Association of short-term exposure to air pollution with mortality in a middle eastern tourist city

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Received: 7 April 2020 / Accepted: 7 July 2020 / Published online: 17 July 2020
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Abstract

This study investigated the association of short-term exposure to PM₁₀, PM_{2.5}, NO₂, O₃, and CO with daily all-cause, cardiovascular, ischemic heart disease (IHD), cerebrovascular, and respiratory deaths in Mashhad, a tourist megacity in Iran (2014–2018). A distributed-lag-day, nonlinear model (DLNM) and generalized additive model (GAM) based on the quasi-Poisson distribution were used to explore the exposure-lag-day-response associations. The average ($\pm$ standard deviation) concentrations of PM₁₀, PM_{2.5}, NO₂, O₃, and CO were 67.1 ($\pm$ 35.5), 29.6 ($\pm$ 14.2), 57.3 ($\pm$ 24.1), 55.9 ($\pm$ 16.9), and 1907.6 ($\pm$ 1362.7) $\mu\text{g}/\text{m}^3$, respectively. NO₂ was associated with IHD mortality in lag-days 0 to 0–7, and lag-day 1. The relative risks (RRs) for a 10 $\mu\text{g}/\text{m}^3$ increase in NO₂ ranged from 1.01 (95% CI 0.93, 1.11) at lag-day 0 to 1.04 (95% CI 0.94, 1.16) and 1.03 (95% CI 0.93, 1.14) for lag-day 0–1 (cumulative) and lag-day 1 (non-cumulative), respectively. For all-cause mortality, cumulative exposure to PM_{2.5} for lag-day 0–7 (1.07, 95% CI 1.00, 1.15) and non-cumulative exposure to NO₂ at lag-day 6 (1.02, 95% CI 1.00, 1.03) were significant. Exposure to PM₁₀ (per 10 $\mu\text{g}/\text{m}^3$) was significantly associated with respiratory mortality at several lag-days. Adjusting for Ramadan did not significantly affect the results. PM₁₀ had significant associations with respiratory mortality of people > 65 years old, and men for several lag-days. For IHD, NO₂ affected older people, and men and women over different lag-days. Results of multi-pollutant models were similar to the single-pollutant model outcomes. In conclusion, NO₂ and PM₁₀ had more significant relationships with adverse health outcomes than the other pollutants.

Keywords Particulate matter · Particles · Outdoor air pollution · Health · Mashhad

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s11869-020-00875-x>) contains supplementary material, which is available to authorized users.

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Introduction

Outdoor air pollution is known to be an important risk factor for human health. About 4.2 million annual deaths have been attributed to exposure to particulate matter worldwide (WHO 2014). Short- and long-term exposure to particulate matter (PM₁₀ and PM_{2.5}) and gaseous pollutants such as nitrogen dioxide (NO₂), ozone (O₃), and carbon monoxide (CO) have been associated with various health outcomes such as cardiovascular, cerebrovascular, and respiratory mortality and morbidity (Moolgavkar et al. 2013; Nabizadeh et al. 2019; R. Chen et al. 2014). Short-term high exposures from pollution peaks affect daily mortality on the same day or the next few days through their lag-day effects (Liu et al. 2019).

The associations between acute exposure to air pollution and adverse health outcomes have been increasingly reported during recent years (Nabizadeh et al. 2019). Many studies have been performed in most of the world, but especially in Western Europe, Northern America, and China. A study in 38 Chinese large cities found that PM₁₀ exposure was significantly associated with daily mortality with lag-days of up to 2 days (Yin et al. 2017). In another study in 10 US cities, 7-day and 2-day averages of PM₁₀ were associated with respiratory and cardiovascular health outcomes, including pneumonia (relative risk (RR) = 2.7% on average), chronic obstructive pulmonary disease (1.7%), all cardiovascular diseases (1.0%), and myocardial infarction (0.7%) (Braga et al. 2001). In a systematic review by Atkinson et al. (2014), 110 time-series studies investigating the daily mortality and hospitalization were identified through 2011. The overall results of meta-analysis showed that a 10 µg/m³ increase in PM_{2.5} was associated with an average of 1.04% increase in the number of deaths (Atkinson et al. 2014). In a more comprehensive study, Liu et al. (2019) considered 652 cities worldwide to investigate the effect of short-term exposure to particles. Cumulative 2-day exposure to PM₁₀ increased all cause, cardiovascular, and respiratory mortality by 44%, 0.36%, and 0.47%, respectively. The corresponding percentages for PM_{2.5} were 0.68%, 0.55%, and 0.74%, respectively (Liu et al. 2019). However, the authors found that the risks varied substantially by region, indicating the effects of differing population vulnerability and/or differential toxicity of sources, pollutant mixtures, and pollution monitoring (Atkinson et al. 2014).

Air pollution exposure-response associations have been shown to vary by geographical location and different PM compositions (Mohseni Bandpi et al. 2016) with potentially different shapes for the exposure-response curve, and differing effect modifications (Croft et al. 2019; Hopke et al. 2019; Rich et al. 2019). As these factors change geographically and temporally, new analyses in various urban areas can bring additional insights into our current knowledge and understanding about the association between different air pollutants and different health outcomes. In addition, very limited

relevant evidence has been published for Iranian cities where high concentrations of air pollutants are normally monitored relative to many other parts of the world (Hadei et al. 2018; Ghorbani et al. 2017; Ghorbani et al. 2019). One of the typical limitations of assessing the impacts of air pollution is the lack of locally relevant relative risk (RR) values. This work will provide RR values for a number of important health outcomes and those will help provide more accurate air pollution health assessments in other locations in the region. The present study investigated the association of short-term exposure to PM₁₀, PM_{2.5}, NO₂, O₃, and CO with all cause, total cardiovascular, ischemic heart disease (IHD), total cerebrovascular, and total respiratory deaths in Mashhad Iran during 2014–2018.

Methods

Study area

Mashhad is located in northeastern Iran (36°18'N 59°36'E) and has a population about 3 million people. Due to its touristic attractions, millions of people visit this city every year contributing to emission of significant amounts of traffic-related air pollution. In addition, industrial emissions are another major influence on air quality. In this study, we investigated the associations between short-term exposure to PM₁₀, PM_{2.5}, NO₂, O₃, and CO and daily cause-specific mortality in Mashhad. The study period was from March 2014 to March 2018.

Exposure assessment

Hourly concentrations of PM₁₀, PM_{2.5}, NO₂, O₃, and CO were acquired from Department of Environment of Iran. Only data from monitoring stations were included that had at least 75% of hourly concentrations available. In cases where only one station remained, a criterion of at least 50% were chosen for better estimation of population exposure. The final number of monitors after validation was as follows: PM₁₀ 11, PM_{2.5} 12, NO₂ 11, O₃ 1, and CO 13. Except for O₃, 24-h averages were calculated for other pollutants. For O₃, maximum 8-h moving averages were calculated for each day. In addition, daily mean values of air temperature and relative humidity were calculated from data acquired from Meteorological Organization of Iran.

Health outcomes

The health outcomes considered in this study included: all non-accidental causes of mortality (ICD-10 A00–R99), respiratory diseases (ICD-10 J00–J99), cerebrovascular diseases (ICD-10 I60–I69), ischemic heart disease (IHD, ICD-10 I20–I25), and cardiovascular diseases (ICD-10 I00–I99). The daily

number of deaths for each outcome was obtained from the Ministry of Health and Medical Education of Iran. For all outcomes, the mortality data were categorized in three age groups < 16 years old, 16–65 years old, and > 65 years old.

Statistical analysis

Due to the non-linear nature of relationship between outdoor air pollution and health, we used a distributed-lag, nonlinear model (DLNM), and a generalized additive model (GAM) based on the quasi-Poisson distribution to explore the exposure-lag-response associations (Guo et al. 2017). We used a single-pollutant model with adjustments for meteorological and time variables.

First, separate cross-basis functions were created for each pollutant and temperature. Then, a basic model was constructed using the defined cross-basis functions, day of week (DOW) as an indicator variable, a dummy variable to control for holidays, a natural spline function of “time” to control for long-term trends ($n = 1, 2, 3, \dots, 1462$), and a natural spline function for relative humidity. The following general equation was the result:

$$\begin{aligned} \text{Log}(E(\mu_t))\alpha + \beta^* \text{pollutant} + \gamma^* \text{Temperature} \\ + \text{ns}(\text{Time}, \text{df}_1) + \text{ns}(\text{Relative humidity}, \text{df}_2) \\ + \delta^* \text{DOW} + \varepsilon^* \text{Holiday} \end{aligned} \quad (1)$$

Where (μ_t) is the expected number of deaths in day t . Pollutant and temperature are the cross-basis functions defined in the previous step. β and γ are the regression coefficients and are the concentration—mortality rates associated with a unit increase in the levels of air pollutant and temperature, respectively. df_1 and df_2 are the degrees of freedom for time and relative humidity natural spline functions. δ and ε are the regression coefficients for the day of week (DOW) and holiday variables.

In the next step, the degrees of freedom for the concentrations/values and lag-days of the air pollutant and temperature in cross-basis functions and the degree of freedom for relative humidity variable in basic model were determined. To this, a trial and error approach was used to select the mentioned degrees of freedom from a range of 1 to 7 based on the minimum quasi-Akaike's information criterion (Q-AIC). In this trial and error, to determine the df values, PM_{10} and all-cause mortality were entered into the model. A range of 1–7 was assigned for each df. The model was run for every possibility of df values, and finally, the minimum Q-AIC was found to be 9602. The assigned dfs for concentrations and lag-days of PM_{10} were 4 and 3, for values and lag-days of temperature were 5 and 5, and for relative humidity was 3. These degrees of freedom were used in all other models.

In the final stage, to explore the lag-day-effect, up to a 7-day lag-day was selected for both cumulative and non-cumulative exposures. In this context, non-cumulative refers to the examining the effect of exposure on day 0 to lag-day n . Cumulative refers to examining the effect of average concentration during 0- n days for lag-day 0- n . Only one pollutant was entered to the model at the time (single-pollutant), and the association was adjusted for temperature, relative humidity, long-term trends, holiday, and day of week.

Given that the mortality rate can change during the Ramadan (Abazid et al. 2018; Zimhony et al. 2018), another model was developed to adjust for the effect of this month. In this model that was similar to the main model, only a binary (0 and 1) variable of not-Ramadan or Ramadan were introduced to control for the possible effect of any changes in mortality rate. Sub-group analyses were also conducted for different age groups. The relative risks (RRs) were estimated for a $10 \mu\text{g}/\text{m}^3$ increase in PM_{10} , $\text{PM}_{2.5}$, and NO_2 , a $1000 \mu\text{g}/\text{m}^3$ increase in CO, and also a $10 \mu\text{g}/\text{m}^3$ increase in O_3 with a threshold of $70 \mu\text{g}/\text{m}^3$. In addition, a multi-pollutant model was developed with the simultaneous presence of $\text{PM}_{2.5}$ and NO_2 to explore their effect on all-cause and IHD mortality.

All analyses were performed using R software (version 3.3.3) and the *dlm* package. The RRs were reported at the 95% confidence level.

Results

The relationships between exposure to five criteria air pollutants (PM_{10} , $\text{PM}_{2.5}$, NO_2 , O_3 , and CO) and all-non-accidental cause and cause-specific mortality with lag-days up to 7 days were investigated. The descriptive statistics for the air pollutants concentrations, daily number of deaths, and daily meteorological parameter values are presented in Table 1. During the study period, 57,235 deaths due to all non-accidental causes have been recorded, of which 33.4% ($n = 19,134$) and 9.2% ($n = 5290$) were from cardiovascular and respiratory diseases, respectively. The average ($\pm$ standard deviation) concentrations of PM_{10} , $\text{PM}_{2.5}$, NO_2 , O_3 , and CO were $67.1 (\pm 35.5)$, $29.6 (\pm 14.2)$, $57.3 (\pm 24.1)$, $55.9 (\pm 16.9)$, and $1907.6 (\pm 1362.7) \mu\text{g}/\text{m}^3$, respectively.

Figures 1 and 2 illustrate the results for the associations between cumulative and non-cumulative exposure to particulate matter and gaseous pollutants and IHD mortality. In Fig. 1, same-day exposure to $10 \mu\text{g}/\text{m}^3$ increases in PM_{10} and $\text{PM}_{2.5}$ concentrations showed inconsistent and imprecise associations with daily IHD death with the RRs of 1.01 (95% CI 0.98, 1.03) and 1.03 (95% CI 0.96, 1.10), respectively. In fact, none of the RRs for the IHD-PM relationship was statistically significant. On lag-day 7, the RRs for PM_{10} and $\text{PM}_{2.5}$ were 1.01 (95% CI 0.99, 1.03) and 1.03 (95% CI 0.97, 1.10),

Table 1 Descriptive statistics of mortality, air pollution, and meteorological variables

Variable	Unit	Sum	Mean daily	SD	Minimum	Q1	Median	Q3	Maximum
Mortality									
All cause	N	57,234	39.2	8.7	13.0	33.0	38.0	45.0	95.0
Respiratory	N	5290	3.6	2.4	0.0	2.0	3.0	5.0	15.0
Cardiovascular	N	19,134	13.1	4.4	2.0	10.0	13.0	16.0	32.0
Cerebrovascular	N	3988	2.7	1.8	0.0	1.0	2.0	4.0	10.0
IHD	N	5998	4.1	2.3	0.0	2.0	4.0	5.0	17.0
Air pollution									
PM ₁₀	µg/m ³	-	67.1	35.5	7.1	43.7	59.3	82.6	418.4
PM _{2.5}	µg/m ³	-	29.6	14.2	4.9	19.6	27.0	36.1	115.1
NO ₂	µg/m ³	-	57.3	24.1	14.5	38.2	50.5	74.1	141.5
O ₃	µg/m ³	-	55.9	16.9	7.2	43.7	56.5	68.2	105.8
CO	µg/m ³	-	1908	1363	713	1426	1685	1977	5355
Meteorological									
Temperature	°C	-	16.4	9.8	-7.0	7.7	16.8	25.4	34.7
Relative humidity	%	-	55.2	12.6	15.0	31.1	55.9	70.4	86.8

respectively, higher than the values for the previous days. For both PM₁₀ and PM_{2.5}, the trend for non-cumulative exposure was decreasing from lag-day 1 to lag-day 3, and then increased up to lag-day 7.

For NO₂, cumulative exposure at all lag-days and non-cumulative exposure at lag-day 1 were significantly associated with the daily mortality of IHD (Fig. 2a, b). The response to the cumulative exposure to 10 µg/m³ NO₂ increased from 1.12 (95% CI 1.03, 1.23) for the same day to 1.34 (95% CI 1.07, 1.68) for lag-day 0–7. An inverse trend was observed in case of non-cumulative exposure to NO₂, starting from 1.08 (95% CI 1.03, 1.13) for the lag-day 1 and decreasing to 1.01 (95% CI 0.94, 1.09) for the lag-day 7. However, all estimates were positive.

No statistically significant associations were found between 10 µg/m³ increase in ozone and IHD mortality (Fig. 2c, d). The association increased from 1.01 (95% CI 0.93, 1.11) on lag-day 0 to 1.04 (95% CI 0.94, 1.16) and 1.03 (95% CI 0.93, 1.14) for the lag-day 0–1 (cumulative) and lag-day 1 (non-cumulative), respectively. An inconsistency was observed in the trends, particularly in the case of lag-day 2 and lag-day 0–2. The overall trend of the lag-day-response relationship decreased.

For carbon monoxide (CO), the relationships with daily IHD mortality were not significant for both cumulative and non-cumulative exposures (Fig. 2e, f). Per 1000 µg/m³ increase in CO concentrations, RRs in the lag-day 0, lag-day 1, and lag-day 0–1 were 0.99 (95% CI 0.92, 1.06), 0.99 (95% CI 0.95, 1.03), and 0.98 (95% CI 0.88, 1.09), respectively. On lag-day 4 to lag-day 7, increases in CO concentrations were associated with IHD mortality, but the RRs were not statistically significant.

Tables 2 and 3 present the results for the association between non-cumulative and cumulative exposures to 10 µg/m³ PM₁₀, PM_{2.5}, NO₂, O₃, and 1000 µg/m³ CO and cause-specific mortality including death due to all causes, respiratory diseases, cardiovascular diseases, and cerebrovascular diseases. All the associations between cumulative and non-cumulative exposure to each of the pollutants and health outcomes were positive, but only a few were statistically significant. For all-cause mortality, cumulative exposure to PM_{2.5} on lag-day 0–7 (1.07, 95% CI 1.00, 1.15) and non-cumulative exposure to NO₂ on lag-day 6 (1.02, 95% CI 1.00, 1.03) were significant.

Exposure to PM₁₀ (per 10 µg/m³ increase) was significantly associated to respiratory mortality on lag-day 1, lag-day 5, lag-day 6, lag-day 7 (non-cumulative), and lag-days 0–2 to 0–7 (cumulative). The RRs increased from 1.01 (95% CI 1.00, 1.03) in lag-day 1 to 1.02 (95% CI 1.00, 1.04) in lag-day 7, and from 1.04 (95% CI 1.00, 1.09) in lag-day 0–2 to 1.12 (95% CI 1.05, 1.20) in lag-day 0–7. Other pollutants did not show any significant associations with daily respiratory mortality.

A 10 µg/m³ increase in ozone concentrations was significantly associated with daily deaths from cardiovascular diseases on lag-day 3 (1.08, 95% CI 1.02, 1.15). PM₁₀ in lag-day 4, ozone in lag-day 3, and CO in lag-day 2 had significant relationships with cerebrovascular mortality with RRs of 1.01 (95% CI 1.00, 1.03), 1.17 (95% CI 1.05, 1.31), and 1.05 (95% CI 1.00, 1.10), respectively. Effects of other pollutants on cardiovascular and cerebrovascular mortality were insignificant.

After adjusting for Ramadan, all the associations were still positive, and the values were very close to those in the base

Fig. 1 Relative risks (RRs) for the association of cumulative and non-cumulative exposure to **a** and **b** PM₁₀. **c** and **d** PM_{2.5} with IHD mortality

model (unadjusted for Ramadan), but a few changes in the RR values were observed (Tables A1 and A2 in the Appendix). For instance, the association between non-cumulative exposure to NO₂ and all-cause mortality in lag-day 6, non-cumulative exposure to CO and cerebrovascular mortality in lag-day 3 and cumulative exposure to PM_{2.5} and all-cause mortality in lag-day 0–7 were statistically insignificant in the Ramadan-adjusted model. In addition, cumulative exposure to PM₁₀ and respiratory mortality in lag-day 0–1 was significant in this model. No other remarkable changes in the RR values and patterns can be identified.

Sub-group analyses were conducted to investigate the effect modification of age and gender. Age was stratified into three groups: < 16, 16–65, and > 65 years old. The results of subgroup analysis are presented in Tables A3 to A12 in the

Appendix. All the RRs were positive, but only a few were statistically significant. Table 4 presents the PM₁₀ respiratory mortality and NO₂ IHD mortality relationships. The daily death rate due to respiratory causes for people aged over 65 years was significantly associated with the exposure to PM₁₀ on previous days, i.e., lag-day 0–1 (1.04, 95% CI 1.00, 1.09) to lag-day 0–7 (1.14, 95% CI 1.06, 1.24). The relationships on lag-day 1, lag-day 5, and lag-day 6 were significant. In addition, exposure to PM₁₀ showed a stronger association for women than men. The cumulative exposure associations were statistically significant from lag-day 0–1 (1.09, 95% CI 1.04, 1.15) to lag-day 0–7 (1.20, 95% CI 1.09, 1.32). The same-day exposure to PM₁₀ was also associated with a 5.9% RR for respiratory mortality in women (1.06, 95% CI 1.02, 1.10).

Fig. 2 Relative risks (RRs) for the association of cumulative and non-cumulative exposure to **a** and **b** NO_2 ($10 \mu\text{g}/\text{m}^3$). **c** and **d** O_3 ($10 \mu\text{g}/\text{m}^3$). **e** and **f** CO ($1000 \mu\text{g}/\text{m}^3$) with IHD mortality

A $10 \mu\text{g}/\text{m}^3$ increase in concentrations of NO_2 had significant associations with IHD mortality. The RRs of 1.16 (95% CI 1.04, 1.29), 1.10 (95% CI 1.04, 1.16), and 1.06 (95% CI 1.01, 1.12) were estimated for the lag-day 0, lag-day 1, and lag-day 2. Cumulative exposure to NO_2 was associated with IHD mortality on all lag-days, namely, from lag-day 0–1 (1.27, 05% CI 1.09, 1.49) to lag-day 0–7 (1.49, 95% CI 1.14, 1.94). The associations for younger age groups were insignificant. IHD mortalities in both men and women were affected by NO_2 . The current-day exposure caused 13.4% increase in IHD mortality in men. Cumulative exposure in lag-day 0–1 was also associated with IHD death in men with an RR (1.22, 95% CI 1.03, 1.44) slightly higher than that for women (1.21, 95% CI 1.01, 1.46).

For controlling the effect of co-exposures, a multi-pollutant model was developed including $\text{PM}_{2.5}$ and NO_2 (Table 5). The results of multi-pollutant model were mostly similar to the single-pollutant model. All the RRs for $\text{PM}_{2.5}$ with all-cause and IHD mortality were positive, but not significant. In addition, similar to the single-pollutant model, the association of NO_2 with IHD mortality was significant on all cumulative lag-days and also on lag-days 0 and 1, with RRs slightly higher in most cases. The RR for NO_2 IHD on lag-day 0 in the single-pollutant model was 1.13 (95% CI 1.03, 1.23), while in the multi-pollutant model, it was 1.13 (95% CI 1.03, 1.24). For all-cause death, despite the single-pollutant model (1.08,

95% CI 1.00, 1.17), the association of cumulative exposure in lag-day 0–7 was significant (1.08, 95% CI 1.00, 1.17).

Discussion

This study is one of the few to evaluate the short-term associations of exposure to air pollution and health in Iran. In this study, exposure to PM_{10} , $\text{PM}_{2.5}$, NO_2 , O_3 , and CO and cause-specific mortality were investigated. The results showed that NO_2 had a stronger association with IHD deaths compared with the other pollutants. In addition, mortality due to respiratory causes for the entire population, older people, and women was more significantly associated with PM_{10} . People aged over 65 years were more susceptible to IHD death due to PM_{10} . Results of the multi-pollutant model were mostly similar to the single-pollutant model.

These results can be compared with the associations found in North America and Western Europe that are used by WHO as the basis for health impact assessment studies around the world (WHO 2013). In the case of NO_2 , the association with daily all causes of mortality is reported to be 1.0027 (95% CI 1.0016, 1.0038) (WHO 2013), which is lower than our estimates on most lag-days for both cumulative and non-cumulative exposures. However, in our study, only non-cumulative exposure to NO_2 on lag-day 6 (1.02, 95% CI

Table 2 Relative risks (RRs) for the association of non-cumulative exposure to 10 $\mu\text{g}/\text{m}^3$ increase in PM_{10} , $\text{PM}_{2.5}$, NO_2 , O_3 , and 1000 $\mu\text{g}/\text{m}^3$ CO

	All causes	Respiratory	Cardiovascular	Cerebrovascular
PM_{10} (10 $\mu\text{g}/\text{m}^3$)				
Lag-day 0	1.00 (0.99–1.01)	1.02 (0.99, 1.05)	0.99 (0.98, 1.00)	0.97 (0.95, 0.99)
Lag-day 1	1.00 (0.99–1.00)	1.01 (1.00, 1.03)	0.99 (0.99, 1.00)	0.99 (0.98, 1.00)
Lag-day 2	1.00 (0.99–1.00)	1.01 (0.99, 1.02)	1.00 (0.99, 1.00)	1.01 (0.99, 1.02)
Lag-day 3	1.00 (0.99–1.00)	1.01 (0.99, 1.02)	1.00 (0.99, 1.01)	1.01 (0.99, 1.03)
Lag-day 4	1.00 (0.99–1.00)	1.01 (0.99, 1.02)	1.00 (0.99, 1.01)	1.01 (1.00, 1.03)
Lag-day 5	1.00 (0.99–1.00)	1.01 (1.00, 1.02)	1.00 (0.99, 1.00)	1.01 (0.99, 1.02)
Lag-day 6	1.00 (0.99–1.00)	1.02 (1.00, 1.03)	1.00 (0.99, 1.00)	1.00 (0.98, 1.01)
Lag-day 7	1.00 (0.99–1.01)	1.02 (1.00, 1.04)	1.00 (0.99, 1.01)	0.99 (0.96, 1.01)
$\text{PM}_{2.5}$ (10 $\mu\text{g}/\text{m}^3$)				
Lag-day 0	1.01 (0.98, 1.03)	0.99 (0.92, 1.07)	1.00 (0.96, 1.04)	0.96 (0.88, 1.04)
Lag-day 1	1.01 (0.99, 1.02)	1.01 (0.97, 1.06)	1.00 (0.98, 1.02)	0.99 (0.95, 1.03)
Lag-day 2	1.01 (0.99, 1.02)	1.03 (0.99, 1.07)	1.00 (0.98, 1.02)	1.01 (0.97, 1.05)
Lag-day 3	1.01 (0.99, 1.02)	1.03 (0.99, 1.08)	1.00 (0.98, 1.03)	1.02 (0.97, 1.07)
Lag-day 4	1.01 (0.99, 1.02)	1.04 (0.99, 1.08)	1.00 (0.98, 1.03)	1.02 (0.97, 1.06)
Lag-day 5	1.01 (0.99, 1.02)	1.03 (0.99, 1.07)	1.01 (0.99, 1.03)	1.00 (0.97, 1.04)
Lag-day 6	1.01 (0.99, 1.02)	1.02 (0.98, 1.07)	1.01 (0.99, 1.03)	0.98 (0.94, 1.03)
Lag-day 7	1.01 (0.99, 1.03)	1.01 (0.95, 1.08)	1.01 (0.98, 1.05)	0.96 (0.90, 1.03)
NO_2 (10 $\mu\text{g}/\text{m}^3$)				
Lag-day 0	1.00 (0.97, 1.04)	1.01 (0.92, 1.12)	1.01 (0.96, 1.06)	0.92 (0.83, 1.01)
Lag-day 1	1.00 (0.99, 1.02)	1.01 (0.96, 1.06)	1.01 (0.99, 1.04)	0.97 (0.92, 1.03)
Lag-day 2	1.00 (0.99, 1.02)	1.01 (0.96, 1.06)	1.02 (0.99, 1.04)	1.02 (0.97, 1.07)
Lag-day 3	1.00 (0.99, 1.02)	1.00 (0.95, 1.06)	1.02 (0.99, 1.05)	1.04 (0.99, 1.11)
Lag-day 4	1.01 (0.99, 1.02)	0.99 (0.95, 1.05)	1.02 (0.99, 1.04)	1.05 (0.99, 1.11)
Lag-day 5	1.01 (0.99, 1.03)	0.99 (0.96, 1.04)	1.01 (0.99, 1.04)	1.04 (0.99, 1.09)
Lag-day 6	1.02 (1.00, 1.03)	0.99 (0.94, 1.05)	1.01 (0.99, 1.04)	1.02 (0.97, 1.08)
Lag-day 7	1.02 (0.99, 1.05)	0.99 (0.91, 1.08)	1.01 (0.97, 1.05)	0.99 (0.92, 1.09)
O_3 (10 $\mu\text{g}/\text{m}^3$)				
Lag-day 0	0.99 (0.96, 1.02)	0.98 (0.89, 1.08)	0.98 (0.94, 1.03)	0.98 (0.89, 1.08)
Lag-day 1	1.02 (0.98, 1.05)	1.00 (0.89, 1.12)	1.04 (0.98, 1.10)	0.99 (0.88, 1.11)
Lag-day 2	1.00 (0.96, 1.03)	1.04 (0.93, 1.16)	0.95 (0.90, 1.00)	0.96 (0.85, 1.08)
Lag-day 3	1.02 (0.98, 1.05)	0.96 (0.85, 1.08)	1.08 (1.02, 1.15)	1.17 (1.05, 1.31)
Lag-day 4	0.98 (0.95, 1.02)	0.95 (0.85, 1.07)	0.98 (0.92, 1.03)	0.92 (0.82, 1.03)
Lag-day 5	1.01 (0.97, 1.04)	1.05 (0.94, 1.17)	0.99 (0.94, 1.05)	0.92 (0.82, 1.03)
Lag-day 6	0.98 (0.95, 1.02)	1.03 (0.91, 1.15)	0.96 (0.91, 1.02)	1.01 (0.90, 1.13)
Lag-day 7	1.02 (0.99, 1.06)	1.04 (0.94, 1.15)	1.01 (0.96, 1.06)	0.99 (0.89, 1.10)
CO (1000 $\mu\text{g}/\text{m}^3$)				
Lag-day 0	1.00 (0.97, 1.02)	0.99 (0.91, 1.07)	0.98 (0.94, 1.02)	1.00 (0.91, 1.09)
Lag-day 1	0.99 (0.98, 1.01)	0.98 (0.94, 1.02)	1.00 (0.98, 1.02)	1.03 (0.98, 1.08)
Lag-day 2	0.99 (0.98, 1.01)	0.98 (0.94, 1.02)	1.01 (0.99, 1.04)	1.05 (1.00, 1.10)
Lag-day 3	1.00 (0.98, 1.01)	0.98 (0.94, 1.03)	1.02 (0.99, 1.04)	1.05 (0.99, 1.10)
Lag-day 4	1.00 (0.99, 1.01)	1.00 (0.96, 1.04)	1.02 (0.99, 1.04)	1.03 (0.98, 1.08)
Lag-day 5	1.00 (0.99, 1.01)	1.02 (0.98, 1.05)	1.01 (0.99, 1.03)	1.00 (0.96, 1.04)
Lag-day 6	1.01 (0.99, 1.02)	1.04 (0.99, 1.08)	0.99 (0.97, 1.02)	0.96 (0.92, 1.01)
Lag-day 7	1.01 (0.99, 1.04)	1.06 (0.99, 1.14)	0.98 (0.94, 1.01)	0.92 (0.85, 1.00)

Bold RRs are significant at 0.05 level

1.00, 1.03) was statistically significant. The same phenomenon can be observed for the relationship between O_3 and all

non-accidental cause mortality (1.0029, 95% CI 1.0014, 1.0043), cardiovascular (1.0049, 95% CI 1.0013, 1.0085),

Table 3 Relative risks (RRs) for the association of cumulative exposure to 10 $\mu\text{g}/\text{m}^3$ increase in PM_{10} , $\text{PM}_{2.5}$, NO_2 , O_3 , and 1000 $\mu\text{g}/\text{m}^3$ CO

	All causes	Respiratory	Cardiovascular	Cerebrovascular
PM_{10} (10 $\mu\text{g}/\text{m}^3$)				
Lag-day 0–1	1.00 (0.99, 1.0)	1.03 (0.99, 1.07)	0.99 (0.97, 1.01)	0.96 (0.93, 1.00)
Lag-day 0–2	1.00 (0.99, 1.0)	1.04 (1.00, 1.09)	0.99 (0.97, 1.01)	0.97 (0.93, 1.01)
Lag-day 0–3	1.00 (0.99, 1.0)	1.05 (1.00, 1.10)	0.99 (0.96, 1.01)	0.98 (0.94, 1.03)
Lag-day 0–4	1.00 (0.98, 1.0)	1.06 (1.01, 1.12)	0.99 (0.96, 1.01)	0.99 (0.94, 1.05)
Lag-day 0–5	1.00 (0.98, 1.0)	1.07 (1.02, 1.14)	0.98 (0.96, 1.01)	1.00 (0.94, 1.06)
Lag-day 0–6	1.00 (0.98, 1.0)	1.09 (1.03, 1.16)	0.98 (0.95, 1.01)	1.00 (0.94, 1.06)
Lag-day 0–7	1.00 (0.98, 1.0)	1.12 (1.05, 1.20)	0.98 (0.95, 1.01)	0.99 (0.92, 1.06)
$\text{PM}_{2.5}$ (10 $\mu\text{g}/\text{m}^3$)				
Lag-day 0–1	1.01 (0.98, 1.05)	1.00 (0.90, 1.12)	1.00 (0.95, 1.06)	0.94 (0.84, 1.07)
Lag-day 0–2	1.02 (0.98, 1.07)	1.03 (0.91, 1.17)	1.00 (0.94, 1.07)	0.96 (0.83, 1.10)
Lag-day 0–3	1.03 (0.99, 1.08)	1.07 (0.92, 1.23)	1.01 (0.94, 1.08)	0.98 (0.84, 1.14)
Lag-day 0–4	1.04 (0.99, 1.10)	1.11 (0.94, 1.30)	1.01 (0.93, 1.10)	0.99 (0.84, 1.18)
Lag-day 0–5	1.05 (0.99, 1.12)	1.14 (0.95, 1.36)	1.02 (0.93, 1.11)	0.99 (0.82, 1.20)
Lag-day 0–6	1.06 (0.99, 1.13)	1.17 (0.96, 1.41)	1.03 (0.94, 1.13)	0.98 (0.80, 1.20)
Lag-day 0–7	1.07 (1.00, 1.15)	1.18 (0.95, 1.47)	1.04 (0.94, 1.16)	0.94 (0.76, 1.18)
NO_2 (10 $\mu\text{g}/\text{m}^3$)				
Lag-day 0–1	1.01 (0.96, 1.05)	1.02 (0.88, 1.18)	1.03 (0.96, 1.10)	0.89 (0.77, 1.04)
Lag-day 0–2	1.01 (0.96, 1.06)	1.03 (0.87, 1.21)	1.04 (0.96, 1.13)	0.91 (0.77, 1.08)
Lag-day 0–3	1.01 (0.96, 1.07)	1.03 (0.86, 1.23)	1.06 (0.97, 1.16)	0.95 (0.79, 1.14)
Lag-day 0–4	1.02 (0.96, 1.09)	1.03 (0.85, 1.25)	1.08 (0.98, 1.19)	1.00 (0.82, 1.22)
Lag-day 0–5	1.04 (0.97, 1.11)	1.03 (0.83, 1.27)	1.10 (0.99, 1.22)	1.04 (0.84, 1.30)
Lag-day 0–6	1.05 (0.98, 1.13)	1.02 (0.81, 1.28)	1.11 (0.99, 1.24)	1.06 (0.84, 1.34)
Lag-day 0–7	1.08 (0.99, 1.17)	1.02 (0.79, 1.31)	1.12 (0.99, 1.27)	1.06 (0.82, 1.38)
O_3 (10 $\mu\text{g}/\text{m}^3$)				
Lag-day 0–1	1.01 (0.97, 1.05)	0.98 (0.87, 1.10)	1.02 (0.96, 1.08)	0.97 (0.86, 1.09)
Lag-day 0–2	1.01 (0.97, 1.05)	1.02 (0.90, 1.15)	0.97 (0.91, 1.03)	0.93 (0.82, 1.06)
Lag-day 0–3	1.03 (0.98, 1.07)	0.97 (0.85, 1.12)	1.05 (0.98, 1.12)	1.09 (0.95, 1.25)
Lag-day 0–4	1.01 (0.97, 1.06)	0.92 (0.80, 1.07)	1.02 (0.95, 1.10)	1.00 (0.86, 1.16)
Lag-day 0–5	1.02 (0.97, 1.07)	0.97 (0.83, 1.13)	1.02 (0.94, 1.10)	0.92 (0.78, 1.08)
Lag-day 0–6	1.00 (0.95, 1.05)	0.99 (0.85, 1.16)	0.98 (0.90, 1.06)	0.92 (0.78, 1.10)
Lag-day 0–7	1.02 (0.97, 1.08)	1.03 (0.88, 1.21)	0.98 (0.90, 1.07)	0.91 (0.76, 1.09)
CO (1000 $\mu\text{g}/\text{m}^3$)				
Lag-day 0–1	0.99 (0.95, 1.03)	0.97 (0.86, 1.08)	0.98 (0.93, 1.04)	1.03 (0.90, 1.17)
Lag-day 0–2	0.98 (0.94, 1.03)	0.95 (0.83, 1.07)	1.00 (0.93, 1.06)	1.08 (0.93, 1.24)
Lag-day 0–3	0.98 (0.94, 1.03)	0.93 (0.81, 1.07)	1.01 (0.94, 1.09)	1.12 (0.96, 1.32)
Lag-day 0–4	0.98 (0.93, 1.03)	0.93 (0.80, 1.08)	1.03 (0.95, 1.12)	1.16 (0.97, 1.38)
Lag-day 0–5	0.98 (0.93, 1.04)	0.94 (0.80, 1.12)	1.04 (0.95, 1.13)	1.15 (0.96, 1.39)
Lag-day 0–6	0.99 (0.94, 1.05)	0.98 (0.83, 1.17)	1.03 (0.94, 1.13)	1.11 (0.91, 1.35)
Lag-day 0–7	1.01 (0.94, 1.07)	1.04 (0.87, 1.26)	1.01 (0.91, 1.11)	1.03 (0.83, 1.27)

Bold RRs are significant at 0.05 level

and respiratory (1.0029, 95% CI 0.9989, 1.0070) mortality (WHO 2013). These values are lower than our results, but none of our estimates is statistically significant. A different pattern can be identified for $\text{PM}_{2.5}$. According to HRAPIE, all-cause mortality is associated with short-term exposure to $\text{PM}_{2.5}$ with an RR of 1.023 (95% CI 1.0045, 1.0201) (WHO 2013). These values are higher than the RRs estimated in this

study for the non-cumulative exposure, while they are lower than the lag-days 0–3 (1.03, 95% CI 0.99, 1.08) to 0–7 (1.07, 95% CI 1.00, 1.15). These comparisons show that the application of associations taken from the areas with different range of concentrations in health impact assessment studies should be used with caution since they may under- or over-estimate the mortality rates (Hopke et al. 2018).

Table 4 Results of sub-group analysis for the association of exposure to PM₁₀ and NO₂ with respiratory and IHD mortality per 10 µg/m³ increase in concentrations

Cause	Age < 16	Age 16–65	Age > 65	Male	Female
PM₁₀ Respiratory					
Lag-day 0	1.09 (0.97, 1.22)	1.00 (0.95, 1.04)	1.02 (0.99, 1.05)	0.99 (0.96, 1.02)	1.06 (1.02, 1.10)
Lag-day 1	1.05 (0.99, 1.12)	0.99 (0.97, 1.02)	1.02 (1.00, 1.03)	1.00 (0.98, 1.02)	1.03 (1.01, 1.05)
Lag-day 2	1.02 (0.97, 1.08)	0.99 (0.97, 1.02)	1.01 (0.99, 1.03)	1.01 (0.99, 1.03)	1.01 (0.99, 1.03)
Lag-day 3	1.01 (0.95, 1.07)	0.99 (0.97, 1.02)	1.01 (0.99, 1.03)	1.01 (0.99, 1.03)	1.00 (0.98, 1.02)
Lag-day 4	1.00 (0.95, 1.06)	1.00 (0.98, 1.02)	1.01 (0.99, 1.03)	1.02 (0.99, 1.03)	1.00 (0.98, 1.02)
Lag-day 5	1.00 (0.95, 1.05)	1.01 (0.99, 1.03)	1.01 (1.00, 1.03)	1.01 (0.99, 1.03)	1.01 (0.99, 1.03)
Lag-day 6	1.00 (0.95, 1.06)	1.02 (0.99, 1.04)	1.02 (1.00, 1.03)	1.01 (0.99, 1.03)	1.03 (1.01, 1.05)
Lag-day 7	1.01 (0.92, 1.10)	1.03 (0.99, 1.07)	1.02 (0.99, 1.05)	1.00 (0.98, 1.03)	1.05 (1.02, 1.08)
Lag-day 0–1	1.14 (0.97, 1.35)	0.99 (0.93, 1.06)	1.04 (1.00, 1.09)	0.99 (0.95, 1.04)	1.09 (1.04, 1.15)
Lag-day 0–2	1.17 (0.97, 1.42)	0.98 (0.91, 1.06)	1.06 (1.01, 1.11)	1.00 (0.95, 1.05)	1.10 (1.04, 1.16)
Lag-day 0–3	1.18 (0.95, 1.46)	0.98 (0.90, 1.07)	1.07 (1.02, 1.13)	1.02 (0.96, 1.08)	1.10 (1.03, 1.17)
Lag-day 0–4	1.18 (0.93, 1.50)	0.98 (0.89, 1.08)	1.08 (1.02, 1.15)	1.03 (0.96, 1.10)	1.10 (1.02, 1.18)
Lag-day 0–5	1.18 (0.91, 1.53)	0.99 (0.89, 1.10)	1.10 (1.03, 1.17)	1.04 (0.97, 1.12)	1.11 (1.03, 1.21)
Lag-day 0–6	1.18 (0.90, 1.55)	1.01 (0.90, 1.13)	1.12 (1.04, 1.20)	1.05 (0.97, 1.14)	1.15 (1.05, 1.25)
Lag-day 0–7	1.19 (0.88, 1.61)	1.04 (0.92, 1.18)	1.14 (1.06, 1.24)	1.06 (0.97, 1.15)	1.20 (1.09, 1.32)
NO₂-IHD					
Lag-day 0	1.16 (0.59, 2.28)	1.06 (0.90, 1.24)	1.17 (1.04, 1.29)	1.13 (1.01, 1.27)	1.11 (0.98, 1.26)
Lag-day 1	1.16 (0.81, 1.66)	1.02 (0.94, 1.11)	1.10 (1.04, 1.16)	1.07 (1.01, 1.14)	1.09 (1.02, 1.17)
Lag-day 2	1.15 (0.83, 1.58)	1.00 (0.92, 1.08)	1.06 (1.01, 1.12)	1.03 (0.97, 1.09)	1.07 (1.00, 1.14)
Lag-day 3	1.12 (0.78, 1.60)	0.98 (0.90, 1.08)	1.03 (0.97, 1.10)	1.00 (0.94, 1.07)	1.05 (0.97, 1.13)
Lag-day 4	1.08 (0.78, 1.49)	0.98 (0.90, 1.06)	1.02 (0.97, 1.08)	1.00 (0.94, 1.06)	1.03 (0.96, 1.09)
Lag-day 5	1.04 (0.80, 1.36)	0.98 (0.92, 1.05)	1.01 (0.97, 1.06)	1.01 (0.96, 1.06)	1.00 (0.95, 1.06)
Lag-day 6	0.99 (0.70, 1.42)	0.99 (0.91, 1.07)	1.01 (0.96, 1.07)	1.03 (0.97, 1.10)	0.98 (0.91, 1.05)
Lag-day 7	0.95 (0.53, 1.69)	1.00 (0.87, 1.14)	1.02 (0.93, 1.11)	1.06 (0.96, 1.16)	0.96 (0.86, 1.06)
Lag-day 0–1	1.34 (0.49, 3.65)	1.09 (0.86, 1.37)	1.27 (1.09, 1.49)	1.22 (1.03, 1.44)	1.21 (1.01, 1.46)
Lag-day 0–2	1.53 (0.50, 4.75)	1.08 (0.83, 1.41)	1.35 (1.14, 1.60)	1.25 (1.03, 1.51)	1.30 (1.05, 1.60)
Lag-day 0–3	1.72 (0.50, 5.88)	1.07 (0.80, 1.42)	1.40 (1.16, 1.68)	1.25 (1.02, 1.54)	1.36 (1.08, 1.71)
Lag-day 0–4	1.86 (0.49, 7.13)	1.04 (0.76, 1.43)	1.42 (1.16, 1.75)	1.25 (0.99, 1.57)	1.39 (1.08, 1.80)
Lag-day 0–5	1.93 (0.46, 8.12)	1.02 (0.72, 1.45)	1.44 (1.15, 1.81)	1.27 (0.99, 1.62)	1.40 (1.06, 1.84)
Lag-day 0–6	1.92 (0.42, 8.68)	1.01 (0.70, 1.46)	1.46 (1.15, 1.86)	1.30 (1.00, 1.70)	1.37 (1.02, 1.83)
Lag-day 0–7	1.82 (0.34, 9.79)	1.01 (0.67, 1.51)	1.49 (1.14, 1.94)	1.38 (1.03, 1.84)	1.30 (0.94, 1.80)

Bold RRs are significant at 0.05 level

PM₁₀ and NO₂ showed the strongest relationships with daily mortality. The same results were also observed in another study in Iran by Dehghan et al. (2018). They found that NO₂ (RR = 1.04, 95% CI 1.02, 1.07) and PM₁₀ (RR = 1.03, 95% CI 1.02, 1.04) were associated with respiratory death on lag-day 0 (Dehghan et al. 2018). In a study in Mashhad, NO₂ concentrations during 2011 were significantly associated with daily cardiovascular mortality (1.01, 95% CI 1.006, 1.014). No significant association was found for PM₁₀ (Ghorbani et al., 2017). In another study in Mashhad, NO₂ was statistically related to daily COPD death in 2011 with a ratio of the incidence rate of 1.01. PM₁₀ also was not associated with the COPD mortality (Ghorbani et al., 2019). The difference between our results can be mainly due to the different statistical

models, and study period and duration (Nabizadeh et al., 2019).

In another study in Iran, the associations of the six criteria air pollutants with mortality were investigated. The RRs for the association with PM₁₀ on respiratory mortality in lag-day 0, lag-day 14, and lag-day 0–14 were 1.03 (95% CI 1.00, 1.051), 1.07 (95% CI 1.01, 1.13), and 1.03 (95% CI 1.01, 1.05), respectively. Alternatively, the overall estimates for NO₂ associations were not significant, and the RRs for the lag-days 0 and 14 were 0.99 (95% CI 0.98, 1.01) and 0.97 (95% CI 0.93, 1.02). Some strong associations were found for NO₂ in the sub-group analyses (Dastoorpoor et al. 2018a). Some significant associations in different lag-days have been found in another study in Ahvaz, where ozone on lag-day 3

Table 5 Results of multi-pollutant model (PM_{2.5} + NO₂) for the association of exposure to PM_{2.5} and NO₂ with all-cause and IHD mortality per 10 µg/m³ increase in concentrations

Lag-days	NO ₂		PM _{2.5}	
	All causes	IHD	All causes	IHD
Lag-day 0	1.01 (0.98, 1.04)	1.13 (1.03, 1.24)	1.00 (0.97, 1.03)	1.00 (0.92, 1.09)
Lag-day 1	1.00 (0.99, 1.02)	1.08 (1.03, 1.13)	1.00 (0.99, 1.02)	0.98 (0.94, 1.03)
Lag-day 2	1.00 (0.99, 1.02)	1.04 (0.99, 1.09)	1.00 (0.99, 1.02)	0.98 (0.94, 1.02)
Lag-day 3	1.00 (0.99, 1.02)	1.02 (0.97, 1.07)	1.01 (0.99, 1.02)	0.98 (0.93, 1.03)
Lag-day 4	1.01 (0.99, 1.02)	1.01 (0.96, 1.06)	1.01 (0.99, 1.02)	0.99 (0.95, 1.04)
Lag-day 5	1.01 (0.99, 1.03)	1.00 (0.97, 1.04)	1.01 (0.99, 1.02)	1.01 (0.97, 1.05)
Lag-day 6	1.02 (1.00, 1.04)	1.01 (0.96, 1.05)	1.00 (0.99, 1.02)	1.03 (0.99, 1.08)
Lag-day 7	1.03 (0.99, 1.05)	1.01 (0.93, 1.09)	1.00 (0.98, 1.03)	1.06 (0.98, 1.14)
Lag-day 0–1	1.01 (0.97, 1.06)	1.22 (1.07, 1.39)	1.00 (0.96, 1.04)	0.98 (0.87, 1.11)
Lag-day 0–2	1.01 (0.96, 1.07)	1.27 (1.10, 1.48)	1.00 (0.95, 1.05)	0.96 (0.83, 1.11)
Lag-day 0–3	1.02 (0.96, 1.08)	1.30 (1.11, 1.53)	1.01 (0.95, 1.07)	0.94 (0.80, 1.11)
Lag-day 0–4	1.03 (0.96, 1.09)	1.31 (1.09, 1.57)	1.01 (0.95, 1.08)	0.94 (0.78, 1.12)
Lag-day 0–5	1.04 (0.97, 1.11)	1.31 (1.08, 1.60)	1.02 (0.95, 1.09)	0.95 (0.77, 1.16)
Lag-day 0–6	1.06 (0.98, 1.14)	1.32 (1.08, 1.62)	1.02 (0.95, 1.10)	0.98 (0.79, 1.21)
Lag-day 0–7	1.08 (1.00, 1.17)	1.34 (1.06, 1.68)	1.03 (0.94, 1.12)	1.04 (0.81, 1.32)

Bold RRs are significant at 0.05 level

(among men), PM₁₀ on lag-day 3 and 13 (people aged > 60 and < 18 years), CO in lag-day 11 (people aged < 18 years), and NO₂ in lag-day 13 (people aged > 60 years) were related to cardiovascular mortality (Dastoorpoor et al. 2018a).

Limited evidence is available in Iran for comparison, especially in the case of NO₂. However, due to relatively comparable concentrations, Chinese studies can be a good alternative for comparison purposes. In a multi-site time-series study in China, an IQR increase in PM₁₀ concentrations led to 1.70% (95% CI 0.01, 3.32%) increase of daily respiratory deaths (Yang et al. 2015). In a meta-analysis of Chinese time-series studies, a 10 µg/m³ increase in NO₂ was associated with total mortality (excess rate (ER) = 1.30%, 95% CI 1.19, 1.41%), respiratory mortality (ER = 1.62%, 95% CI 1.32, 1.92%), and cardiovascular mortality (ER = 1.46%, 95% CI 1.27, 1.64%) (Shang et al. 2013).

In our study, the associations for PM_{2.5} on most of the lag-days were not statistically significant although in a number of cases, the lag-day patterns suggested the possibility of an association. These results are in agreement with previous studies in Mashhad. Ghorbani et al. (2017) and Ghorbani et al. (2019) found that short-term exposure to PM_{2.5} was not associated with daily cardiovascular mortality (Ghorbani et al., 2017) and COPD mortality (Ghorbani et al., 2019). This result is different from a previous study in Iran. Dehghan et al. (2018) reported that PM_{2.5} was associated with respiratory mortality on lag-day 0 (RR = 1.04, 95% CI 1.00, 1.08), lag-day 1 (RR = 1.06, 95% CI 1.02, 1.10), and lag-day 2 (RR = 1.04, 95% CI 1.00, 1.08) (Dehghan et al. 2018). In a recent study by Shahsavani et al. (2020), no statistically significant associations were identified between PM_{2.5} and daily mortality in Ahvaz, while the associations increased significantly during non-dust

days in Tehran at lag-days 2 and 3 (Shahsavani et al. 2020). In a systematic review of studies in China, short-term exposure to 10 µg/m³ increase in PM_{2.5} was correlated to total mortality (ER = 0.38%, 95% CI 0.31, 0.45%), respiratory mortality (ER = 0.51%, 95% CI 0.30, 0.73%), and cardiovascular mortality (ER = 0.44%, 95% CI 0.30, 0.54%) (Shang et al. 2013). Recent studies have shown that PM_{2.5} concentrations may not be a good index for exposure assessment. Therefore, PM_{2.5} daily excessive concentration hours (PM_{2.5} DECH) has been introduced as an alternative (Lin et al. 2017). In a study in Tehran (Iran), an interquartile range (IQR) increase in PM_{2.5} DECH was related to 2.26% (95% CI 0.85, 3.69%) increase in cardiovascular diseases (D. Chen et al. 2019).

Women and people older than 65 years were more susceptible to short-term exposure to air pollution. In previous studies, older people have been proven to be more affected by outdoor air pollution compared with people in other age groups (Simoni et al. 2015; Renjie Chen et al. 2017). In the study of Dehghan et al. (2018), NO₂, O₃, PM₁₀, and PM_{2.5} had significant relations with respiratory mortality in the older age groups. PM₁₀ and PM_{2.5} had stronger effect in age > 60 years than age < 60 years (Dehghan et al. 2018). However, a study in Tehran indicated that 0–64 years old people suffered more from PM_{2.5} pollution than people at older ages (D. Chen et al. 2019). In a study conducted in Ahvaz, people aged over 60 years were more affected by NO₂ and CO than those in younger ages (Dastoorpoor et al. 2018b). In the same study, the effects of PM₁₀, O₃, and SO₂ were stronger for women than men (Dastoorpoor et al. 2018b). These results are consistent with the present study. In addition, Dehghan et al. reported that the effect of NO₂ and PM_{2.5} were stronger among

women (Dehghan et al. 2018). Chen et al. (2019) found that men are more susceptible to PM_{2.5} DECH than women in the case of cardiovascular mortality (D. Chen et al. 2019). Similar to this, in our study, significant associations found between NO₂ and IHD mortality in men were stronger than those in women.

This study has some limitations that should be acknowledged. First, the study period was limited to only 3 years (2014–2018). Longer study periods will provide more reliable results. However, health data before 2014 were not reliable due to insufficiencies in the death registering system. Second, the observed concentrations of air pollutants at the monitoring stations may not provide an accurate estimation for exposure of the whole population. However, there was no other choice for exposure assessment. Third, we used 24-h averaged values for PM₁₀, PM_{2.5}, NO₂, and CO that may not properly reflect the effects of short-term peaks. Fourth, assuming the same exposure for all inhabitants on each day is certainly not likely to reflect the actual exposure of the whole population.

Conclusions

In this study, we investigated the association of short-term exposure to five air pollutants including PM₁₀, PM_{2.5}, NO₂, O₃, and CO with daily mortality due to natural cause, respiratory, cardiovascular, and cerebrovascular diseases. For IHD mortality, NO₂ on lag-days 0 to 0–7 was significantly associated with daily death. The other pollutants did not show significant relationships. PM₁₀ had significant associations with respiratory mortality in the whole population, people older than 65 years old, and men in several lag-days. In the case of IHD, NO₂ affected older people, men, and women in different lag-days. Adjusting for Ramadan did not affect the results significantly. This study is one of the few studies investigating the relationship of air pollution and mortality in Iran. The results indicated that NO₂ and PM₁₀ are more critical for health than the other pollutants in Mashhad. Control policies and actions should be enacted to reduce the concentrations of these pollutants.

Funding information This study was funded by Shahid Beheshti University of Medical Sciences, Tehran, Iran (grant number #22414).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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