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RESEARCH ARTICLE

Mortality assessment attributed to long-term exposure to fine particles in ambient air of the megacity of Tehran, Iran

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Abstract

Few studies regarding the health effects of long-term exposure to particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) have been carried out in Asia or the Middle East. The objective of our study was to assess total, lung cancer and chronic obstructive pulmonary disease (COPD) mortality attributed to long-term exposure to $PM_{2.5}$ among adults aged over 30 years in Tehran from March 2013 to March 2016 using AirQ$^+$ software. AirQ$^+$ modeling software was used to estimate the number of deaths attributed to $PM_{2.5}$ concentrations higher than 10 $\mu g\ m^{-3}$. Air quality data were obtained from the Department of Environment (DOE) and Tehran Air Quality Control Company (TAQCC). Only valid stations with data completeness of 75% in all 3 years were selected for entry into the model. The 3-year average of the 24-h concentrations was 39.17 $\mu g\ m^{-3}$. The results showed that the annual average concentration of $PM_{2.5}$ in 2015–2016 was reduced by 13% compared to that in 2013–2014. The annual average number of all natural, COPD, and lung cancer deaths attributable to long-term exposure to $PM_{2.5}$ in adults aged more than 30 years was 5073, 158, and 142 cases, respectively. The results of all three health endpoints indicate that the mortality attributable to $PM_{2.5}$ decreased yearly from 2013 to 2016 and that the reduced mortality was related to a corresponding reduction in the $PM_{2.5}$ concentration. Considering these first positive results, the steps that have been currently taken for reducing air pollution in Tehran should be continued to further improve the already positive effects of these measures on reducing health outcomes.

Keywords AirQ$^+$ · $PM_{2.5}$ · Lung cancer · COPD · Public health · Air pollution · Health impact · Tehran

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Introduction

Air pollution is described as the most important environmental health risk worldwide (Krzyzanowski et al. 2014). Adverse effects of air pollution on health in terms of premature deaths and disability-adjusted life years (DALYs) can reduce economic development and quality of life as well as eventually cause a reduction in income and productivity (World Bank 2016). In fact, according to the World Bank, exposure to air pollution is the fourth leading cause of death in the world after metabolic risks, dietary risks, and tobacco smoke (World Bank 2016). It is well recognized that short- and long-term exposure to ambient particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) is associated with increased mortality and morbidity due to various adverse health effects (Dianat et al. 2016, Halonen et al. 2016, Khamutian et al. 2015, Mohseni Bandpi et al. 2016, Soleimani et al. 2016, Zanobetti et al. 2014).

$PM_{2.5}$ is more harmful to health than particulate matter with an aerodynamic diameter of 10 μm or less (PM_{10}) because $PM_{2.5}$ can be inhaled more deeply into the lungs due to its small size with respect to PM_{10} and because it has a greater surface area; hence, $PM_{2.5}$ could provide potentially larger concentrations of adsorbed or condensed air toxicants per unit mass (Tsai et al. 2014). The number of deaths attributable to air pollution worldwide is estimated by the World Bank to be 5,500,000 deaths annually (World Bank 2016), and a World Health Organization (WHO) report showed that more than 7,000,000 premature deaths occur per year due to air pollution, 3,000,000 of which are due to outdoor air quality (WHO 2014c). Air pollution-related diseases include lung cancer, heart disease, stroke, acute respiratory infections (Carey et al. 2013, Mohseni Bandpi et al. 2017) and chronic obstructive pulmonary diseases (COPD) (World Bank 2016). It is estimated that more than 87% of the world's population is living in areas in which the $PM_{2.5}$ concentration is higher than the World Health Organization's guidelines (Brauer et al. 2016).

A health impact assessment of air pollution can be an effective tool for policy-makers and authorities to assess the effects of their actions (Likhvar et al. 2015). Additionally, the World Bank has reported that the total welfare losses and contribution of attributable deaths to air pollution to gross domestic product (GDP) were estimated to be 31 billion USD and 2.48% in 2013, respectively. Furthermore, the total labor output loss and its contribution to Iran's GDP were 1471 billion USD and 0.12%, respectively (World Bank 2016). As a result, it is critical to quantify the health impacts of air pollution and to observe the trends over the time.

Tehran is the capital city and economic center of Iran and has more than 8,000,000 residents. In 2014, the PM_{10} and $PM_{2.5}$ annual average concentrations in Tehran were 77 and 32 $\mu g\ m^{-3}$, respectively, which are higher than the WHO guidelines for PM_{10} (20 $\mu g\ m^{-3}$) and $PM_{2.5}$ (10 $\mu g\ m^{-3}$) (WHO 2014a). Several studies have been conducted to estimate the health impacts of air pollution in Iran (Hadei et al. 2017a, b, Hopke et al. 2018, Maleki et al. 2016, Mohammadi et al. 2016, Oliveri Conti et al. 2017), but there are no studies that quantify the health impact of long-term exposure to atmospheric $PM_{2.5}$ and COPD mortality. In addition, the use of AirQ+ software in this field has not been documented. This software was released by the WHO in 2016 and is based on new epidemiological findings. The procedure used in this study to validate monitoring stations was performed according to the European Commission guideline, which has some innovative criteria (EC Directive 2008). Despite previous studies, the baseline incidence of mortality used in this study is based on trustworthy information acquired from Ministry of Health and Medical Education (Khosravi et al. 2016).

The objective of this study was to estimate total, lung cancer and COPD mortality attributed to long-term exposure to ambient $PM_{2.5}$ among adults aged over 30 years in the megacity of Tehran from March 2013 to March 2016 using WHO $AirQ^{+}$ software.

Materials and methods

Data collection

According to the Persian calendar, three 1-year periods were considered in this study. The first period was from 21 March 2013 to 20 March 2014. The second period was from 21 March 2014 to 20 March 2015. The third period was between 21 March 2015 and 19 March 2016.

The hourly concentrations of ambient $PM_{2.5}$ measured by 15 fixed monitoring stations associated with the Department of Environment (DOE) and 22 fixed monitoring stations of the Tehran Air Quality Control Company (TAQCC) from 21 March 2013 to 19 March 2016 were used in this study (Fig. 1).

Demographic information, including the yearly population and different age groups of Tehran, was obtained from the Statistical Center of Iran. The number of deaths classified by age groups was obtained from the center of Health Networks associated with the Public Health Deputy, Ministry of Health and Medical Education (Khosravi et al. 2016).

AirQ+ estimates the health impacts attributed to air pollution in predefined age groups. This is due to the fact that prior works (Burnett et al. 2014, Hoek et al. 2013, WHO-Europe 2013) has suggested that depending on health outcome, the risk estimates for people older than a certain age are more robust than those including younger individuals. Based on this information, the baseline incidence rate of natural mortality in adults aged over 30 years in Tehran was calculated to be 943 deaths per 100,000 people. In addition, the baseline incidences of lung cancer and COPD mortality have been reported to be 15.50 and 21.73 deaths per 100,000 people. The

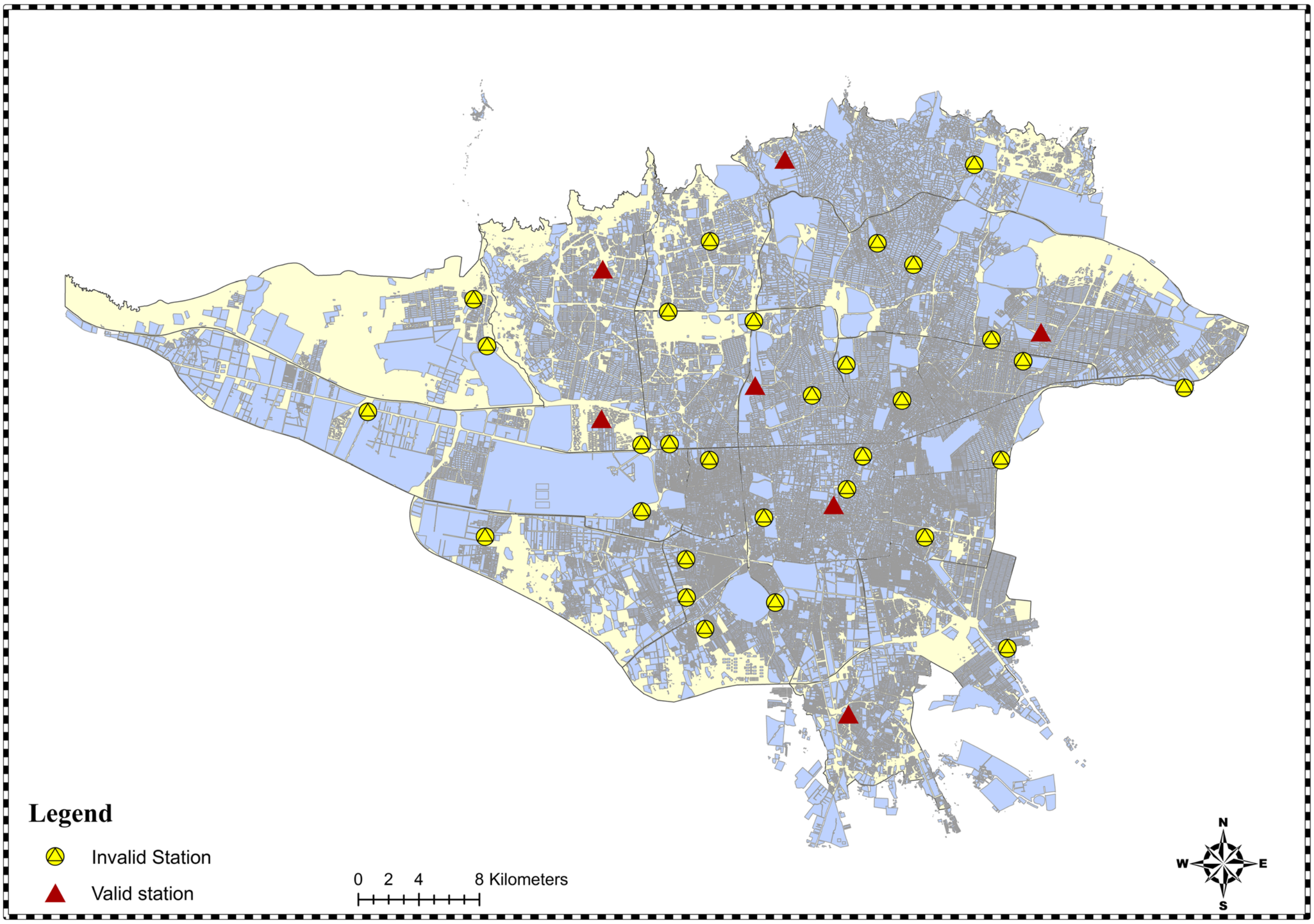

Fig. 1 Air quality monitoring stations in Tehran (red and yellow signs represent invalid and valid monitoring stations, respectively)

Ministry of Health and Medical Education statistics were from 2012. Due to the lack of any recent formal and approved reports, the same value was used for the whole study period.

Data validation

The initial determination of the hourly $PM_{2.5}$ concentrations involved the deletion of negative and false zero values. At first, the 24-h averages were calculated for days that had more than 75% of hourly data. Then, an annual average for each station was calculated only for the stations that had more than 90% of valid hourly values or (if not available) 24-h values over 1 year (EC Directive 2008). Stations that could not meet this criterion were excluded from the study. Then, only valid stations for all 3 years were selected to enter the model, and the others were excluded. This was done to develop a constant assumption for population exposure to $PM_{2.5}$. Additionally, the spatial distribution of the selected stations was determined. Out of the 37 fixed monitoring stations over these 3 years, 7 stations (19% of the total) were valid to enter the model, and these stations are illustrated in Fig. 1. The overall 24-h averages of the city were calculated from the 24-h averages of all of the selected stations on each day.

AirQ+

The World Health Organization, Regional Office for Europe, developed $AirQ^+$ 1.0 to estimate the magnitude of the short- and long-term health impacts of air pollution in a specific population. $AirQ^+$ calculates the attributable proportion of cases, number of attributable cases, number of attributable cases per 100,000 people of the at-risk population, and proportion of cases per category of the air pollutant concentration. Epidemiological studies are the source of the methodology and concentration-response functions used in $AirQ^+$ (WHO Regional Office for Europe 2016).

To quantify the long-term effects of $PM_{2.5}$, the following data should be provided as the input: 24-h averages of $PM_{2.5}$ concentrations; at-risk population; health data, such as the baseline rates of health outcomes; a cutoff value for consideration; and relative risk (RRs) values (Pierpaolo Mudu and Dunbar 2016).

The attributable proportion (*AP*) is the attributed fraction of the health outcome due to the exposure in a given population for a certain period of time, and it can be calculated using Eq. 1:

$$\mathrm{AP} = ?\left\{(\mathrm{RR(c)\text{-}1})^{*}\ \mathrm{p(c)}\right\}/?\left(\mathrm{RR(c)}^{*}\ \mathrm{p(c)}\right) \qquad (1)$$

where

RR(c) is the relative risk for the health outcome in the category of exposure *(c)*, and *p(c)* is the proportion of the population in the category of exposure *(c)*.

With a certain baseline incidence (*B*) of the selected health endpoint in the population, the rate or the number of cases per unit population (*BE*) can be calculated as:

$$\mathrm{BE} = \mathrm{B}^{*}\ \mathrm{AP} \qquad (2)$$

For a population of a given size *N*, the number of attributable cases (*NE*) can be estimated (Krzyzanowski 1997):

$$\mathrm{NE} = \mathrm{BE}^{*}\ \mathrm{N} \qquad (3)$$

The daily average concentrations of the 3-year period, demographic data, and baseline incidence rate were prepared for entry into the model. AirQ^{+} software provides default RR values. To avoid overestimation, the linear-log method was selected over log-linear calculations. These two methods are two types of modeling approaches to deal with different types of dose-response curves and estimating relative risks for different concentrations.

Statistics

All of the calculations were performed using SPSS 14. One-way ANOVA was used to analyze whether the reduction of the Annual $PM_{2.5}$ concentration over the whole period was significant.

Results and discussion

We used AirQ^{+} to estimate the total mortality attributed to long-term exposure to $PM_{2.5}$ in ambient air in the megacity of Tehran from March 2013 until March 2016. In addition, the number of lung cancer and COPD deaths attributable to long-term exposure to $PM_{2.5}$ was estimated.

$PM_{2.5}$ concentration

Descriptive statistics of ambient fine particulate matter, including the median, quartiles, minimum, maximum, and outlier values, in Tehran from 2013 to 2016 are reported in Fig. 2. These values are published elsewhere (Hadei et al. 2017b). The annual averages were 41.90, 31.17, and 36.43 μg m^{-3}, respectively. The 3-year average of the 24-h averages was 39.17 μg m^{-3}.

The results of one-way ANOVA showed that the reduction in $PM_{2.5}$ concentrations over the 2013–2016 period was

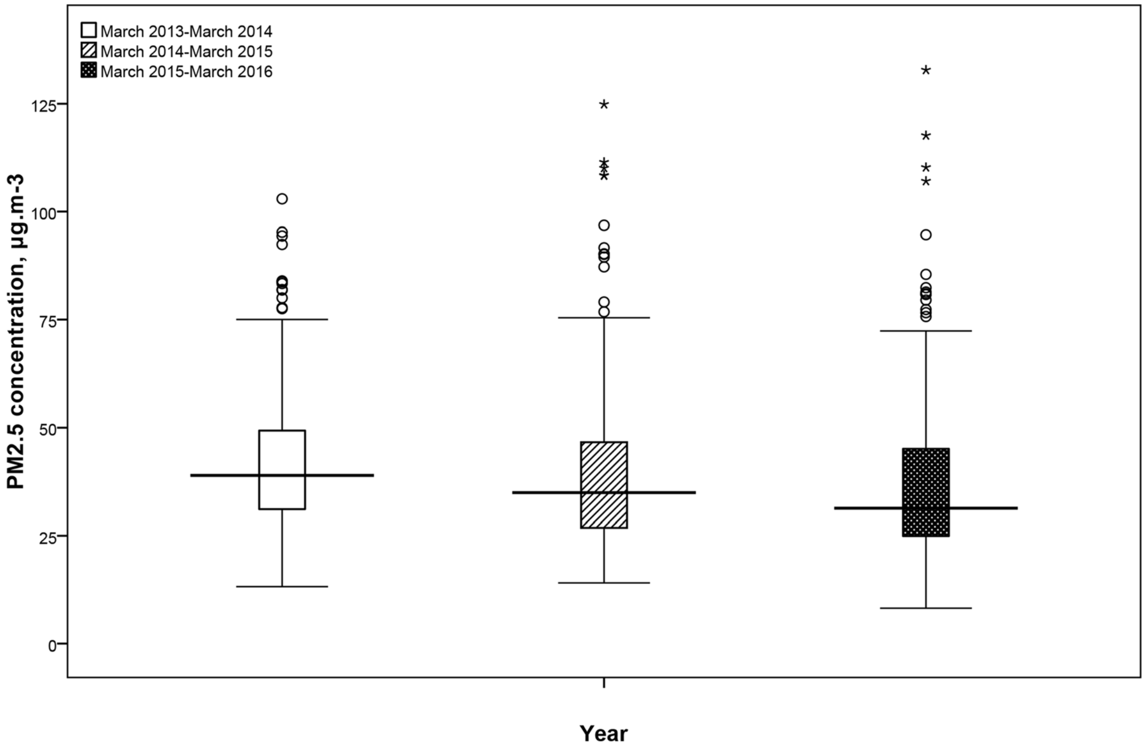

Fig. 2 Descriptive statistics of the $PM_{2.5}$ concentrations of ambient air, Tehran (March 2013–March 2016), including the median, quartiles, minimum and maximum (whiskers), outliers (circles), and extreme values (asterisks)

statistically significant (p value < 0.05). This is an important finding because, in recent years, many efforts have been made to reduce the concentration of particulate matter in Tehran. These efforts have included fuel substitution in mobile sources and the industrial sector as well as replacing older vehicles with new ones, among others, and these efforts may be the reason for this reduction (Department of Environment (DOE) 2017). However, the average annual concentration was still far from the guidelines set by the WHO. The annual concentrations of $PM_{2.5}$ in March 2013–March 2014, March 2014–March 2015, and March 2015–March 2016 were, respectively, 4.2, 3.9, and 3.6 times higher than the guideline value of 10 μg m^{-3}, which is the annual average recommended by the WHO (WHO 2006). The annual average $PM_{2.5}$ concentration in 2015–2016 was reduced by 13% compared to that in 2013–2014 (from 41.90 to 36.43 μg m^{-3}). According to the latest WHO report, the annual average $PM_{2.5}$ concentration in Tehran (2014) was 32.00 μg m^{-3} (WHO 2014a). This difference might be due to the different criteria used to quantify valid stations to calculate the average concentration.

The reason for the high $PM_{2.5}$ concentrations in Tehran can be found in a report published by TAQCC (Shahbazi et al. 2015). The authors, in fact, declare that there are more than 3,000,000 personal cars in Tehran, 25% of which are older than 10 years and 75% of which have emissions that meet the Euro-2 standard and less. In addition, there are approximately 750,000 motorcycles, 40% of which are older than 10 years, and more than 95% of their emissions meet the Euro-2 standard and less. The Tehran Air Quality Control Company's calculations show that each year more than 8600 tons of particulate matter from vehicles is released in Tehran. In total, the major sources of particulate matter in Tehran include: mobile sources (70.2%), the energy conversion sector (19.6%), industries (7.1%), households and commercial emissions (2.1%), and public terminals (0.9%) (Asl et al. 2015, Shahbazi et al. 2015). It is necessary to conduct studies to more precisely apportion the sources of particulate matter in Tehran, as it is carried out in Ahvaz, which has an average PM_{10} concentration of 319.60 μg m^{-3} and is one of the most polluted cities in Iran and the world, due to the Middle Eastern dust storms and improper management of water resources (Ashrafi et al. 2018, Moghaddam et al. 2017, Shahsavani et al. 2017, Sowlat et al. 2013).

Figure 3 illustrates the number of days during which people were exposed to daily $PM_{2.5}$ concentrations from March 2013 to March 2016. The number of days with a lower concentration than the WHO's 24-h guideline value of 25 μg m^{-3} increased by 57% in the period from March 2015–March 2016 in comparison to the period from March 2013–March 2014 (from 40 to 94 days in a year). The number of days with concentrations of less than 30 μg m^{-3} has increased from the first period to the third period. This may be due to the decrease in the number of days with concentrations higher than 30 μg m^{-3}, and also the decrease in the number of days with dust storms (average $PM_{2.5}$ concentrations higher than 35 μg m^{-3}) in the third year (Arhami et al. 2017, Shahbazi

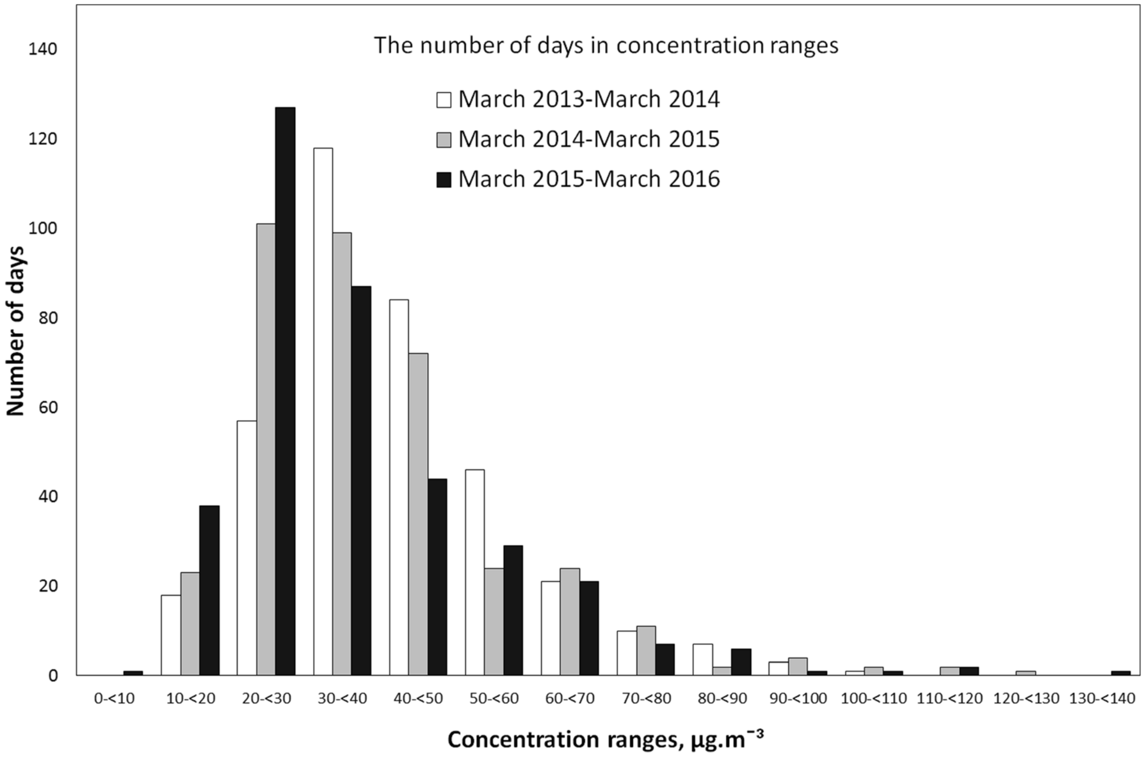

Fig. 3 The number of days with concentrations in each $PM_{2.5}$ concentration interval

et al. 2015). This improve in air quality might be due to several actions performed during the past few years, such as improving the quality of fuel, upgrading the standards of vehicles, phasing-out of old cars and increasing the size of the public transport fleet (Shahbazi et al. 2015, Sharafi et al. 2015).

Total mortality estimation

Table 1 shows the long-term health impacts of exposure to $PM_{2.5}$ concentrations above 10 μg m^{-3} including the attributable proportion (AP) and attributable cases of natural mortality in adults aged more than 30 years from March 2013 to March 2016. In total, 15,219 deaths can be attributed to long-term exposure to fine particulate matter from 2013 to 2016. On average, the number of deaths was 5073 cases over the 3 years.

In 2015–2016, natural mortality was reduced by 2.4 and 8.4% compared to 2014–2015 and 2013–2014, respectively. Despite the increase in population from 2013 to 2016, the attributable proportion and cases of deaths were decreased due to the reduction of the $PM_{2.5}$ concentration. As mentioned before, the baseline incidence rate was kept constant during the 3 years. The results showed that 58 deaths per 100,000 people in the whole population were attributable to long-term exposure to $PM_{2.5}$ in Tehran during 2013–2016, while the world average number of deaths was 53 per 100,000 people (WHO 2014b).

The results of Fisher's study indicated that long-term exposure to PM_{10} was directly related to mortality in adults older than 30 years old. They reported that for each 10 μg m^{-3} increase in PM_{10}, the associated hazard ratio was 1.08 (95% CI 1.07–1.09) (Fischer et al. 2015). Carugno's investigation on air pollution exposure and cause-specific deaths confirmed the strong relationship between the concentration of PM_{10} and natural mortality (Carugno et al. 2016). There is no study on the long-term effects of $PM_{2.5}$ on mortality in Tehran. However, quantification of the short-term effects of other air pollutants has been performed in some studies. Naddafi et al. (2012) estimated all natural deaths due to short-term exposure to PM_{10} in the whole population of Tehran. The results showed that there were annually 2194 attributable deaths to PM_{10} exposure (Naddafi et al. 2012). This value is less than the number of attributable deaths estimated in this study. This difference is because despite Naddafi et al., we considered long-term health impacts, not short-term impacts.

COPD mortality estimation

Another objective of the study was to estimate the attributable proportion (AP) and cases of mortality of COPD caused by long-term exposure to a concentration of $PM_{2.5}$ above the reference concentration of 10 μg m^{-3} in adults aged over 30 years between 2013 and 2016. Table 2 shows that 474 people died due to COPD due to long-term exposure to fine particulate matter in Tehran from 2013 to 2016. The annual average of attributable COPD deaths was 158 cases. Our findings demonstrated that the number of deaths attributable to COPD was also reduced by 9% over the research period. This decrease was attributable to the reduction in the fine particulate matter concentration over the last 3 years. As mentioned before, the baseline incidence rate was kept constant during the 3 years.

The results of the Neuberger et al. (2013) study also indicated that short-term exposure to a 10 μg m^{-3} increase in $PM_{2.5}$ caused a 14% (95% CI 4.9–24) increase in mortality, and this increase in mortality was marked by a 0- to 7-day lag from exposure to death (Neuberger et al. 2013). According to the WHO in 2014, each year, approximately 389,000 people in the world died due to COPD caused by exposure to ambient air pollution. The result of this report showed that COPD, after ischemic heart disease (IHD) and stroke, was the third leading cause of death from exposure to ambient air pollution (WHO 2014b). According to the report of the global burden of disease in 2013, COPD was the ninth cause of years of life lost in Iran (Global Burden of Disease (GBD) 2015). There is no health impact assessment study on estimating COPD mortality attributed to air pollution in Iran. However, the number of COPD hospital admissions due to gaseous pollutants has been well documented (Naddafi et al. 2012).

Lung cancer mortality estimation

Table 3 shows the attributable cases of lung cancer mortality due to long-term exposure to $PM_{2.5}$ in adults aged over

Table 1 Estimated attributable proportion (AP) and attributable cases of all natural mortality in adults aged over 30 years due to $PM_{2.5}$ exposure, Tehran (2013–2016)

Year	Total population	Population over 30 years	RR (95% CI) per 10 μg m^{-3}	AP % (95% CI)	Attributable cases (95% CI)
2013–2014	8,209,730	4,638,750	1.062 (1.04–1.083)	12.02 (8.01–15.62)	5263 (3507–6836)
2014–2015	8,652,820	4,815,000	1.06 (1.04–1.083)	11.31 (7.52–14.68)	5137 (3419–6681)
2015–2016	8,866,500	4,988,250	1.06 (1.04–1.08)	10.24 (6.79–13.34)	4819 (3201–6270)

RR relative risk, *AP* attributable proportion, *CI* confidence interval

Table 2 Estimated attributable proportion (AP) and attributable cases of COPD mortality (ICD-10: J40–J44) in adults aged over 30 years due to $PM_{2.5}$ exposure, Tehran (2013–2016)

Year	Total population	Population over 30 years	RR (95% CI) per 10 $\mu g\ m^{-3}$	AP % (95% CI)	Attributable cases (95% CI)
2013–2014	8,209,730	4,638,750	1.18 (1.07–1.31)	16.38 (7.41–25.41)	165 (75–253)
2014–2015	8,652,820	4,815,000	1.17 (1.07–1.293)	15.25 (6.54–23.63)	159 (68–247)
2015–2016	8,866,500	4,988,250	1.15 (1.06–1.269)	13.88 (5.66–21.26)	150 (61–237)

RR relative risk, *AP* attributable proportion, *CI* confidence interval

30 years in Tehran from 2013 to 2016. The results provided in Table 3 show that 427 cases of lung cancer deaths were attributable to long-term exposure to fine particulate matter in Tehran during the whole period. On average, the annual number of lung cancer deaths was 142. Our study demonstrated that the number of lung cancer deaths was reduced by approximately 9% in 2016 compared to 2013. As mentioned before, the baseline incidence rate was kept constant during the 3 years.

The WHO reported that, each year, approximately 227,000 people in the world died due to lung cancer caused by exposure to ambient air pollution. Furthermore, the report indicated that lung cancer is the fourth leading cause of death because of exposure to ambient air pollution (WHO 2014c). In addition, the WHO has reported the number of deaths, years of life lost (YLL) and disability-adjusted life years (DALY) due to lung cancer caused by air pollution in each country. The number of deaths, YLLs, and DALYs of lung cancer caused by particulate air pollution in Iran during 2012 were 1460, 37,894, and 38,258, respectively (WHO 2016). It can be concluded that our results are consistent with the WHO's report because Tehran's population is approximately one tenth of the total country, as well as one tenth of the estimated number of lung cancer deaths. In an industrial area in Italy, approximately 433 and 1204 YLLs were attributed to a $PM_{2.5}$ concentration higher than 10 $\mu g\ m^{-3}$ during the first year and next 10 years, respectively. The yearly average concentration of $PM_{2.5}$ in that region was 42 $\mu g\ m^{-3}$ (Fattore et al. 2011).

Tomczak et al.'s (2016) study on long-term exposure to fine particulate matter air pollution and the risk of lung cancer among participants of the Canadian National Breast Screening Study showed that a 10 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ was associated with an elevated lung cancer risk (HRs 1.34; 95% CI = 1.10, 1.65) (Tomczak et al. 2016). The finding of Villeneuve et al. (2015) from a cohort study showed that a 10 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ exposure was associated with elevated risks of lung cancer (HRs 1.12; 95% CI = 0.94, 1.34) (Villeneuve et al. 2015). In another cohort study by Cesaroni et al. (2013), it was found that long-term exposure to $PM_{2.5}$ was associated with increased mortality due to lung cancer in this large population-based cohort (Cesaroni et al. 2013).

Conclusion

AirQ$^+$ modeling software was used to estimate the number of total, lung cancer and COPD mortality cases attributed to long-term exposure to ambient $PM_{2.5}$ among adults aged over 30 years in the megacity of Tehran from March 2013 until March 2016. The results showed that the annual averages of $PM_{2.5}$ from March 2013–March 2014, March 2014–March 2015, and March 2015–March 2016 years were higher than the guideline value recommended by the WHO. However, the annual concentration from March 2015–March 2016 decreased compared to that from March 2013–March 2014. The 3-year averages of all natural, COPD, and lung cancer deaths attributable to long-term exposure to ambient $PM_{2.5}$ were 5073, 158, and 142 deaths, respectively. The mortality attributable to $PM_{2.5}$ decreased from 2013 to 2016, which is a consequence of the reduction in the $PM_{2.5}$ concentration. This might be due to several factors, such as improving the quality of fuel, upgrading of standards of vehicles, phasing-out of old cars and an increasing the size of the public

Table 3 Estimated attributable proportion (AP) and attributable cases of lung cancer mortality (ICD10 code: C33–C34) in adults aged over 30 years due to $PM_{2.5}$ exposure, Tehran (2013–2016)

Year	Total population	Population over 30 years	RR (95% CI) per 10 $\mu g\ m^{-3}$	AP % (95% CI)	Attributable cases (95% CI)
2013–2014	8,209,730	4,638,750	1.24 (1.06–1.41)	20.63 (5.66–30.36)	148 (41–218)
2014–2015	8,652,820	4,815,000	1.22 (1.05–1.38)	19.32 (5.61–29.05)	144 (42–217)
2015–2016	8,866,500	4,988,250	1.199 (1.04–1.34)	17.44 (4.76–26.54)	135 (37–205)

RR relative risk, *AP* attributable proportion, *CI* confidence interval transport fleet. Considering these results, the trend of reducing particulate air pollution in Tehran should be continued to reduce its health impacts.

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Compliance with ethical standards

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

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