Is Morning or Evening Better for Outdoor Exercise? An Evaluation Based on Nationwide PM_{2.5} Data in China

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ABSTRACT

Proper sports exercise is important to health, both physically and mentally. However, the benefits from outdoor exercise may be impaired by potential health risks due to air pollution. As air pollution varies spatially and temporally within a day and a season, it is important to know the proper time for outdoor exercise in order to avoid or minimize potential health risks from inhalation of atmospheric particulate matter such as PM_{2.5} (i.e., particulate matter having a diameter less than 2.5 μm). The present study determined the increment of inhalation exposure (referred to as ΔF_{in}) to PM_{2.5} during outdoor exercise due to differences in PM_{2.5} concentrations between indoor and outdoor environments. Based on PM_{2.5} data collected by a total of 1505 air quality monitoring stations across 367 Chinese cities in 2014, we investigated the variation of ΔF_{in} between morning (6–8 AM) and evening (6–8 PM) periods in different provinces or districts across China as well as seasonal variations of ΔF_{in} . The results revealed an overall decreasing gradient in ΔF_{in} from the morning to evening periods in most Chinese regions, suggesting that outdoor exercise in the evening leads to less inhalation exposure to PM_{2.5} and should be given preference over morning exercise. However, the patterns also varied seasonally and geographically, leading to different health advisories on the choice of exercise time.

Keywords: PM_{2.5}; Inhalation exposure; Morning exercise; Evening exercise.

INTRODUCTION

China has had an increasing frequency of haze occurrence in some regions (Jiang *et al.*, 2015; Li *et al.*, 2015; Li *et al.*, 2018). Atmospheric particulate matter, particularly those having an aerodynamic diameter less than 2.5 μm (PM_{2.5}), are believed to be one of the major causes for the occurrence of haze (Sun *et al.*, 2006; Lin *et al.*, 2018; Zhang *et al.*, 2018). PM_{2.5} is also one of the priority air pollutants subject to air quality assessments worldwide (Munir, 2018; Park *et al.*, 2018; Zhao *et al.*, 2018b). These fine particles carry many hazardous chemicals and microbes (Chen *et al.*, 2017; Nguyen Thi Thu *et al.*, 2018), have long retention time in the atmosphere and are subject to long-range transport (Offenberg and Baker, 1999). After oral inhalation by humans, PM_{2.5} particles may penetrate into small airways and alveoli and finally into the blood stream (Gao *et al.*, 2017). Health outcomes from PM_{2.5} exposure may include allergic reactions, increased vulnerability of lung tissues to pathogenic microorganisms, oxidative stress,

dysfunction of immune system, altered cardiac autonomic function, accelerated atherosclerosis, and carcinogenesis (Gao *et al.*, 2017; Abe *et al.*, 2018).

Outdoor exercise has been getting more and more popular in China. Studies have shown that outdoor exercise not only improves physical health and decreases the prevalence of diseases, but also benefits the development of intelligence and emotion quotients and relieves mental pressure (Vella *et al.*, 2017). However, the public's passion for outdoor exercise has been discouraged by severe air pollution in many regions of China (Le *et al.*, 2014). Those who have routine outdoor exercise are concerned over air pollution and related health risks and would like to know what would be the best time for outdoor exercise in order to avoid or minimize inhalation of atmospheric pollutants. Some people prefer morning exercise, while others choose evening time for outdoor exercise. The periods of 6–8 AM and 6–8 PM have been mostly used for outdoor exercise. Given that air pollution varies temporarily within a day and the daily change pattern also varies from season to season, it is important to know whether the morning or evening period is safer for outdoor exercise in terms of potential PM_{2.5} exposure. To address this question, our study determined the increment of inhalation exposure (referred to as ΔF_{in}) due to differences in PM_{2.5} concentrations between

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indoor and outdoor environments as an approach to assess exposure risk during outdoor exercise. Based on the real-time PM_{2.5} data, we determined and compared ΔF_{in} data between morning (6–8 AM) and evening (6–8 PM) periods on a national scale and investigated seasonal and geographical variations in the morning to evening ΔF_{in} ratios.

MATERIALS AND METHODS

Data Sources and Treatments

Our study utilized the real-time PM_{2.5} data collected in 2014 by 1505 air quality monitoring stations scattered across 367 Chinese cities covering all provinces of mainland China (excluding Hainan, HongKong, Macao and Taiwan). The data can be found at <http://www.pm25x.com/city/hefei.htm>. Only the data from two time slots (i.e., 6–8 AM and 6–8 PM) were used for our analysis, representing the two most popular periods for outdoor exercise. Four seasons of a year were grouped March to May (spring), June to August (summer), September to November (fall) and December to February (winter). Geographically, the mainland China is divided into northeastern (including Liaoning, Jilin and Heilongjiang Provinces), northern (including Beijing, Tianjin, Hebei and Shanxi, Inner Mongolia Provinces/Districts), middle (including Henan, Hunan and Hubei Provinces), eastern (including Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Shanxi and Shandong Provinces/Districts), southern (including Guangdong, Guangxi and Hainan Provinces), southwestern (including Chongqing, Sichuan, Guizhou, Yunnan and Tibet Provinces/Districts), and northwestern territories (including Shaanxi, Gansu, Qinghai and Ningxia Provinces/Districts).

Estimation of Inhalation Exposure

Inhalation is the main route of exposure to PM_{2.5} for humans (Ott, 1983; Zhang *et al.*, 2015). Given that inhalation exposure is related to exposure period, respiration rate and body weight, we estimated the per body weight inhalation exposure to PM_{2.5} within a certain time period (F_{in} ; $\mu\text{g kg}^{-1}$) using Eq. (1):

$$F_{in} = C \times V \times t / M \quad (1)$$

where C ($\mu\text{g m}^{-3}$) is the PM_{2.5} concentration during the exposure period; V ($\text{m}^3 \text{h}^{-1}$) is respiration rate; t (h) is the period of exposure; BW (kg) represents an average body weight of the studied population.

Given that human respiration rate differs between outdoor exercise and normal activities, inhalation exposure to PM_{2.5} may be enhanced by outdoor exercise. Assuming people who do not perform outdoor exercise during the study periods stay inside of their homes, offices or other indoor environments and conduct activities requiring mid-level physical strength, we estimated the increment of inhalation exposure due to outdoor exercise (i.e., ΔF_{in}) using Eq. (2):

$$\Delta F_{in} = \frac{[C_{outdoor}V_s - C_{indoor}V_m]t}{BW} \quad (2)$$

where $C_{outdoor}$ and C_{indoor} represent outdoor and indoor PM_{2.5} concentrations, respectively; V_s and V_m are the respiration rates during activities requiring high-level and mid-level physical strength, respectively, and are used to represent the respiration rates during outdoor exercise and indoor activities, respectively; t is exposure period; and BW is body weight. Chen and Zhao summarized the comparative findings between indoor and outdoor PM_{2.5} concentrations from 77 published studies worldwide and realized that the ratios of indoor to outdoor PM_{2.5} concentrations generally approached 1.0, despite of large variations among regions or studies (Chen and Zhao, 2011). Therefore, our study assumed that $C_{outdoor}$ and C_{indoor} were equal at any time point. Considering that age, sex, and geographical location all influence human respiration rate, we utilized the respiration rate data from the Handbook of Inhalation Exposure Parameters for Chinese Populations (Adults) published by the China Environmental Protection Agency (EPA) (Ministry of Environmental Protection of the People's Republic of China, 2013). This handbook summarizes the short-term respiration rates of adults by province, location, age, or sex based on the study of 91,059 individuals from the nation, thus providing solid respiration data for our present study (Table 1).

In order to compare the differences in PM_{2.5} inhalation exposure between morning (M) and evening (E) periods, we also calculated the ratio of ΔF_{in} during the 6–8 AM period to that in 6–8 PM (referred to as M/E) as a quantitative index to determine whether the morning or evening time would be better for outdoor exercise.

$$M/E = \frac{\Delta F_{in}(M)}{\Delta F_{in}(E)} = \frac{C(M) \times (V_s - V_m) \times t / M}{C(E) \times (V_s - V_m) \times t / M} \quad (3)$$

where $\Delta F_{in}(M)$ and $\Delta F_{in}(E)$ represent the increment of inhalation exposure in the morning (6–8 AM) and evening (6–8 PM), respectively. If the respiration rates in the morning and evening are assumed to be the same, then M/E is entirely determined by the relative PM_{2.5} concentrations between morning and evening periods. A M/E greater than 1 suggests that outdoor exercise in the evening faces less PM_{2.5} exposure and is recommended, whereas a M/E less than 1 suggests a preference of morning exercise.

RESULTS AND DISCUSSION

PM_{2.5} Pollution Status in China

Among the 30 studied provinces, cite regions directly under central government governance, or autonomous districts, only one of them (Tibet) had an annual mean PM_{2.5} concentration less than $35 \mu\text{g m}^{-3}$ in 2014 during the period of 6–8 AM, whereas five of them (Beijing, Tianjin, Henan, Hebei and Hubei) had annual mean concentrations during the same time period greater than $75 \mu\text{g m}^{-3}$ (Fig. 1(a)), which significantly higher than the daily average PM_{2.5} limits of ambient air quality standard in China ($35 \mu\text{g m}^{-3}$ for Grade I and $75 \mu\text{g m}^{-3}$ for Grade II) (Ministry of Environmental Protection of the People's Republic of

Table 1. Respiration rate during activities requiring high-level (V_s , L min⁻¹) and mid-level (V_m , L min⁻¹) physical strength, and weight body (BW, kg) for adult males and females in China. All data was from Handbook of Inhalation Exposure Parameters for Chinese Populations (Adults) published by the China Environmental Protection Agency (EPA) (Ministry of Environmental Protection of the People's Republic of China, 2013).

	male			female		
	V_m (L min ⁻¹)	V_s (L min ⁻¹)	BW (kg)	V_m (L min ⁻¹)	V_s (L min ⁻¹)	BW (kg)
Beijing	26.4	39.6	72.9	21.1	31.7	63.5
Tianjin	26.3	39.4	73.4	21	31.4	63.5
Hebei	26.1	39.2	71.9	21.1	31.6	63.9
Shanxi	26.2	39.3	71.5	20.8	31.2	60.5
Inner Mongolia	26.2	39.3	72.2	20.8	31.3	62.2
Liaoning	26.5	39.8	72.8	21	31.5	63
Jinlin	26	39	70.6	20.9	31.3	62.4
Heilongjiang	26.9	40.4	75.3	20.6	30.9	59.7
Shanghai	25.6	38.4	68.7	20.3	30.4	58.1
Jiangsu	25.7	38.6	69.2	20.3	30.4	58.2
Zhejiang	25.6	38.3	68.1	20.1	30.2	56.7
Anhui	25.7	38.5	68.1	20.7	31	59.3
Fujian	25.1	37.7	65.2	20	30	54.9
Jiangxi	24.9	37.4	64.2	19.9	29.8	54.5
Shandong	26.1	39.1	71.3	20.9	31.3	62.9
Henan	25.9	38.9	71	20.8	31.2	60.7
Hubei	25.4	38	66.5	20.3	30.4	57.3
Hunan	25.5	38.3	66.4	20	29.9	54.8
Guangdong	24.7	37.1	64.2	24.7	37.1	55.4
Guangxi	24.02	36.4	62.2	19.8	29.7	55
Hainan	24.9	37.4	64.7	20	29.9	54.1
Chongqing	24.8	37.2	64	20	29.9	54.9
Sichuan	24.9	37.3	63.6	20	29.9	55.4
Guizhou	22.2	33.3	63.2	19.9	29.8	54.4
Yunnan	24.5	36.7	63.6	19.9	29.8	54.5
Tibet	24.6	36.8	65.9	20.8	31.2	61.7
Shaanxi	25	37.6	66.9	20.4	30.6	58.3
Gansu	25.4	38.1	68.2	20.7	31	60
Qinghai	26.5	39.7	71.2	20.5	30.7	59.7
Ningxia	26.1	39.1	70.5	20.3	30.5	57.4
Xijiang	25.7	38.5	69.9	20.7	31.1	62.1

China, 2013). The other provinces/districts had annual mean concentrations ranging from 35–75 $\mu\text{g m}^{-3}$, they were also higher than the daily average $\text{PM}_{2.5}$ limit for Grade I of ambient air quality standard in China (35 $\mu\text{g m}^{-3}$) (Ministry of Environmental Protection of the People's Republic of China, 2013). In the evenings (6–8 PM), Tibet remained to be the only region with an annual mean $\text{PM}_{2.5}$ concentration less than 35 $\mu\text{g m}^{-3}$ and three other provinces/districts (Beijing, Henan and Hubei) had annual mean concentrations greater than 75 $\mu\text{g m}^{-3}$ (Fig. 1(b)). A total of 25 provinces/districts had $\text{PM}_{2.5}$ concentrations lower in the evening than in the morning. The morning to evening gradient was more significant in regions with greater $\text{PM}_{2.5}$ concentrations. By geographical regions as classified in the method, middle and northern parts of China had the greatest $\text{PM}_{2.5}$ concentrations, whereas southern and southwestern parts had the lowest $\text{PM}_{2.5}$ pollution (Fig. 1). Similar results also were reported (Gao *et al.*, 2017; Zhang *et al.*, 2017; Zhao *et al.*, 2018a). All geographical regions exhibited declining trends in annual mean $\text{PM}_{2.5}$ concentrations from morning

to evening periods (Fig. 1).

Inhalation Exposure to $\text{PM}_{2.5}$ during Outdoor Exercise for Adult Chinese Populations

Outdoor exercise in the mornings would increase the inhalation of $\text{PM}_{2.5}$ in a rate of $45.9 \pm 18.1 \mu\text{g h}^{-1}$ and $37.0 \pm 14.2 \mu\text{g h}^{-1}$ for male and female adults, respectively. While the increase of inhalation exposure to fine particle was calculated at a rate of $40.9 \pm 14.6 \mu\text{g h}^{-1}$ and $33.0 \pm 11.4 \mu\text{g h}^{-1}$ for males and females, respectively, during outdoor exercise in the evening. Based on the consideration of the average body weights of male and female adults (Ministry of Environmental Protection of the People's Republic of China, 2013), all ΔF_{in} values were calculated and checked with normal distribution by Kolmogorov-Smirnov test (p values greater than 0.05). On a national base, male adults had a mean ΔF_{in} of $0.67 \pm 0.25 \mu\text{g kg}^{-1}$ for 1-hour outdoor exercise in the morning and a mean ΔF_{in} of $0.60 \pm 0.21 \mu\text{g kg}^{-1}$ in the evening. Therefore, higher increment of inhalation exposure due to outdoor exercise

in the mornings for male adults was found compared to in the evenings by a paired-samples T test ($p < 0.01$). Female adults had a mean ΔF_{in} of $0.63 \pm 0.23 \mu\text{g kg}^{-1}$ for 1-hour outdoor exercise in the morning and a mean ΔF_{in} of $0.56 \pm 0.19 \mu\text{g kg}^{-1}$ in the evening (Fig. 2). Compared to morning exercise, outdoor exercise in the evenings would result in a decrease of inhaled amount of $\text{PM}_{2.5}$ per hour to be $5.01 \pm 7.79 \mu\text{g}$ for males and $4.01 \pm 6.24 \mu\text{g}$ for females. Paired-samples T test also should higher inhalation exposure in the mornings than in the evenings due to outdoor exercise for female adults ($p < 0.01$). Furthermore, male adults exposed higher $\text{PM}_{2.5}$ due to outdoor exercise than female adults did ($p < 0.01$). Pope et al. reported that the mortality from cardiovascular diseases and lung cancer increased by 6% and 8%, respectively, for every daily average $\text{PM}_{2.5}$ concentration increase of $10 \mu\text{g m}^{-3}$ or the inhaled $\text{PM}_{2.5}$ increase of $144 \mu\text{g}$ (Pope et al., 2011). Leiva et al. (2013) found that the risk of emergency hospital admissions for cerebrovascular problems increased by 1.29% for every $\text{PM}_{2.5}$ concentration increase of $10 \mu\text{g m}^{-3}$. Therefore, male adults have a greater risk of cardiovascular death than females due to elevated $\text{PM}_{2.5}$ exposure during outdoor exercise on a regular base. Outdoor exercise in the morning

versus in the evening also enhanced the risk of cardiovascular death from a nationwide assessment.

Spatial and Temporal Variations M/E in the Morning to Evening

Spatial variation of M/E ratios during different seasons was shown in Fig. 3. The results reveal that human populated regions in the northern, eastern and northeastern parts of China generally had M/E ratios greater than 1.0. Northern China, particularly Beijing, Tianjin and Hebei, could have a M/E up to 2.3. Outdoor exercise is recommended in the evenings in these regions. By contrast, most of the southern, northwestern, and southwestern parts of China (including the Qinghai–Tibet Plateau region) had M/E less than 1.0 (as low as 0.38), suggesting morning exercise a wiser choice.

Seasonal variation in M/E ratios also revealed the choice of morning or evening time for outdoor exercise in a location may depend on the season. Geographically, the regions favoring evening exercise expanded in the summer and winter, but in the fall outdoor exercise in the mornings should be more favored in most regions. Northern and eastern China had M/E ratios greater than 1.0 all the year

Fig. 1. Annual mean $\text{PM}_{2.5}$ concentrations in the mornings (6–8 AM, a) and evenings (6–8 PM, b) in different regions of China.

Fig. 2. Normal distribution of increment of inhalation exposure to $\text{PM}_{2.5}$ (ΔF_{in}) for (a) male and (b) female adults in the mornings (6–8 AM, M) and evenings (6–8 PM, E) in 2014. All normal distributions were checked by Kolmogorov-Smirnov test and all p values were greater than 0.05.

Fig. 3. Spatial distribution and seasonal changes of the morning to evening ΔF_{in} ratios (M/E) in 2014. (a), (b), (c), and (d) represent the spring, summer, fall, and winter season, respectively.

round; thus outdoor exercise in the evenings is always recommended. These regions have the greatest human population densities across China and subject to severe $PM_{2.5}$ pollution. Northeastern, northwestern, and middle parts had M/E ratios greater than 1.0 in the summer and spring and less than 1.0 in the fall. The greatest M/E ratio (2.89) was found in northwestern China (City of Urumchi in Xinjiang District), which was likely caused by large morning to evening temperature gradients (Wang *et al.*, 2015). Southern China had M/E less than 1.0 in the spring and greater than 1.0 in the rest of year. Southwestern China (e.g., Yunnan Province) had your-round M/E ratios greater than 1.0. However, given that this region had much lower $PM_{2.5}$ pollution, the selection of morning or evening time for outdoor exercise would not produce a difference in $PM_{2.5}$ exposure as significantly as what was expected in northern China. In the winter, the nationwide mean M/E was 1.08, generally lower than the values in other seasons. Although the western part of China had elevate M/E ratios in the winter compared to other seasons, this broad region is largely unoccupied by humans and have very low $PM_{2.5}$ pollution.

M/E in Capital Cities

Given that the capital city of each province/district usually has a high human population density and represents the economic status of each region, the present study also focused on these capital cities for the M/E ratio analysis. Among the 31 capital cities under study, five of them had M/E less than 1.0, while the rest all had M/E greater than 1.0. The lowest M/E (0.91) was observed in Lhasa, the capital city of Tibet. As the $PM_{2.5}$ concentrations were generally less than $20 \mu g m^{-3}$ in Lhasa, outdoor exercise

either in the mornings or evenings would not result in significant $PM_{2.5}$ exposure (Fig. 4). A total of 18 capital cities had M/E greater than 1.1. Exercise in the evenings is recommended for people living in these cities. However, some of these cities, such as Wuhan, Zhengzhou, Tianjin and Shenyang, had $PM_{2.5}$ greater than $80 \mu g m^{-3}$ during both morning and evening periods. Thus outdoor exercise may lead to substantial $PM_{2.5}$ exposure at any time. This is also true for some of the 12 cities with M/E between 0.9 and 1.1, where relatively high $PM_{2.5}$ pollution occurred in both mornings and evenings. Outdoor exercise may not be recommended in general in these highly polluted cities.

CONCLUSIONS

- (1) In 2014, the northern and middle parts of China were subject to most severe $PM_{2.5}$ pollution. Southern and southwestern China generally had the lowest $PM_{2.5}$ pollution. Approximately 83.3% of the studied provinces/districts had elevated $PM_{2.5}$ concentrations at 6–8 AM compared to those at 6–8 PM.
- (2) Outdoor exercise in the morning would increase the inhalation of $PM_{2.5}$ in a rate of $45.9 \pm 18.1 \mu g h^{-1}$ and $37.0 \pm 14.2 \mu g h^{-1}$ for male and female adults, respectively. Outdoor exercise in the evening would increase the inhalation in a rate of $44.9 \pm 14.6 \mu g h^{-1}$ and $33.0 \pm 11.4 \mu g h^{-1}$ for males and females, respectively. Male adults have a greater risk of cardiovascular death than females due to elevated $PM_{2.5}$ exposure during outdoor exercise on a regular base. Outdoor exercise in the morning versus in the evening also enhanced the risk of cardiovascular death in most regions.
- (3) The morning to evening ratios of the increment of

Fig. 4. The morning to evening ΔF_{in} ratios (M/E) in capital cities of studied provinces/districts in China.

PM_{2.5} exposure exhibited spatial and seasonal variations. Whether morning or evening is better for outdoor exercise depends on the location and season. In order to avoid health risks from PM_{2.5} exposure, the time for outdoor exercise should be carefully considered. In heavily polluted regions, outdoor exercise is not even recommended.

CONFLICTS OF INTEREST

The authors declare no competing financial interest.

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