duration decreases to fewer than 3 MET-h (or 1 h) per week when background PM$_{2.5}$ concentrations reach 383, 236, 171, and 134 μg/m^3, respectively.

Fig. 2D shows the estimates of the optimal outdoor MPA duration in response to different PM$_{2.5}$ concentration levels among adults aged 60 years and older. In comparison to the general adult population, adults older than 60 years have a substantially steeper curve. For them, the optimal outdoor MPA duration decreases to 7.5 MET-h (or 2.5 h) per week when

background PM$_{2.5}$ concentration increases to 45 μg/m^3 and further decreases to 3 MET-h (or 1 h) per week when background PM$_{2.5}$ concentration reaches 57 μg/m^3.[25]

4. Discussion

Engaging in PA in polluted air creates a dilemma because one should weigh the health benefits of PA against the health risks of air pollution. A growing body of literature suggests that air pollution discourages people from engaging in outdoor activities through impaired exercise capacity and performance due to decreased lung function, elevated blood pressure,[34−36] and other cardiovascular and respiratory symptoms while exercising in polluted air.[15,16,37] The appearance of smog and other visible pollutants can also deter people from being outdoors.[38] In addition, alerts and warnings of poor air quality from the news and public affairs programs have increased public awareness of air pollution.[39,40] These warnings can influence individuals' decisions to engage in outdoor activities.[39,40] The Air Quality Health Index developed by the Canadian government issues recommendations to "reduce or reschedule strenuous activities outdoors" on days when there are high levels of air pollution.[41]

Using a risk-benefit analysis, this study estimated the optimal duration of weekly outdoor MPA under ambient PM$_{2.5}$ pollution. Three sets of findings emerged. First, we found an inverse nonlinear relationship between optimal MPA duration and background PM$_{2.5}$ concentration levels. In particular, when background PM$_{2.5}$ concentrations increased to about 186 μg/m^3, the optimal outdoor MPA duration was 7.5 MET-h (or 2.5 h) per week, the current minimum level recommended by

the guidelines. When background $PM_{2.5}$ concentrations further increased to 235 μg/m^3, the optimal outdoor MPA duration decreased to 3 MET-h (or 1 h) per week. Second, the relationship between optimal MPA duration and background $PM_{2.5}$ concentration levels was stronger when exercising at a location closer to a source of air pollution. Finally, compared to the general adult population, adults aged 60 years and older had a substantially steeper curve—the recommended MPA duration of 7.5 MET-h (or 2.5 h) per week was optimal at a background $PM_{2.5}$ concentration of 45 μg/m^3.

Overall, our findings echoed reports from previous studies suggesting that the benefits of outdoor PA in the form of active commuting outweigh the risk of $PM_{2.5}$ air pollution.[27,29] In our study, the optimal duration of outdoor MPA still meets the current guidelines of 2.5 h per week when the $PM_{2.5}$ concentration level is as high as 186 μg/m^3, which can be uncommon in most regions, even in developing countries with heavy air pollution, such as India and China. In U.S. counties, the average $PM_{2.5}$ concentrations were 8.5 μg/m^3 in 2016,[42] far below the 186 μg/m^3 required to lower the optimal MPA duration to the recommended minimum. The WHO[43] documented a global average urban background $PM_{2.5}$ concentration of 22 μg/m^3. According to data from the U.S. Department of State,[44] there were only 5 days in the entire year of 2016 when the $PM_{2.5}$ concentrations exceeded 186 μg/m^3 in Beijing, China, a megacity infamous for its air pollution during the past 2 decades. In other words, the health benefits of engaging in outdoor MPA for 2.5 h per week outweigh the health risk of air pollution all year round except for 1 week in one of the most polluted places in the world.

The effects of $PM_{2.5}$ pollution on optimal outdoor MPA duration differed by exercise location. MPA engagement close to a major source of $PM_{2.5}$ pollution significantly reduced the optimal outdoor MPA duration through increased exposure to air pollution. Andersen et al.[26] found that cyclists were, on average, exposed to twice the amount of air pollution as the background (i.e., area-average) concentration level. Given these findings, people should try to avoid heavily polluted areas, such as busy roads, construction fields, and air pollutant-emitting factories when exercising.[45] On the other hand, policymakers should make efforts to reduce air pollution levels in urban areas where people often exercise.

The relationship between the optimal duration of outdoor MPA and $PM_{2.5}$ concentration tends to be substantially stronger among older adults aged 60 years and older. Evidence from existing studies has demonstrated that older adults are more susceptible to air pollution-induced health effects compared to younger adults or the general population.[46] In particular, older adults are documented to be more vulnerable to particulate matter than to other types of air pollutants, with specific effects sometimes resulting in acute hospitalization and cardio-respiratory mortality.[47]

The ongoing coronavirus disease-2019 (COVID-19) pandemic may have profoundly impacted people's PA.[48] A study of adult Fitbit (San Francisco, CA) users worldwide found that daily PA was reduced by 10%−20% across countries.[49] In the meantime, air pollution levels have declined in many parts of the world during the pandemic.[49] The dynamic relationship among COVID-19, air pollution, and PA warrants further investigation because such studies may hold the key to knowing when to intervene and help people to engage safely in adequate PA during the pandemic.[50]

A few policy recommendations may emerge from our findings. First, the message that government agencies convey to the general public—that aiming for or maintaining a weekly PA level following the WHO's PA guidelines (e.g., at least 2.5 h of MPA throughout the week)—should be safe. Following the guidelines represents a desirable lifestyle choice because the health benefit of PA is greater than the health risk of air pollution on most days. Second, high-volume exercisers and professional athletes whose weekly exercise level is considerably higher than a few folds (i.e., 3- to 5-fold) above the recommended minimum level given by PA guidelines should pay close attention to elevated air pollution if they wish to minimize its adverse health effects. Some safeguarding measures may be taken, such as wearing masks to filter the particulates, avoiding highly polluted roadways, or switching to indoor facilities with air purifiers. Third, adults aged 60 years and older are substantially more susceptible to the impact of $PM_{2.5}$ pollution than the general adult population. For this population, outdoor MPA may need to be reduced or switched to indoor PA in order to avoid severe health consequences if ambient air pollution levels increase to an alarmingly high level (e.g., more than 3-fold the global urban average $PM_{2.5}$ concentration level).

Our study has several limitations. First, people's PA levels are constrained primarily by the resources (e.g., availability of parks and exercise facilities) and the leisure time they have.[51,52] Our study assumed that people could freely choose the locations and durations of outdoor PA, but, in reality, most people have little choice about when and where they practice their daily PA. Second, our study considered only 1 particular type of air pollutant, namely $PM_{2.5}$, given its high prevalence in urban settings and detrimental health impacts. In contrast, other air pollutants, such as nitrogen dioxide, sulfur dioxide, and PM_{10}, were not modeled, nor were overall air pollution levels (usually measured by some air-quality indices). In some neighborhoods, the overall air pollution level might be high despite a relatively low $PM_{2.5}$ concentration; in these cases, the optimal outdoor MPA duration would be lower than our model suggests. Therefore, it would be inappropriate and potentially risky to generalize the findings of this study to other air pollutant types or to the overall ambient air pollution level. Third, our model assumes that people engage in outdoor MPA only, even when ambient air pollution worsens; but if it does, they may decide to engage in indoor MPA. Current literature about when individuals switch from outdoor to indoor PA due to air pollution is almost nonexistent. Also, the gains in health-risk reduction by switching exercise locations could be highly contingent on the indoor air quality (e.g., a gym with open windows *vs.* a gym equipped with a high-performance air purifier). Moreover, accessibility may not imply use. Various barriers, such as budget and time, may make people forgo the opportunity of exercising in a gym but choose to exercise in a house or apartment, where others cook or smoke or where there are other sources of indoor air pollution. Fourth, the

short- and mid-term health effects of MPA (e.g., improved physical and mental fitness) and air pollution (e.g., asthma and chronic bronchitis) are not incorporated into the risk-benefit analysis. A more sophisticated model may simulate people's life stages so that changes in quality of life attributable to the disease burdens associated with MPA and PM$_{2.5}$ can be taken into consideration in the risk-benefit calculations.

Findings from this study pertain only to the general adult population, whereas those who are highly vulnerable or sensitive to air pollution, such as fragile older adults and patients with respiratory diseases, may face a much deeper decreasing curve for their optimal outdoor MPA duration in response to elevated PM$_{2.5}$ concentration levels. We were unable to model those subpopulations due to the lack of data concerning their specific mortality risk ratios in response to MPA duration and air pollution concentration. Given the multitude of sources of uncertainty associated with the calculation of the optimal MPA duration, it would be an adequate choice for the majority of young and middle-aged people to follow the WHO's PA guidelines. Moreover, even with a reasonably high PM$_{2.5}$ concentration level (e.g., ~180 µg/m^3), it would still be safe for the majority of people, except for those aged 60 years and older or with existing chronic conditions, to engage in MPA outside for at least 2.5 h per week, although outdoor PA locations could make a difference in the optimal MPA duration. Our model assumed the same rate of reduction in mortality risk associated with MPA for the general adult population and older adults because we did not identify concurrent large-scale meta-analyses at the global scale on age-group-specific estimates. Woodcock et al.[53] reported a larger reduction in mortality from lower PA doses in adults aged 65 years and older, but the difference was small (i.e., relative risks of 0.78 in older adults *vs.* 0.81 in all adults) and statistically nonsignificant. If older adults, indeed, have a higher payoff for PA than their younger counterparts, our model would underestimate their optimal MPA levels in response to PM$_{2.5}$ air pollution. Finally, the duration of exercise depends upon the type and intensity of exercise performed. We selected the lower range of MPA that is relevant to adults who exercise casually for health and pleasure. However, more vigorous-intensity exercise requires deeper and more frequent ventilation, which may increase one's exposure to the PM$_{2.5}$ pollution.

We have several recommendations for future research on the risk-benefit tradeoff in PA engagement under air pollution. First, measures for other major air pollutant types and overall air pollution levels measured by a composite air pollution index should be adopted. Second, future research should assess people's decision-making processes related to when they switch from outdoor to indoor PA in response to air pollution or when they decide to wear masks when exercising outdoors. Additionally, other short- and mid-term health effects of MPA and air pollution should be incorporated into the risk-benefit model. Third, future research should explore the optimal PA duration based on both PM$_{2.5}$ concentrations and the MET intensity of the exercise. Finally, additional data on certain subpopulations, such as children, older adults, and patients with preexisting medical conditions, should be made available so that estimations of the optimal MPA duration under conditions of air pollution can be extended to these highly susceptible subgroups.

5. Conclusion

This study estimated the optimal duration of outdoor MPA under varying PM$_{2.5}$ concentration levels and explored whether the optimal duration changed by exercise locations and age. Although the optimal duration of outdoor MPA was inversely associated with background PM$_{2.5}$ concentration levels, the optimal duration still met the guidelines-recommended MPA of 2.5 h per week at a concentration level as high as 186 µg/m^3. Optimal duration decreased when PA took place closer to a major source of air pollution. Adults aged 60 years and older were substantially more susceptible to the impact of PM$_{2.5}$ pollution than the general adult population and, therefore, may need to reduce their duration of MPA under elevated PM$_{2.5}$ exposure. Future research should examine other air pollutants and indoor PA, incorporate short- and mid-term health effects of MPA and air pollution into the risk-benefit analysis, and provide estimates specific to high-risk population subgroups.

Authors' contributions

RA designed the study, compiled the data, constructed the simulation model, and wrote the manuscript; HK contributed to the simulation model construction and optimization; LC and XX contributed to interpreting the modeling results and revising the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

Supplementary materials

Supplementary materials associated with this article can be found, in the online version, at doi:10.1016/j.jshs.2020.09.008.

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