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Physical Activity

Benefits of physical activity not affected by air pollution: a prospective cohort study

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Abstract

Background: Physical activity (PA) is beneficial to human health, whereas long-term exposure to air pollution is harmful. However, their combined effects remain unclear. We aimed to estimate the combined (interactive) mortality effects of PA and long-term exposure to fine particulate matter ($PM_{2.5}$) among older adults in Hong Kong.

Methods: Participants aged $\geq$65 years from the Elderly Health Service Cohort ($n = 66\,820$) reported their habitual PA at baseline (1998–2001) and were followed up till 31 December 2011. We used a satellite-based spatiotemporal model to estimate $PM_{2.5}$ concentration at the residential address for each participant. We used Cox proportional hazards regression to assess the interaction between habitual PA and long-term exposure to $PM_{2.5}$ on cardiovascular and respiratory mortality. We tested for additive interaction by estimating relative excess risk due to interaction and multiplicative interaction employing *P*-value for the interaction term.

Results: The death risks were inversely associated with a higher volume of PA and were positively associated with long-term exposure to $PM_{2.5}$. The benefits of PA were more pronounced for participation in traditional Chinese exercise (e.g. Tai Chi) and aerobic exercise (e.g. cycling). We found little evidence of interaction between PA (volume and type) and long-term exposure to $PM_{2.5}$ on either additive or multiplicative scales.

Conclusions: In this cohort of older Chinese adults, PA may decrease the risk of mortality, be it in areas of relatively good or bad air quality. The beneficial mortality effects of habitual PA outweighed the detrimental effects of long-term exposure to air pollution in Hong Kong.

Key words: air pollution, physical activity, cohort study, older

Key Messages

- Moderate to high volume of physical activity is associated with a lower risk of cardiovascular and respiratory mortality.
- Traditional Chinese exercise and aerobic exercise are two recommended types of physical exercise for older adults.
- The long-term benefits of physical activity (volume and type) did not moderate by physical exercise environment of good or bad air quality.
- Physical activity might still be recommended to older adults residing in relatively more polluted areas.

Introduction

Physical inactivity is a significant lifestyle-related risk factor and potentially modifiable.[1] There is convincing evidence that physical activity reduces risks of non-accidental and cardiovascular mortality over a wide age range.[2–5] The global and country-specific physical-activity guidelines recommend people to improve their health through regular physical activity.[6–8]

Air pollution is recognized as the world's largest single environmental risk factor,[9] associated with an elevated risk of cardiopulmonary diseases.[10,11] An estimated 4.2 million deaths globally are attributable to ambient air pollution each year.[12] Due to an increased ventilation rate, the uptake of air pollution during physical activity increases considerably, potentially intensifying the detrimental health effects of air pollution.

It is of significant public health interest to examine the risk–benefit relationship between the health benefits of physical activity and the intensified harmful effects of air pollution during physical activity. Emerging evidence showed that the benefits of physical activity were lost after acute exposure to higher levels of air pollution (temporal changes in air pollution).[13–15] However, evidence on the modification effects of long-term exposure to air pollution (levels of air pollution where people usually perform physical activity) on the health benefits of physical activity is scarce.

To our best knowledge, we identified a total of six related studies, including the Danish Diet, Cancer and Health Cohort,[16–18] the Swiss Cohort Study on Air Pollution and Lung and Heart Diseases,[19] a cohort in Taiwan[20] and a cohort in southern California.[21] These studies were all conducted in countries with relatively good air quality, which may limit the power to assess the modification effects of air pollution on the health benefits of physical activity. No study has been conducted in areas with relatively high air pollution levels.

Hong Kong is one of the world's most populous territories located in the Pearl River Delta area, one of the most polluted areas in China. The annual mean concentration of air pollution in Hong Kong greatly exceeds the World Health Organization (WHO) air quality guidelines.[22] We sought to evaluate the combined mortality effects of habitual physical activity and long-term exposure to air pollution defined by annual concentration of fine particulate matter ($PM_{2.5}$) among ∼70 000 older adults in Hong Kong.

Methods

Study population

The Chinese Elderly Health Service Cohort is a prospective cohort, into which all Hong Kong residents aged ≥65 years were eligible to enrol. From 1998 to 2001, 66 820 elders, about 9% of Hong Kong's older population, enrolled into the 18 Elderly Health Centres of the Department of Health, one in each of the 18 districts, and were followed up till December 2011. A face-to-face interview for each participant was carried out by registered nurses and doctors using a standardized and structured questionnaire.[23,24] The collected information included demographic characteristics (e.g. age and sex), socio-economic status (e.g. education attainment and personal monthly expenditure), lifestyle (e.g. smoking status and alcohol consumption), body mass index (BMI) and pre-existing chronic conditions (e.g. hypertension and cerebrovascular accident). Details of cohort profile and data collection have been published elsewhere.[23,24] Ethics approval was obtained from the Ethics Committee of the Faculty of Medicine, The University of Hong Kong and the Department of Health of Hong Kong.

Definition of physical activity

Physical activity was collected by structured interview using questions regarding types of physical activity, the frequency of physical activity per week and duration per session. Participants were asked to report their most frequently performed type of physical activity, which included walking slowly (level ground), stretching exercise, traditional Chinese exercise (Tai Chi, Pak Tuen Kam and Luk Tung Kuen), aerobic exercise (jogging, cycling, swimming, walking uphill and playing ball games), other types not mentioned above (<3%), and no physical exercise. The frequency of physical exercise was specified as 0–7 or ≥8 times per week, and duration for each session was classified as none (no physical exercise), <30 min and ≥30 min. We used a standard metabolic equivalent of task (MET) value to assign the intensity of each physical-exercise type according to the Ainsworth compendium: <1.0 (never), 2.0 (walking slowly), 2.5 (stretching exercises), 4.0 (traditional Chinese exercise) and 6.0 (aerobic exercise).[25] We then quantified the physical-activity volume of each participant by calculating hours of MET per week (MET-h/wk) based on the reported type, frequency and duration of physical activity. We finally categorized MET-h/wk as <1.0, 1.0–20.9 and ≥21.0.[26] These methods to define physical activity have been used in earlier studies using this cohort to reveal the beneficial effects of physical activity.[26,27]

Prospective follow-up

Participants were followed from the date of recruitment to date of death or 31 December 2011, whichever came first. We used a common unique identifier to link the cohort with the death registration in the Department of Health, which covered all deaths in Hong Kong.[28] We coded deaths according to International Classification of Diseases, 10th revision (ICD-10): cardiovascular cause (I00–I99) and respiratory disease (J00–J47, J80–J99).

Air pollution assessment

We selected $PM_{2.5}$ as a proxy for air pollution exposure since $PM_{2.5}$ is the most commonly used proxy indicator of air pollution.[29] We used a satellite-based spatiotemporal model to estimate the annual concentration of $PM_{2.5}$ at the residential address of each participant between 1998 and 2011, as previously described.[30,31] Briefly, aerosol optical depth (AOD), an indicator of $PM_{2.5}$ concentration in the troposphere, was retrieved from the remote sensing data of the two National Aeronautics and Space Administration (NASA) Earth Observing System satellites.[32] It was initially retrieved at a 10 × 10 km resolution and then refined into 1 × 1 km resolution by modifying the moderate resolution imaging spectroradiometer (MODIS) algorithm.[33] The annual surface extinction coefficients (SEC) from AOD were regressed on the yearly $PM_{2.5}$ concentration measured from the ground-level air monitoring stations using grid cells with both SEC and $PM_{2.5}$ measurements. We then used this calibration to estimate yearly $PM_{2.5}$ concentrations at the geocoded residential addresses for all participants. The estimated $PM_{2.5}$ has been validated and was used to assess the associations of long-term exposure to $PM_{2.5}$ with morbidity[34,35] and mortality[30] in this cohort.

We used the baseline concentration of $PM_{2.5}$ at the residential address of each participant as a proxy for long-term air pollution exposure (Figure 1)[30,34–37] as the temporal trend of $PM_{2.5}$ concentrations did not vary in space in Hong Kong (Supplementary Figure S1, available as Supplementary data at *IJE* online). In sensitivity analyses we also used the average concentrations of $PM_{2.5}$ over the follow-up to define long-term air pollution exposure.

Covariates

Potential confounders were selected according to the literature.[30,34,35] We controlled for individual-level

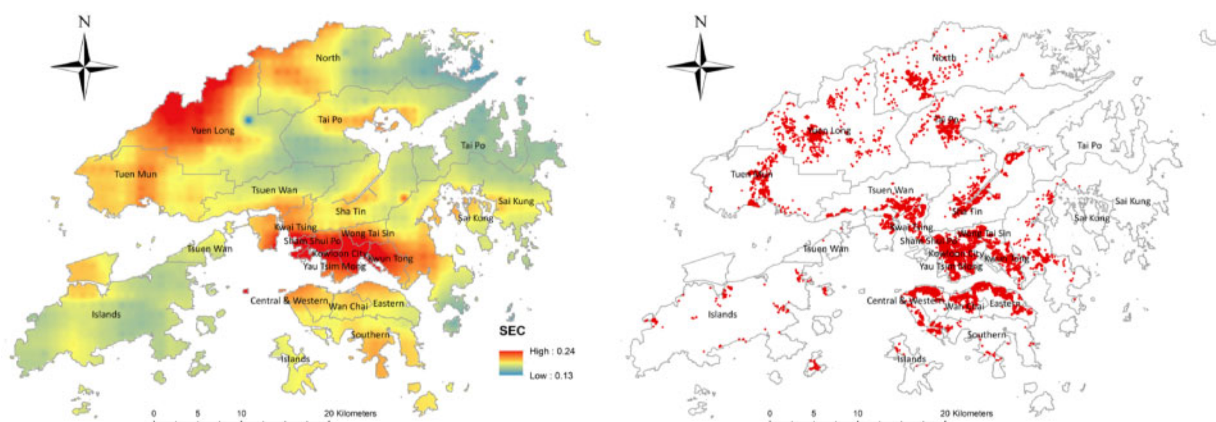

Figure 1. Spatial distribution of air pollution exposure and participants of the Elderly Health Service Cohort in Hong Kong. The left panel shows varying levels of surface extinction coefficients (SEC) indicating the concentrations of fine particulate matter ($PM_{2.5}$) at baseline. The right panel shows the spatial distribution of the Elderly Health Service Cohort participants (n = 58 643).

confounders, including age (strata variable, continuous), sex, BMI (kg/m^2, a natural spline with three degrees of freedom), smoking status, education attainment, personal monthly expenditure, medication taken and pre-existing chronic conditions (hypertension, cerebrovascular accident, heart disease and chronic obstructive pulmonary disease). As a tertiary planning unit (TPU) is the smallest administrative area unit used in the Hong Kong population census report (Supplementary Figure S2, available as Supplementary data at *IJE* online), we also controlled for three TPU-level covariates including % of population aged $\geq$65 years, % with tertiary education and % with income $\geq$\$1923 USD per month. We additionally adjusted for smoking rate among residents >15 years old at the district level.

Statistical analyses

Cox proportional hazards regression with follow-up time as the underlying time scale was used to estimate the associations of physical activity (volume and type) and long-term exposure to $PM_{2.5}$ with cardiovascular and respiratory mortality. To allow for possible non-proportionality of hazard, age in year was treated as a stratification variable. We estimated the hazard ratio (HR) adjusted for individual-, TPU- and district-level confounders as mentioned above.

To investigate whether the beneficial effects of physical activity outweigh the detrimental effects of air pollution, we examined the combined effects of physical activity and air pollution and tested their interaction on both additive and multiplicative scales.

To assess the additive interaction, we first classified participants into those residing in low (lower 50th percentile of exposure range: <35.3 μg/m^3) and high (upper 50th percentile of exposure range: $\geq$35.3 μg/m^3) $PM_{2.5}$ areas. Together with physical-activity volume (<1.0, 1.0–20.9 and $\geq$21.0 MET-h/wk), we then created a new variable with six categories representing six combinations of physical-activity volume and $PM_{2.5}$ exposure. We also created a new variable with ten categories representing ten combinations of exercise types (no exercise, walking slowly, stretching exercise, traditional Chinese exercise and aerobic exercise) and $PM_{2.5}$ exposure.

To test the additive interaction, we calculated the relative excess risk due to interaction (RERI) and the corresponding 95% confidence interval (CI).[38] When calculating RERI, it has been recommended to recode preventive factors to risk factors.[39] In the present study, we recoded physical activity as physical inactivity, and set the highest volume or intensity of physical activity ($\geq$21.0 MET-h/wk or aerobic exercise) and low air pollution as the joint reference group. A RERI of 0 indicates no additive interaction (i.e. the combined excess risk calculated as HR-1 is exactly the sum of their individual excess risks), a RERI >0 indicates positive interaction (i.e. the combined excess risk is more than the sum of their individual excess risks) and a RERI of <0 means negative interaction, or that the combined excess risk is less than the sum of their individual excess risks. A positive RERI value in the present study would indicate that air pollution diminishes the health benefits of physical exercise.

We further evaluated the multiplicative interaction and tested the multiplicative interaction by adding a product term between $PM_{2.5}$ (low and high) and volume (<1.0, 1.0–20.9, and $\geq$21.0 MET-h/wk) or types (no exercise, walking slowly, stretching exercise, traditional Chinese exercise and aerobic exercise) of physical activity. We used likelihood tests to evaluate the product term by comparing the model with and without the interaction term. $P < 0.05$ of the product term indicates a multiplicative interaction.

In the secondary analyses, we conducted stratified analysis to examine whether the additive and multiplicative interaction between physical activity and long-term exposure to $PM_{2.5}$ varied by sex.

We performed a series of sensitivity analyses to confirm the robustness of our findings. First, to check the suitability of baseline $PM_{2.5}$, we used the average concentrations of $PM_{2.5}$ over the follow-up to define long-term exposure to air pollution. Second, to exclude the possibility of reverse causality, we excluded participants who died within the first year after enrolment. Participants who had severe diseases at baseline were prone to be physically inactive. Third, to reduce air pollution exposure misclassification due to participants' movement, we did analyses by excluding participants who moved residence during the follow-up period. Fourth, to be aware of the influence of changing physical activity habits, we stratified participants by baseline pre-existing chronic conditions. Participants with pre-existing diseases are more likely to change their physical activity habits due to their deteriorating health. Fifth, we varied cut-offs defined by percentiles of $PM_{2.5}$ to dichotomize air pollution and refitted the regression models to test the multiplicative interactions. All analyses were two-sided and a P-value < 0.05 was considered as statistically significant. We conducted all analyses in *R* software (version 3.4.3) with 'survival' package (version 2.44–1.1) for survival analysis.

Results

A total of 66 820 older adults were enrolled in the initial study cohort. After excluding 5352 (8.0%) participants due to problems in geocoding or satellite data, 1259

(1.9%) with missing covariates, and 1566 (2.3%) who reported types of physical activities that were listed as others in the questionnaire, a total of 58 643 (87.8%) participants were included in the final analyses (Figure 1). During the follow-up, there were 4600 deaths from cardiovascular disease and 3106 from respiratory disease (Table 1).

The mean age of the 58 643 participants at baseline was 71.9 years old, and ~65.7% of the participants were females. Only 4.4% of the participants were current smokers, about half received primary education or above (54.4%) or took medications regularly (52.9%), and more than one-third (35.9%) had hypertension.

Most participants (80.9%) performed a low to moderate volume of physical activity (1.0–20.9 MET-h/wk). For types of physical exercise, about one-third of participants (38.1%) chose stretching exercise, followed by walking slowly (18.4%), traditional Chinese exercise (17.8%) and aerobic exercise (10.0%). We found males were more likely to participate in activities of walking slowly or aerobic exercise, whereas females were more likely to participate in stretching exercise or traditional Chinese exercise (Table 1).

After adjustment for individual-, TPU- and district-level confounders, the HR per 10 μg/m^3 increase in $PM_{2.5}$ concentration was 1.19 (95% CI: 1.05, 1.35) for cardiovascular and 1.02 (95% CI: 0.87, 1.19) for respiratory mortality. We found elders residing in high $PM_{2.5}$ areas were positively associated with a higher risk of cardiovascular mortality compared with participants residing in low $PM_{2.5}$ areas in the fully adjusted models (Table 2). The elevated risk of mortality associated with $PM_{2.5}$ was also observed across gender (Supplementary Figure S3, available as Supplementary data at *IJE* online).

Participation in a higher volume of physical activity was associated with a lower risk of mortality (Table 2). For example, compared with a low volume of physical activity (<1.0 MET-h/wk), the HR of cardiovascular mortality was 0.91 (95% CI: 0.88, 0.95) and 0.75 (95% CI: 0.68, 0.83) for low to moderate (1.0–20.9 MET-h/wk) and high (≥21 MET-h/wk) volume of physical activity, respectively. We found the beneficial effects of physical activity were more pronounced for aerobic exercise such as jogging and cycling and traditional Chinese exercises such as Tai Chi. We also found suggestive benefits of walking and stretching exercises, although the association did not reach statistical significance. The decreased mortality risk associated with physical activity was more pronounced among females than males (Supplementary Figure S3, available as Supplementary data at *IJE* online).

Table 3 shows the combined effects of physical-activity volume and long-term exposure to $PM_{2.5}$ using the high volume of physical activity (≥21.0 MET-h/wk)–low $PM_{2.5}$ (<35.3 μg/m^3) participants as the reference. The HR of cardiovascular disease for performing a low volume of physical activity (<1.0 MET-h/wk) was 1.46 (95% CI: 1.11, 1.92) in low $PM_{2.5}$ areas (<35.3 μg/m^3) and 1.53 (95% CI: 1.17, 2.00) in high $PM_{2.5}$ areas (≥35.3 μg/m^3), and the corresponding HR for respiratory disease was 1.31 (95% CI: 0.95, 1.82) and 1.50 (95% CI: 1.09, 2.06), respectively. We found little evidence of interaction on either additive or multiplicative scales in overall analysis (Table 3) and gender-specific subgroup analysis (Supplementary Table S1, available as Supplementary data at *IJE* online).

Table 4 represents the combined mortality effects of physical-activity types and long-term exposure to $PM_{2.5}$ using aerobic exercise and low air pollution as the joint reference group. Lower-intensity exercise was associated with a higher risk of mortality irrespective of high or low $PM_{2.5}$ concentrations. For example, compared with the joint reference group, the cardiovascular mortality risk for no exercise was 1.53 (95% CI: 1.27, 1.84) in low $PM_{2.5}$ areas and 1.61 (95% CI: 1.34, 1.92) in high $PM_{2.5}$ areas. We found little evidence of interaction between physical-activity types (no exercise, stretching exercise, traditional Chinese exercise and aerobic exercise) and long-term $PM_{2.5}$ exposure (low and high) on either additive or multiplicative scales, but we found a significant positive RERI [0.301 (95% CI: 0.024, 0.578)] for walking slowly for cardiovascular mortality (Table 4). We also found little evidence of interaction in the subgroup analysis for males or females (Supplementary Table S2, available as Supplementary data at *IJE* online).

Sensitivity analyses excluding participants who died within the first year of follow-up or who moved during the follow-up did not materially change our findings (Supplementary Table S3, available as Supplementary data at *IJE* online). When stratified by pre-existing diseases, participants with and without pre-existing conditions showed similar findings of little evidence of interaction (Supplementary Table S4, available as Supplementary data at *IJE* online). Using the average annual $PM_{2.5}$ concentration over the follow-up to define long-term exposure to air pollution (Supplementary Tables S5 and S6, available as Supplementary data at *IJE* online) or varying cut-off selected by percentile of $PM_{2.5}$ to define low and high air pollution areas did not change our findings of little evidence of interaction between physical activity (volume and type) and long-term exposure to $PM_{2.5}$ (Supplementary Figure S4, available as Supplementary data at *IJE* online).

Discussion

In this large prospective elderly cohort, habitual physical activity was associated with a lower risk of cardiovascular

Table 1. Baseline characteristics of the Elderly Health Service Cohort by sex ($n = 58\,643$)

Personal characteristics	Overall ($n = 58\,643$)	Males ($n = 20\,100$)	Females ($n = 38\,543$)
Physical-activity volume (MET-h/wk), *n* (%)			
<1.0	9233 (15.7)	3422 (17.0)	5811 (15.1)
1.0–20.9	47 453 (80.9)	15 721 (78.2)	31 732 (82.3)
≥21.0	1957 (3.3)	957 (4.8)	1000 (2.6)
Physical-activity type, *n* (%)			
No exercise	9233 (15.7)	3422 (17.0)	5811 (15.1)
Walking slowly	10 800 (18.4)	5064 (25.2)	5736 (14.9)
Stretching exercise	22 335 (38.1)	6324 (31.5)	16 011 (41.5)
TCE	10 423 (17.8)	2220 (11.0)	8203 (21.3)
Aerobic exercise	5852 (10.0)	3070 (15.3)	2782 (7.2)
$PM_{2.5}$ level, $\mu g/m^3$, *n* (%)			
Low (<35.3)	29 139 (49.7)	9970 (49.6)	19 169 (49.7)
High (≥35.3)	29 504 (50.3)	10 130 (50.4)	19 374 (50.3)
Individual covariates			
Age at cohort entry, years, mean (SD)	71.9 (5.5)	72.0 (5.3)	71.9 (5.6)
BMI quartile (kg/m^2), *n* (%)			
1st (< 21.6)	13 466 (23)	4895 (24.4)	8571 (22.2)
2nd–3rd (21.6-26.3)	29 783 (50.8)	10 765 (53.6)	19 018 (49.3)
4th (> 26.3)	15 394 (26.3)	4440 (22.1)	10 954 (28.4)
Smoking status, *n* (%)			
Never	41 709 (71.1)	7706 (38.3)	34 003 (88.2)
Quit	8589 (14.6)	6181 (30.8)	2408 (6.2)
Current	2582 (4.4)	1812 (9.0)	770 (2.0)
Occasional	5763 (9.8)	4401 (21.9)	1362 (3.5)
Education attainment, *n* (%)			
≥Secondary	10 082 (17.2)	6172 (30.7)	3910 (10.1)
Primary	21 804 (37.2)	10 341 (51.4)	11 463 (29.7)
<Primary	26 757 (45.6)	3587 (17.8)	23 170 (60.1)
Expenses per month (US$), *n* (%)			
<128	8610 (14.7)	2317 (11.5)	6293 (16.3)
128–384	40 508 (69.1)	13 699 (68.2)	26 809 (69.6)
≥385	9525 (16.2)	4084 (20.3)	5441 (14.1)
Medication taken regularly, *n* (%)			
Yes	31 027 (52.9)	10 457 (52.0)	20 570 (53.4)
No	27 616 (47.1)	9643 (48.0)	17 973 (46.6)
Pre-existing chronic conditions, *n* (%)			
Hypertension			
Yes	21 039 (35.9)	6871 (34.2)	14 168 (36.8)
No	37 604 (64.1)	13 229 (65.8)	24 375 (63.2)
Diabetes			
Yes	7185 (12.3)	2375 (11.8)	4810 (12.5)
No	51 458 (87.7)	17 725 (88.2)	33 733 (87.5)
Heart disease			
Yes	7199 (12.3)	2320 (11.5)	4879 (12.7)
No	51 444 (87.7)	17 780 (88.5)	33 664 (87.3)
Cerebrovascular accident			
Yes	1714 (2.9)	755 (3.8)	959 (2.5)
No	56 929 (97.1)	19 345 (96.2)	37 584 (97.5)
TPU level covariates, mean (SD)			
% of population aged ≥65 years	12.1 (4.2)	12.2 (4.2)	12.1 (4.2)
% with tertiary education	13.1 (8.0)	13.2 (8.0)	13.0 (8.0)
% with income ≥$1923 USD per month	59.6 (11.6)	59.7 (11.5)	59.5 (11.6)
District level covariates, mean (SD)			
Smoking rate	11.6 (0.4)	11.5 (0.4)	11.6 (0.4)

SD, standard deviation; BMI, body mass index; $PM_{2.5}$, particles with aerodynamic diameter ≤2.5 μm; TPU, tertiary planning unit; TCE, traditional Chinese exercise; MET-h/wk, hours of metabolic equivalent of task per week.

Table 2. Hazard ratio (HR) and 95% confidence interval (CI) of mortality associated with the volume and type of physical activity and long-term exposure to fine particulate matter air pollution in the Elderly Health Services Cohort ($n = 58\,643$)[a]

Category	Cardiovascular ($n = 4600$)	Respiratory ($n = 3106$)
$PM_{2.5}$ level ($\mu g/m^3$)		
Low [<35.3]	1.00 [Reference]	1.00 [Reference]
High [≥35.3]	1.07 (1.01, 1.14)	1.02 (0.95, 1.10)
Continuous (per 10$\mu g/m^3$)	1.19 (1.05, 1.35)	1.02 (0.87, 1.19)
Physical-activity volume (MET-h/wk)		
<1.0	1.00 [Reference]	1.00 [Reference]
1.0-20.9	0.91 (0.88, 0.95)	0.89 (0.82, 0.97)
≥21	0.75 (0.68, 0.83)	0.65 (0.54, 0.79)
Physical-activity type		
No exercise	1.00 [Reference]	1.00 [Reference]
Walking slowly	0.98 (0.93, 1.03)	1.00 (0.90, 1.10)
Stretching exercise	0.98 (0.94, 1.03)	0.95 (0.87, 1.03)
TCE	0.76 (0.72, 0.81)	0.73 (0.66, 0.81)
Aerobic exercise	0.71 (0.67, 0.76)	0.64 (0.56, 0.73)

[a]Models were adjusted for age, sex, body mass index, smoking status, alcohol consumption, education attainment, medication taken, pre-existing chronic conditions (hypertension, heart disease, chronic obstructive pulmonary disease or cerebrovascular accident), personal monthly expenditure, the tertiary planning unit level covariates (including % of population aged ≥65 years, % with tertiary education and % with income ≥$1923 USD per month) and smoking rate at district level.

$PM_{2.5}$, particles with aerodynamic diameter ≤2.5 μm; TCE, traditional Chinese exercise; MET-h/wk, hours of metabolic equivalent of task per week.

and respiratory mortality. The beneficial effects of habitual physical activity were more pronounced for a higher volume of physical activity or higher-intensity exercise like traditional Chinese exercise or aerobic exercise. Long-term exposure to $PM_{2.5}$ was associated with a higher risk of mortality. We found little evidence of interaction between habitual physical activity (volume and type) and long-term exposure to $PM_{2.5}$ in either additive or multiplicative models, which suggest that the benefits of habitual physical activity outweigh the amplified detrimental effects of air pollution among older adults in Hong Kong.

Our findings of decreased mortality risks associated with physical activity are consistent with numerous cohort studies.[5,40] A recent systematic review and meta-analysis summarized 33 cohort studies with a total of 883 372 participants and reported that physical exercise was associated with a 35% (95% CI: 30%, 40%) lower risk of cardiovascular mortality and 33% (95% CI: 28%, 37%) lower risk of all-cause mortality.[5] A recent multi-country cohort study with ~130 000 participants from 17 low-, middle- and high-income countries found that the protective effects of physical activity were consistently observed among countries with different economic levels.[41] We found the health benefits of physical activity were more pronounced among females than males, which was also consistent with previous studies.[5,41]

We found long-term exposure to $PM_{2.5}$ was associated with a higher risk of cardiovascular mortality, which corroborates the evidence of a positive association between long-term exposure to $PM_{2.5}$ and mortality.[42,43] We found that each 10 $\mu g/m^3$ increase in $PM_{2.5}$ was associated with an HR of 1.19 (95% CI: 1.05, 1.35) for cardiovascular mortality, which was similar to most previous studies.[44,45]

A few studies have investigated the interaction between acute or intermediary exposure to air pollution and physical activity, but findings are mixed.[13–15,46–50] Some studies reported that the health benefits from physical exercise were lost on high air pollution days.[13–15] For example, lung function of asthma patients decreased after walking on a polluted street in London for only 2 h.[14] A randomized crossover study among 135 participants in UK also found that acute exposure to traffic-related air pollutants diminished the beneficial cardiopulmonary effects of walking for participants with or without chronic cardiopulmonary diseases.[13] On the other hand, a few other studies found no evidence of cancellation of physical activity benefits by acute or intermediary air pollution exposure.[48–50] For example, a panel study of 122 healthy adults in three European cities (Antwerp, Barcelona and London) reported no evidence of modification effects of short-term or intermediary exposure to black carbon on the benefits of physical activity on blood pressure[49] and subclinical cardiovascular disease (heart rate variability and retinal vessel diameters).[48] Although acute effects of air pollution studies provide a useful context, our findings of the cumulative interaction between physical activity and long-term exposure to air pollution are not directly comparable with the short-term or intermediary exposure studies that assess the acute interplay between physical activity and air pollution.

Our findings of the combined relationships between habitual physical activity and long-term exposure to air pollution are novel. To our knowledge, we only identified six related epidemiologic studies,[16–21] and these studies were all conducted in relatively good air quality areas. Consistent with the mortality study,[17] we also found little evidence of interaction between habitual physical activity and long-term exposure to air pollution. Our findings were also consistent with a health-impact modelling study that tested the risk–benefit balance between physical activity and background $PM_{2.5}$ concentration, and that study found that the health benefits of physical activity generally outweighed the harmful effects of air pollution except in the most extreme air pollution scenario.[51] We found some evidence that the cardiovascular benefits of walking were reduced in more polluted areas, which was consistent with the randomized crossover study.[13] Although the exact

Table 3. The combined mortality effects of physical-activity volume and long-term exposure to fine particulate matter in the Elderly Health Service Cohort ($n = 58\,643$)[a]

	Low $PM_{2.5}$ (<35.3 $\mu g/m^3$)	High $PM_{2.5}$ (≥35.3 $\mu g/m^3$)	RERI	P-value for interaction
Cardiovascular				
Physical-activity volume (MET-h/wk)				0.77
≥21.0	1.00 [Reference]	0.95 (0.66, 1.36)		
1.0–20.9	1.29 (1.00, 1.66)	1.39 (1.08, 1.79)	0.149 (−0.187, 0.485)	
<1.0	1.46 (1.11, 1.92)	1.53 (1.17, 2.00)	0.122 (−0.272, 0.515)	
Respiratory				
Physical-activity volume (MET-h/wk)				0.16
≥21.0	1.00 [Reference]	0.74 (0.47, 1.18)		
1.0–20.9	1.29 (0.95, 1.75)	1.30 (0.96, 1.76)	0.266 (−0.089, 0.622)	
<1.0	1.31 (0.95, 1.82)	1.50 (1.09, 2.06)	0.446 (0.056, 0.836)	

[a]Models were adjusted for age, sex, body mass index, smoking status, alcohol consumption, education attainment, medication taken, pre-existing chronic conditions (hypertension, heart disease, chronic obstructive pulmonary disease or cerebrovascular accident), personal monthly expenditure, the tertiary planning unit level covariates (including % of population aged ≥65 years, % with tertiary education and % with income ≥$1923 USD per month) and smoking rate at district level.

$PM_{2.5}$, particles with aerodynamic diameter ≤2.5 μm; MET-h/wk, hours of metabolic equivalent of task per week; RERI, relative excess risk due to interaction.

Table 4. The combined mortality effects of physical-activity type and long-term exposure to fine particulate matter in the Elderly Health Service Cohort ($n = 58\,643$)[a]

	Low $PM_{2.5}$ (<35.3 $\mu g/m^3$)	High $PM_{2.5}$ (≥35.3 $\mu g/m^3$)	RERI	P-value for interaction
Cardiovascular				
Physical-activity type				0.16
Aerobic exercise	1.00 [Reference]	1.02 (0.81, 1.27)		
TCE	1.17 (0.97, 1.41)	1.13 (0.93, 1.36)	−0.061 (−0.351, 0.229)	
Stretching exercise	1.45 (1.23, 1.71)	1.53 (1.29, 1.80)	0.065 (−0.190, 0.321)	
Walking slowly	1.41 (1.18, 1.68)	1.73 (1.45, 2.06)	0.301 (0.024, 0.578)	
No exercise	1.53 (1.27, 1.84)	1.61 (1.34, 1.92)	0.063 (−0.092, 0.219)	
Respiratory				
Physical-activity type				0.60
Aerobic exercise	1.00 [Reference]	0.94 (0.71, 1.24)		
TCE	1.01 (0.79, 1.28)	1.08 (0.86, 1.37)	0.134 (−0.197, 0.465)	
Stretching exercise	1.54 (1.26, 1.88)	1.53 (1.25, 1.87)	0.046 (−0.264, 0.356)	
Walking slowly	1.48 (1.20, 1.83)	1.48 (1.20, 1.84)	0.061 (−0.279, 0.401)	
No exercise	1.41 (1.12, 1.76)	1.61 (1.30, 2.00)	0.267 (−0.080, 0.615)	

[a]Models were adjusted for age, sex, body mass index, smoking status, alcohol consumption, education attainment, medication taken, pre-existing chronic conditions (hypertension, heart disease, chronic obstructive pulmonary disease or cerebrovascular accident), personal monthly expenditure, the tertiary planning unit level covariates (including % of population aged ≥65 years, % with tertiary education and % with income ≥$1923 USD per month), and smoking rate at district level.

$PM_{2.5}$, particles with aerodynamic diameter ≤2.5 μm; TCE, traditional Chinese exercise; RERI, relative excess risk due to interaction.

reasons for the general protective effects of physical activity on mortality regardless of different $PM_{2.5}$ concentrations have not been elucidated, one potential hypothesis is that the additional inhaled air pollutants due to physical activity only account for a small fraction of the total inhaled air pollutants.[52] It is also possible that the long-term health benefits of habitual physical activity may reverse the acute adverse mortality effects associated with exposure to higher levels of air pollution during physical activity.[17]

Our findings should be interpreted with caution. First, we did not collect information on whether participants performed physical activity indoors or outdoors. However, a territory-wide survey among the elderly in Hong Kong found that up to 85% of their physical activity was performed outdoors.[53] Second, we assessed habits of physical activity at baseline. Changing physical activity habits during the follow-up might influence our results. However, we conducted a series of sensitivity analyses by excluding participants who died within the first year of follow-up or stratifying by pre-existing chronic conditions. Results of these sensitivity analyses suggest that changing habits of physical activity during the follow-up would not influence our findings significantly. Third, we used SEC from AOD within 1 km of ground level to predict concentrations of $PM_{2.5}$. Due to the high population density in Hong Kong, $PM_{2.5}$ maps of higher resolution will be needed in future studies to better differentiate the $PM_{2.5}$ exposure among participants. Fourth, we used $PM_{2.5}$ concentration at residential address as a proxy of long-term air pollution exposure encountered during physical activity. This should work well for this cohort of older participants, as it is reasonable to assume that most of them perform physical activity near their residences.[54] Last but not least, our study is based on a cohort of Chinese older adults (mean age of ~72 years at baseline). Results of this study may not be generalizable to younger populations or populations in other countries.

On the other hand, our study is one of the few studies to evaluate the combined mortality effects of habitual physical activity (volume and type) and long-term exposure to air pollution. Our findings add to the scarce evidence of the risk–benefit relationship between long-term health benefits of habitual physical activity and air pollution. Furthermore, our analyses were conducted in Hong Kong (annual mean concentration of $PM_{2.5}$ among study participants was ~35μg/m^3), a top 20% most polluted city globally, where levels of air pollution greatly exceed the WHO air quality guidelines (10 μg/m^3). Thus, findings of this study should provide a more comprehensive picture of the combined effects of habitual physical activity and long-term air pollution exposure.

Conclusions

In this cohort of Chinese older adults, we found little evidence of the modification effects of long-term exposure to air pollution on the benefits of physical activity on mortality. The beneficial effects of habitual physical activity outweigh the mortality risk associated with air pollution. Findings of this study may support current guidelines on promoting physical activity for disease prevention even for people residing in relatively more polluted areas. Additional studies in higher air pollution areas or among a younger population are still needed to confirm or refute these findings.

Supplementary data

Supplementary data are available at *IJE* online.

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