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Effects of air pollution and habitual exercise on the risk of death: a longitudinal cohort study

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Abstract

Background: Exercise may exacerbate the adverse health effects of air pollution by increasing the inhalation of air pollutants. We investigated the combined effects of long-term exposure to fine particle matter ($PM_{2.5}$) and habitual exercise on deaths from natural causes in Taiwan.

Methods: We recruited 384 130 adults (aged ≥ 18 yr) with 842 394 medical examination records between 2001 and 2016, and followed all participants until May 31, 2019. We obtained vital data from the National Death Registry of Taiwan. We estimated $PM_{2.5}$ exposure using a satellite-based spatiotemporal model, and collected information on exercise habits using a standard self-administered questionnaire. We analyzed the data using a Cox regression model with time-dependent covariates.

Results: A higher level of habitual exercise was associated with a lower risk of death from natural causes, compared with inactivity (hazard ratio [HR] 0.84, 95% confidence interval [CI] 0.80–0.88 for the moderate exercise group; HR 0.65, 95% CI 0.62–0.68 for the high exercise groups), whereas a higher $PM_{2.5}$ exposure was associated with a higher risk of death from natural causes compared with lower exposure (HR 1.02, 95% CI 0.98–1.07, and HR 1.15, 95% CI 1.10–1.20, for the moderate and high $PM_{2.5}$ exposure groups, respectively). Compared with inactive adults with high $PM_{2.5}$ exposure, adults with high levels of habitual exercise and low $PM_{2.5}$ exposure had a substantially lower risk of death from natural causes. We found a minor, but statistically significant, interaction effect between exercise and $PM_{2.5}$ exposure on risk of death (HR 1.03 95% CI 1.01–1.06). Subgroup analyses, stratified by $PM_{2.5}$ categories, suggested that moderate and high levels of exercise were associated with a lower risk of death in each $PM_{2.5}$ stratum, compared with inactivity.

Interpretation: Increased levels of exercise and reduced $PM_{2.5}$ exposure are associated with a lower risk of death from natural causes. Habitual exercise can reduce risk regardless of the levels of $PM_{2.5}$ exposure. Our results suggest that exercise is a safe health improvement strategy, even for people residing in relatively polluted regions.

Air pollution and physical inactivity are both major public health challenges worldwide.[1] Air pollution was the fifth leading cause of disability related to health and accounted for 4.9 million deaths worldwide in 2017.[2] More than 91% of the global population lives in areas where air quality does not meet the World Health Organization (WHO) guidelines.[3] In addition, physical inactivity was the fourth leading risk factor for death globally, accounting for 5.3 million deaths worldwide in 2012.[4] The WHO has challenged its member states to reduce physical inactivity by 15% by 2030.[5]

As people exercise, their ventilation rate increases, which increases the volume of air pollutants they inhale. This may exacerbate the adverse health effects of air pollutants. Thus, the risk–benefit relation between air pollution and exercise needs to be assessed to understand whether it is safe to exercise regularly in polluted regions. Indeed, some studies have shown that acute exposure to air pollution when exercising may override the benefits of exercise.[6,7] It is possible that the effects of long-term exposure to air pollution may be irreversible and cause a much larger disease burden than short-term exposure. Limited information exists on the combined effects of long-term exposure to air pollution and habitual exercise on human health, and findings have been inconsistent depending on health outcome. Three cohort studies have explored the relation between air pollution, physical activity and risk of death in Hong Kong,[8] Denmark and the United States,[9] with relatively small sample sizes.[10] Therefore, we sought to investigate the combined effects of habitual exercise and long-term exposure to fine particle matter ($PM_{2.5}$) on the risk of death from natural causes (i.e., deaths not attributable to accident, suicide or homicide) using a longitudinal cohort of adults in Taiwan, where the annual $PM_{2.5}$ concentrations are 1.6 times higher than the WHO-recommended limit. We hypothesized that the beneficial effects of habitual exercise on risk of death may outweigh the risk of high levels of air pollutants inhaled during exercise.

Methods

Study design and setting

We conducted our study in Taiwan, which has a tropical monsoon climate in the south and subtropical monsoon climate in the north and an annual average temperature of 22°C.[11] Participants were part of an ongoing open cohort, for which details have been described in our previous publications.[12–14] In brief, the MJ Health Management Institution has been providing residents of Taiwan with a standard medical screening program since 1994. Participants join the program through a paid membership and are encouraged to visit the institution periodically. During each medical visit, participants receive a series of medical examinations, including anthropometric measurements, spirometry tests, blood and urinary tests, and imaging tests. They also complete a standard, self-administered questionnaire.

Data from the medical examinations have been managed electronically since 1996. This cohort is an open, dynamic cohort without an end date for recruitment or follow-up. Each year, around 20 000 new members are recruited to the cohort, in addition to revisits by existing members. More than 600 000 residents have been recruited as of December 2016, with 1.5 million medical visits. Written informed consent is given by each participant before each medical examination.

Participants

We included adults (≥ 18 yr) who joined the medical screening program between 2001 and 2016, when $PM_{2.5}$ concentration was available. We excluded participants with missing $PM_{2.5}$ exposure because of incomplete addresses and participants with missing data. We followed participants from their entry date (i.e., the first medical examination) until May 31, 2019, or the date of death, if earlier.

Exposures and outcomes

We obtained information on vital status and causes of death from the National Death Registry, which is maintained by the Ministry of Health and Welfare of Taiwan.[15] The main outcome was death from natural causes (*International Classification of Diseases* [ICD]-9 codes: 001-779; ICD-10 codes: A00–R99). Participants with an accidental cause of death were censored at the time of death.

Details of the $PM_{2.5}$ exposure assessment have been described previously.[12,16,17] In brief, a spatiotemporal model was developed at a resolution of 1 km^2 using aerosol optical depth data collected via the Moderate Resolution Imaging Spectroradiometer from the Terra and Aqua satellites, carried aboard the U.S. National Aeronautics and Space Administration's Earth Observing System. We obtained ground-level aerosol optical depth data from the aerosol robotic network in Taipei, Taiwan, to calibrate the data. Finally, the spatiotemporal model was validated by comparing the estimated $PM_{2.5}$ concentration with the $PM_{2.5}$ concentration from air pollution monitoring stations across Taiwan. We assigned the estimated $PM_{2.5}$ exposure to participants according to their geocoded addresses. We calculated long-term exposure to $PM_{2.5}$ as the 2-year average concentration in the year of medical examination and in the previous year. We conducted our analysis using both continuous $PM_{2.5}$ exposure data (per 10 μg/m^3) and categorical $PM_{2.5}$ exposure, whereby we grouped participants into 3 categories based on the tertile cut-off points (low: < 22.4 μg/m^3, moderate: 22.4–26.0 μg/m^3, high: ≥ 26.0 μg/m^3).

We collected information on habitual exercise; the details have been described in our previous studies.[13,18–20] Briefly, a standard self-administrated questionnaire was used to collect information on leisure time exercise. The questionnaire was validated by comparing exercise levels with data from the National Health Interview Survey, and a test-retest approach was used to assess its reliability.[13] We obtained weekly data on the duration and intensity of habitual exercise in the month before each medical examination. We classified exercise intensity into 4 categories: light (e.g., walking), moderate (e.g., brisk walking), medium–vigorous (e.g., jogging), or high–vigorous (e.g., running). We assigned intensity categories a metabolic equivalent (MET) value of 2.5, 4.5, 6.5 and 8.5, respectively, where 1 MET equals 1 kcal/h/kg bodyweight.[13,21] If a participant did not undertake any exercise, then we assigned a MET value of 0. For participants who reported activities in more than 1 intensity category, we weighted the MET value according to the time spent in each category. We calculated the exercise volume (MET-h) as the product of the intensity (MET) and duration (h). For analysis, we grouped participants into 3 categories based on the tertile cut-off points (i.e., inactive: 0 MET-h, moderate: 0 to 8.75 MET-h, high: > 8.75 MET-h).

Covariates

Participants' weight and height was measured when they were wearing light clothing and no shoes. An overnight fasting blood sample was collected in the morning, and information on demographics, lifestyles, physical activity at work and medical history was measured using a standard self-administered questionnaire.

We included the following covariates in the main analysis: age, sex, education (i.e., less than high school, completed high school, college or university, postgraduate), body mass index, physical labour at work (mostly sedentary, mostly standing or walking, hard labour), cigarette smoking (never, former, current), alcohol drinking (never/seldom, former, current), vegetable and fruit intake (seldom [< 1 serving/day], moderate [1–2 servings/day], frequent [> 2 servings/day]), occupational exposure to dust or solvents, season and year of enrolment.

Additional information on participant selection, outcome ascertainment, $PM_{2.5}$ exposure assessment, evaluation of habitual exercise and covariates is presented in Appendix 1, Figure E1, available at www.cmaj.ca/lookup/doi/10.1503/cmaj.202729/tab-related-content.

Statistical analysis

We used Cox regression models with time-dependent covariates to investigate the combined effects of $PM_{2.5}$ exposure and habitual exercise on deaths from all natural causes. To control for clustering effects within the same city, we used a city-level random intercept. We developed 2 models to incrementally adjust for the covariates. Model 1 adjusted for age, sex and education, and Model 2 further adjusted for body mass index, physical labour at work, smoking status, alcohol consumption, vegetable and fruit intake, occupational exposure to dusts or solvents, season and year of cohort enrolment. We ran additional models that mutually adjusted for $PM_{2.5}$ and exercise for comparison (i.e., further adjusted for exercise for the association between $PM_{2.5}$ exposure and death, or for $PM_{2.5}$ exposure for the association between exercise and death). We performed a trend test across the exercise (i.e., inactive, moderate or high habitual exercise) and $PM_{2.5}$ (i.e., low, moderate or high exposure) groups, respectively, with the corresponding group treated as an ordinal variable. To explore the overall interaction effect, we performed an additional test for interaction by including an interaction term in Model 2 that captured continuous $PM_{2.5}$ (every 10 µg/m^3) by exercise group.

We performed subgroup analyses for each $PM_{2.5}$ and exercise group to evaluate the effects of $PM_{2.5}$ exposure or habitual exercise in each stratum. Finally, we classified participants into 9 groups according to their $PM_{2.5}$ exposure and habitual exercise; we used inactive participants with high $PM_{2.5}$ exposure as the reference group.

We performed a series of sensitivity analyses to evaluate the robustness of our estimates. Firstly, we further adjusted for the presence of common chronic diseases, including diabetes (defined as fasting blood glucose ≥ 126 mg/dL or self-reported, physician-diagnosed diabetes), hypertension (defined as systolic blood pressure ≥ 140 mm Hg or diastolic blood pressure ≥ 90 mm Hg, or self-reported, physician-diagnosed hypertension), dyslipidemia (defined as total cholesterol ≥ 240 mg/dL, triglyceride ≥ 200 mg/dL or high-density lipoprotein cholesterol < 40 mg/dL), cardiovascular disease (defined as self-reported, physician-diagnosed coronary heart disease, stroke, peripheral arterial disease or aortic disease) and chronic obstructive pulmonary disease (defined as physician-diagnosed chronic obstructive pulmonary disease or a ratio of forced expiratory volume in 1 s to forced vital capacity < 70%). In other sensitivity analyses, we used annual $PM_{2.5}$ of the year of medical examination; we included participants who had partial data and used their previous or subsequent medical records to impute the missing values; we restricted the analysis to the participants aged 65 years or older; we restricted the analysis to nonsmokers; we compared the effects on deaths from all causes (i.e., including deaths by accident, suicide and homicide, as well as natural causes) with the effects on death from all natural causes. Lastly, we analyzed only participants who gave a home (as opposed to work) address.

We conducted statistical analyses using software R version 3.6.1. We treated the estimated effects as statistically significant if the 2-tailed p value < 0.05.

Ethics approval

This study is approved by the Joint Chinese University of Hong Kong–New Territories East Cluster Clinical Research Ethics Committee (2018.388) and National Cheng Kung University in Tainan, Taiwan (A-ER-108–081).

Results

Table 1 shows the main characteristics of participants, all observations and deaths from natural causes. We included a total of 384 130 adults (≥ 18 yr), with 842 394 medical examination records between 2001 and 2016, in the main analysis. The median number of medical visits during the study period was 1.0, with an interquartile range (IQR) of 1.0–3.0. The median visit interval was 3.3 years, with an IQR of 1.7–9.5 years. The median duration of follow-up was 13.4 years, with an IQR of 9.4–16.4 years. We followed participants for a total of 4.9 million person-years. Information on medical examinations by the 9 exercise and $PM_{2.5}$ groups are shown in Appendix 1, Table E1. We identified 12 375 natural cause deaths during the study period, for an incidence rate of 2.5 per 1000 person-years. Figure 1 shows the distribution of $PM_{2.5}$ concentrations and participants by year. Concentrations of $PM_{2.5}$ (overall IQR was 21.6–27.8 µg/m^3) varied widely across the island (Figure 2).

The main effects of habitual exercise and $PM_{2.5}$ on risk of death are shown in Table 2. A higher level of habitual exercise was associated with a lower risk of death. In contrast, a higher level of $PM_{2.5}$ exposure was associated with a higher risk of death. Mutual adjustment for $PM_{2.5}$ exposure and exercise did not substantially change the associations. We observed significant trends for the associations. The interaction test showed a minor, but statistically significant, interaction effect of exercise and $PM_{2.5}$ on the risk of death (HR 1.03, 95% CI 1.01–1.06).

In subgroup analyses, habitual exercise was associated with a lower risk of death in each stratum of $PM_{2.5}$ exposure, whereas $PM_{2.5}$ exposure was associated with a higher risk of death in each exercise stratum (except for the inactive stratum) (Table 3).

Figure 3 shows the combined effects of exercise and $PM_{2.5}$ exposure on risk of death. Participants with a high level of exercise and an exposure to low $PM_{2.5}$ concentrations had the lowest risk of death (HR 0.54, 95% CI 0.50–0.58), and inactive participants with an exposure to high $PM_{2.5}$ concentrations had the highest risk of death from natural causes. Risk of death and $PM_{2.5}$ and were positively associated, except for participants who were inactive. Dose–response associations between exercise and risk of death were generally evident for participants exposed to different levels of $PM_{2.5}$ air pollution.

Sensitivity analyses yielded similar results (Appendix 1, Tables E2–E8). The HRs of $PM_{2.5}$ exposures were slightly greater in participants who had higher levels of exercise, and we observed weak interactions between $PM_{2.5}$ and exercise.

Interpretation

We investigated the combined effects of long-term exposure to ambient $PM_{2.5}$ and habitual exercise on the risk of death from natural causes in a large, longitudinal cohort that enabled us to have sufficient power to obtain stable and precise estimates and to conduct subgroup and sensitivity analyses to test the robustness of the associations and identify sensitive subpopulations.

Table 1: Participant characteristics

Characteristics	No. (%) of patients at baseline* n = 384 130	No. (%) of observations* n = 842 394	No. (%) of deaths from natural causes (mortality rate, per 1000 person-years) n = 12 375 (2.5)
Age, yr, mean ± SD	39.2 ± 12.7	41.6 ± 12.5	–
Sex, male	186 985 (48.7)	424 495 (50.4)	7206 (3.1)
Education			
Lower than high school	56 862 (14.8)	110 341 (13.1)	7014 (9.4)
High school	75 248 (19.6)	159 295 (18.9)	2268 (2.3)
College or university	204 730 (53.3)	459 089 (54.5)	2753 (1.1)
Postgraduate	47 290 (12.3)	113 669 (13.5)	340 (0.6)
Cigarette smoking			
Never	284 311 (74.0)	635 672 (75.5)	7671 (2.1)
Former	21 944 (5.7)	50 776 (6.0)	1361 (5.1)
Current	77 875 (20.3)	155 946 (18.5)	3343 (3.4)
Alcohol consumption			
Never or seldom	330 179 (86.0)	720 674 (85.6)	10 002 (2.4)
Former	36 063 (9.4)	82 329 (9.8)	1048 (2.3)
Current	17 888 (4.7)	39 391 (4.7)	1325 (5.9)
Physical labour at work			
Mostly sedentary	242 748 (63.2)	556 806 (66.1)	7559 (2.5)
Sedentary with occasional walking	100 314 (26.1)	208 090 (24.7)	3095 (2.4)
Mostly standing or walking	33 123 (8.6)	63 685 (7.6)	1372 (3.3)
Hard labour	7945 (2.1)	13 813 (1.6)	349 (3.5)
Habitual exercise group†			
Inactive	173 948 (45.3)	323 617 (38.4)	5290 (2.3)
Moderate	113 669 (29.6)	266 415 (31.6)	1904 (2.3)
High	96 513 (25.1)	252 362 (30.0)	5181 (3.0)
Exercise, MET-h, mean ± SD	7.2 ± 13.0	8.5 ± 14.2	–
Vegetable intake			
Seldom	54 200 (14.1)	99 349 (11.8)	2005 (2.9)
Moderate	226 735 (59.0)	493 825 (58.6)	7083 (2.5)
Frequent	103 195 (26.9)	249 220 (29.6)	3287 (2.6)
Fruit intake			
Seldom	132 705 (34.5)	249 169 (29.6)	4164 (2.6)
Moderate	206 117 (53.7)	477 307 (56.7)	6747 (2.6)
Frequent	45 308 (11.8)	115 918 (13.8)	1464 (2.5)
Occupational exposure	31 146 (8.1)	66 118 (7.8)	745 (1.9)
Body mass index (kg/m^2), mean ± SD	23.0 ± 3.7	23.2 ± 3.6	–
$PM_{2.5}$ (µg/m^3)‡, mean ± SD	26.4 ± 7.6	26.3 ± 7.4	–
$PM_{2.5}$ by exercise group†, mean ± SD			
Inactive	26.6 ± 7.6	26.6 ± 7.5	–
Moderate	26.3 ± 7.5	26.2 ± 7.4	–
High	26.2 ± 7.6	26.0 ± 7.4	–

Note: MET = metabolic equivalent, PM2.5 = fine particle matter, SD = standard deviation.
*Unless indicated otherwise.
†The tertile cut-off points for exercise volume using the MET value and duration (h): inactive (0 MET-h), moderate (0 to 8.75 MET-h) and high (> 8.75 MET-h). The tertile cut-off points for $PM_{2.5}$: low (< 22.4 µg/m^3), moderate (22.4 to 26.0 µg/m^3) and high (≥ 26.0 µg/m^3).
‡Refers to the 2-year average $PM_{2.5}$ concentration in the year of medical visit and in the year before the medical visit.

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The longitudinal, open study design allowed for recruitment of a large sample and for the study of changing $PM_{2.5}$ exposure combined with exercise over time. Our results show that high levels of habitual exercise and low levels of $PM_{2.5}$ exposure are associated with lowest risk of death and that habitual exercise reduced the risk of death across $PM_{2.5}$ categories, compared to inactivity. We observed weak interaction effects between $PM_{2.5}$ and exercise on risk of death.

Previous studies have reported similar associations between air pollution and risk of death.[22–24] The association between risk of death and air pollution found in this study (HR 1.18 per 10 μg/m³) was slightly larger than those found in Europe (HR 1.02 per 10 μg/m³)[23] and in the United States (HR 1.07 per 10 μg/m³)[24] possibly because of higher exposures in our cohort. Moreover, we considered clustering effects within the same city, and thus included a city-level random intercept in our analysis, which is known to result in larger HRs.[25]

In line with the benefits of habitual exercise previously documented,[13,26] we identified an inverse association between habitual exercise and risk of death. However, it is difficult to compare the magnitudes of the direct benefits of exercise. Some previous studies did not find a threshold for the benefits of exercise, but showed that even a low level of exercise can benefit human health.[13,27,28]

Unlike most previous studies that used modelling methods based on literature-derived risks of air pollution and benefits of exercise,[29–32] this study provided evidence of the effects of habitual exercise on the risk of death in a population exposed to different levels of $PM_{2.5}$ that were directly measured. The information we collected on physical activity was comprehensive, including various types of exercise and physical activity during leisure time and daily work. Three previous cohort studies targeting older adults[8, 9] and women[10] have been conducted in Hong Kong,[8] Denmark[9] and the US.[10] The Hong Kong study had a similar air pollution level to that of our study, and the studies in Denmark and the US had better air quality. However, the results from our study and all 3 of these studies suggest that habitual exercise is beneficial, even for people living in relatively polluted regions. Unlike previous studies, we observed a weak, but statistically significant, interaction between habitual exercise and $PM_{2.5}$ exposure, probably because of the large sample size or the different population in our study. We did not observe a significant interaction effect in the sensitivity analysis that included only participants aged 65 years and older (Appendix 1, Table E5).

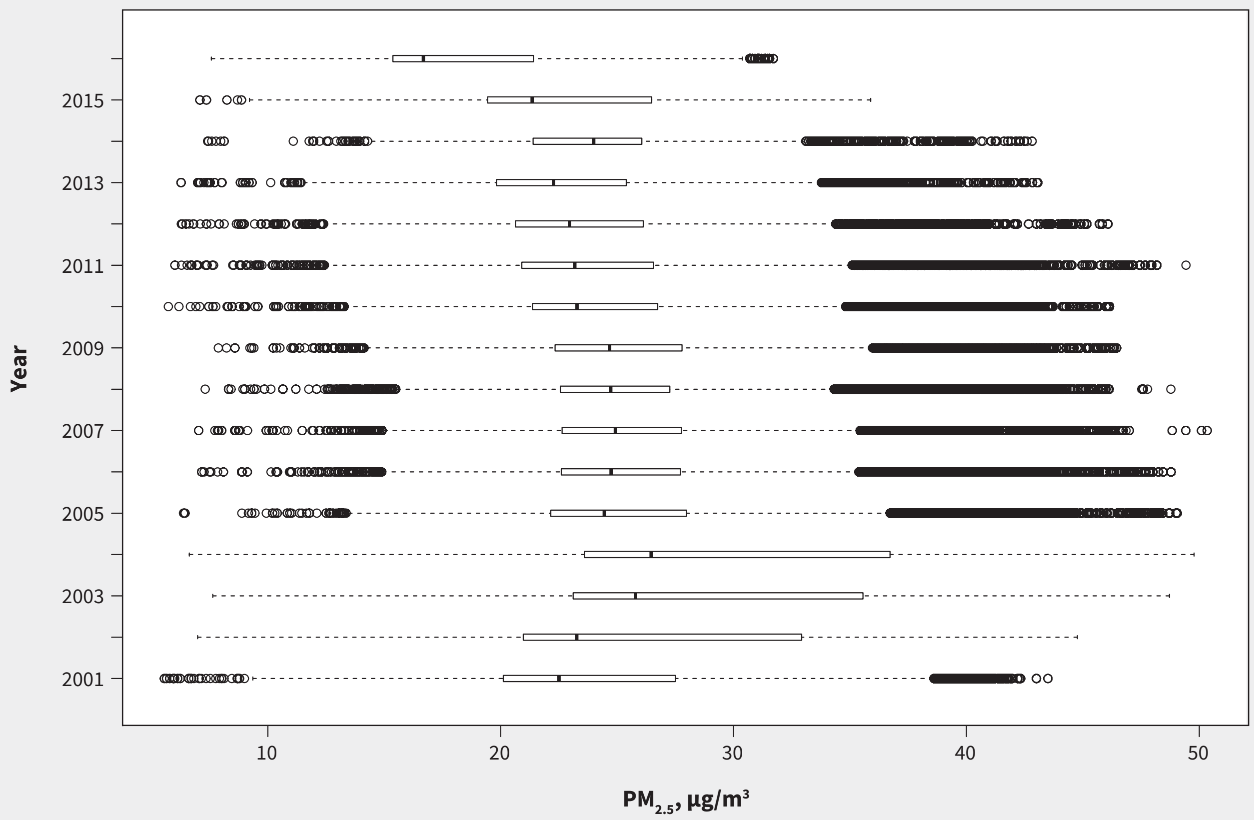

Figure 1: The temporal distribution of the 2-year average air pollution (measured by concentration of fine particle matter, $PM_{2.5}$) by year for the 842 394 medical visits of the 384 130 participants in Taiwan. Boxes represent the interquartile range (IQR), with centre lines showing the median concentration. Whiskers extend to the highest observations within 3 IQRs of the box, with more extreme observations shown as circles.

The results of our study are also in line with those of most previous studies showing that exercise has benefits for people in polluted areas in the context of other health outcomes, including hypertension,[33] diabetes,[34] systemic inflammation,[35] myocardial infarction,[36] lung function,[20] stroke[37] and asthma.[38] Although statistically significant interactions have been reported for lung function, stroke and asthma,[20,37,38] the interaction strengths are generally weak, which is similar to the results of our study. More research is warranted to explore the combined effects on different health outcomes and potential interactions.

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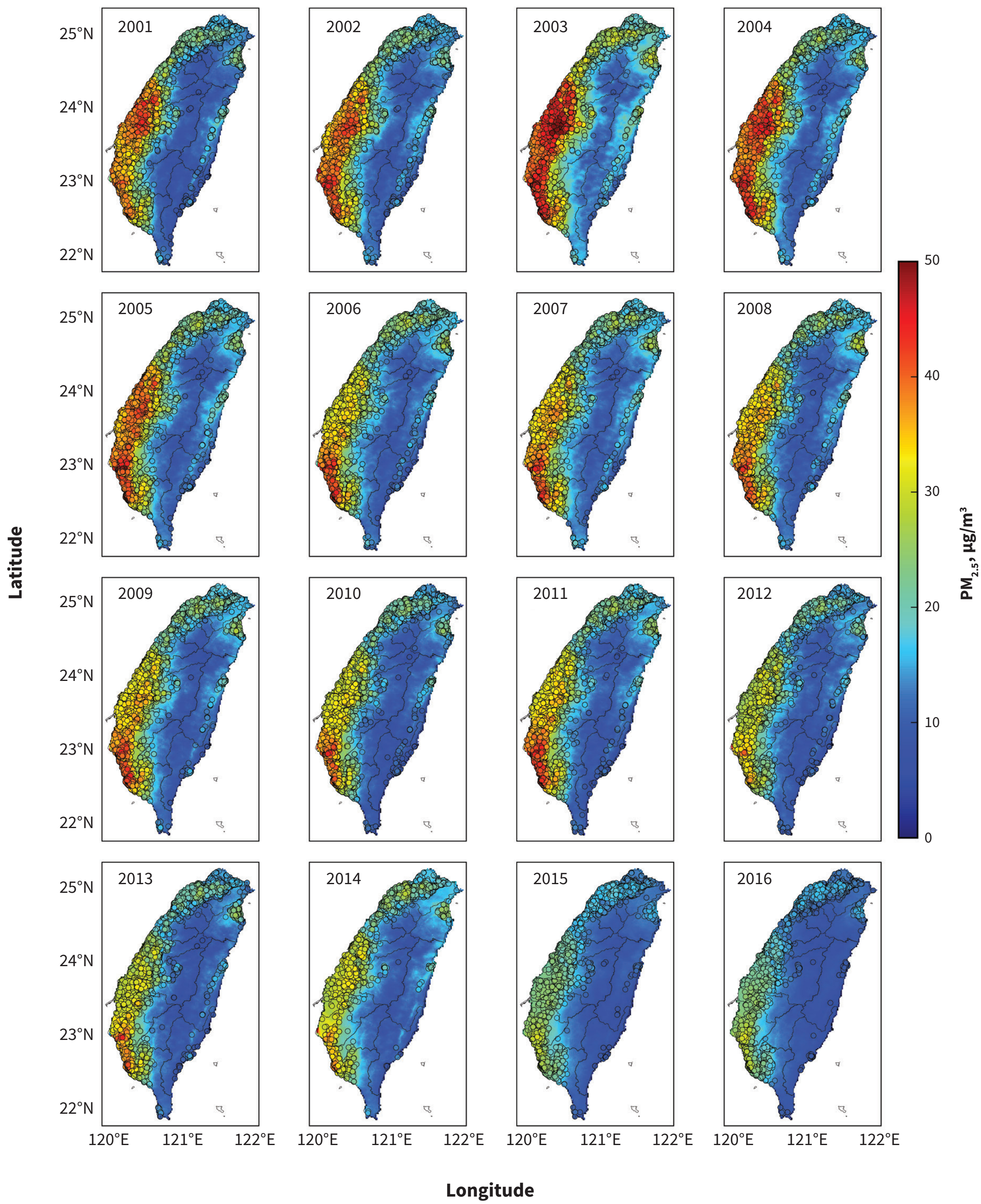

Figure 2: The spatial distribution of participants and air pollution (measured by concentration of fine particle matter, $PM_{2.5}$) in Taiwan. Circles indicate the locations of participants.

Table 2: Associations of death from natural causes with habitual exercise and exposure to air pollution ($PM_{2.5}$) among adults in Taiwan*

Model†	Hazard ratio	*p* value	Hazard ratio‡	*p* value
Main effects of exercise				
Model 1				
Inactive	Reference	–	Reference	–
Moderate exercise	0.79 (0.75–0.82)	< 0.001	0.79 (0.75–0.82)	< 0.001
High exercise	0.59 (0.56–0.61)	< 0.001	0.59 (0.57–0.62)	< 0.001
Test for trend	0.77 (0.75–0.78)	< 0.001	0.77 (0.75–0.79)	< 0.001
Model 2				
Inactive	Reference	–	Reference	–
Moderate exercise	0.84 (0.80–0.88)	< 0.001	0.84 (0.80–0.88)	< 0.001
High exercise	0.65 (0.62–0.68)	< 0.001	0.65 (0.62–0.68)	< 0.001
Test for trend	0.81 (0.79–0.82)	< 0.001	0.81 (0.79–0.83)	< 0.001
Main effects of $PM_{2.5}$ exposure				
Model 1				
Low $PM_{2.5}$	Reference	–	Reference	–
Moderate $PM_{2.5}$	1.03 (0.99–1.08)	0.1	1.02 (0.97–1.06)	0.5
High $PM_{2.5}$	1.14 (1.09–1.19)	< 0.001	1.13 (1.08–1.18)	< 0.001
Test for trend	1.07 (1.05–1.09)	< 0.001	1.06 (1.04–1.09)	< 0.001
Per 10 µg/m³ of exposure	1.26 (1.20–1.31)	< 0.001	1.21 (1.16–1.26)	< 0.001
Model 2				
Low $PM_{2.5}$	Reference	–	Reference	–
Moderate $PM_{2.5}$	1.04 (0.99–1.08)	0.1	1.02 (0.98–1.07)	0.4
High $PM_{2.5}$	1.17 (1.12–1.22)	< 0.001	1.15 (1.10–1.20)	< 0.001
Test for trend	1.08 (1.06–1.10)	< 0.001	1.07 (1.04–1.09)	< 0.001
Per 10 µg/m³ of exposure	1.22 (1.17–1.27)	< 0.001	1.18 (1.14–1.23)	< 0.001

*The tertile cut-off points for exercise volume using the metabolic equivalent (MET) value and duration (h): inactive (0 MET-h), moderate (0 to 8.75 MET-h) and high (> 8.75 MET-h). The tertile cut-off points for $PM_{2.5}$: low (< 22.4 µg/m³), moderate (22.4 to 26.0 µg/m³) and high (≥ 26.0 µg/m³).
†Model 1 adjusted for age, sex and education; Model 2 further adjusted for body mass index, physical labour at work, cigarette smoking, alcohol drinking, vegetable intake, fruit intake, occupational exposure, season, and year of enrolment.
‡Further adjusted for exercise (for the association between $PM_{2.5}$ and death from natural causes) or $PM_{2.5}$ (for the association between exercise and death from natural causes).

Table 3: Associations of death from natural causes with habitual exercise and exposure to air pollution ($PM_{2.5}$) among adults in Taiwan, stratified by categories of $PM_{2.5}$ or habitual exercise*

Model	Hazard ratio	*p* value	Hazard ratio	*p* value	Hazard ratio	*p* value
Stratified by $PM_{2.5}$	**Low $PM_{2.5}$**		**Moderate $PM_{2.5}$**		**High $PM_{2.5}$**	
Inactive	Reference	–	Reference	–	Reference	–
Moderate exercise	0.81 (0.74–0.87)	< 0.001	0.87 (0.81–0.95)	0.001	0.84 (0.78–0.90)	< 0.001
High exercise	0.59 (0.55–0.64)	< 0.001	0.71 (0.65–0.77)	< 0.001	0.67 (0.62–0.72)	< 0.001
Test for trend	0.77 (0.74–0.80)	< 0.001	0.84 (0.81–0.88)	< 0.001	0.82 (0.79–0.85)	< 0.001
Stratified by exercise	**Inactive**		**Moderate exercise**		**High exercise**	
Low $PM_{2.5}$	Reference	–	Reference	–	Reference	–
Moderate $PM_{2.5}$	0.93 (0.86–1.00)	0.04	1.02 (0.94–1.11)	0.7	1.15 (1.07–1.25)	< 0.001
High $PM_{2.5}$	0.99 (0.91–1.07)	0.7	1.13 (1.03–1.24)	0.008	1.34 (1.22–1.47)	< 0.001
Test for trend	0.98 (0.94–1.02)	0.3	1.06 (1.01–1.11)	0.01	1.16 (1.11–1.21)	< 0.001
Per 10 µg/m³	1.06 (1.01–1.11)	0.02	1.10 (1.04–1.16)	0.001	1.44 (1.34–1.55)	< 0.001

*The models fully adjusted for age, sex, educational level, body mass index, physical labour at work, cigarette smoking, alcohol drinking, vegetable intake, fruit intake, occupational exposure, season, and year of enrolment. The tertile cut-off points for exercise volume using the metabolic equivalent (MET) value and duration (h): inactive (MET-h = 0), moderate (MET-h = 0 to 8.75) and high (MET-h > 8.75). The tertile cut-off points for $PM_{2.5}$: low (< 22.4 µg/m³), moderate (22.4 to 26.0 µg/m³) and high (≥ 26.0 µg/m³).

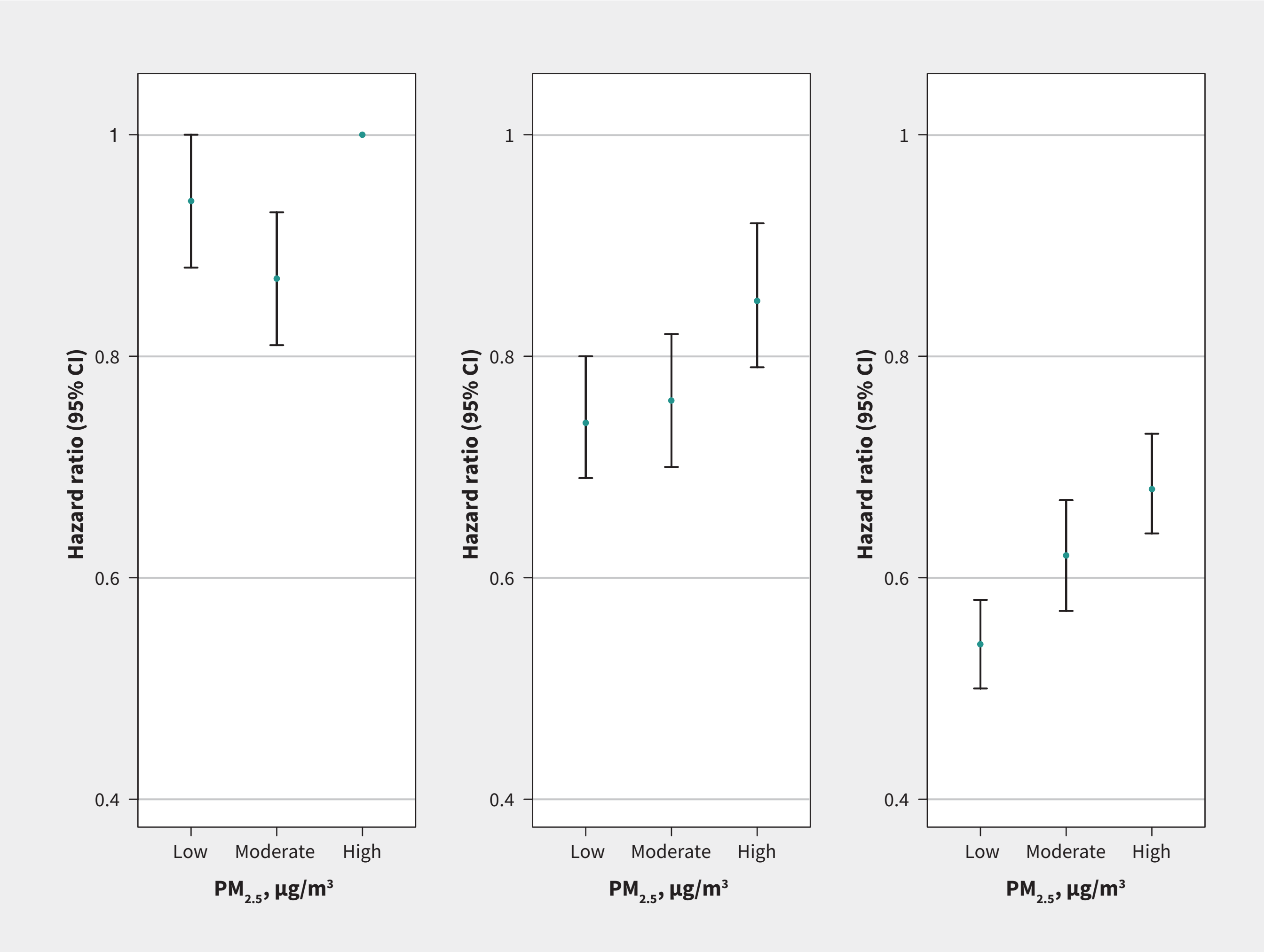

Figure 3: Combined effects of habitual exercise and air pollution (measured by the concentration of fine particle matter, $PM_{2.5}$) on risk of death in adults in Taiwan. Hazard ratios (HRs) with 95% confidence intervals (CIs) show the association of low, moderate or high $PM_{2.5}$ exposure and risk of death among-participants who were (A) inactive, or with (B) moderate or (C) high levels of habitual exercise. Models adjusted for age, sex, education, body mass index, physical labour at work, cigarette smoking, alcohol consumption, vegetable and fruit intake, occupational exposure to dust and solvents, season and year of cohort enrolment. We treated the group of inactive participants with high $PM_{2.5}$ exposure as the reference group. The tertile cut-off points for exercise volume, using the metabolic equivalent (MET) value and duration (h): inactive (0 MET-h), moderate (0 to 8.75 MET-h) and high (> 8.75 MET-h). The tertile cut-off points for $PM_{2.5}$: low (< 22.4 µg/m^3), moderate (22.4 to 26.0 µg/m^3) and high (≥ 26.0 µg/m^3).

Limitations

We did not distinguish between indoor or outdoor habitual exercise. However, 92.7% of Taiwanese residents reported that they preferred outdoor exercise in a national survey in 2017.[39] We used the estimated $PM_{2.5}$ concentrations at participant addresses to indicate the level of exposure during exercise. Although the variation in $PM_{2.5}$ concentrations within a certain area is generally small and most Taiwanese residents have been reported to undertake exercise near their homes,[39] it was difficult to avoid random exposure misclassification, which might attenuate the estimated associations. Similarly, we used the 2-year average concentration as a surrogate measure of $PM_{2.5}$ exposure, which might not be the exact level of exposure during exercise. More advanced technologies are needed for accurate assessment of individual exposure in future studies. Fourth, some participants may have been lost to follow-up if they left Taiwan during the study period. However, only 0.16%–0.28% of people in Taiwan migrated each year during the study period.[40] Therefore, emigration is not expected to bias our main findings. A common limitation of exercise studies is that healthier participants may undertake higher levels of physical activity, and those with health problems may undertake lower levels of physical activity. However, the sensitivity analysis adjusting for the presence of common chronic diseases showed results consistent with our main findings. Participants were enrolled through a paid membership and had relatively high levels of education and economic status, and our study was conducted in a moderately polluted area. Therefore, generalizing results to other populations and regions should be done with caution.

Conclusion

We found that a high level of habitual exercise and a low level of exposure to air pollution was associated with lower risk of death from natural causes, whereas a low level of habitual exercise and a high level of exposure was associated with higher risk of death. Habitual exercise reduces the risk of death regardless of exposure to air pollution, and air pollution generally increases the risk of death regardless of habitual exercise. Thus, habitual exercise should be promoted as a health improvement strategy, even for people residing in relatively polluted areas.

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