Environment International 135 (2020) 105344

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Does the AQHI reduce cardiovascular hospitalization in Hong Kong's elderly population?

Tonya G. Mason, C. Mary Schooling*, JinJun Ran, King-Pan Chan, Linwei Tian*

School of Public Health, Li Ka Shing Faculty of Medicine, The University of Hong Kong, Hong Kong Special Administrative Region

ARTICLE INFO

Handling Editor: Hanna Boogaard

Keywords:
AQHI
Cardiovascular diseases
Elderly
Interrupted time series
Segmented regression

ABSTRACT

Background: Air quality alert programs have been introduced around the world to reduce the short term effects of air pollution on health. Hong Kong, a densely populated city in southern China with high levels of air pollution, introduced its first air quality health index (AQHI) on December 30th 2013. However, whether air quality alert program warnings, such as the AQHI, reduces morbidity is uncertain. Using a quasi-experimental design, we conducted the first evaluation of the AQHI in Hong Kong, focusing on cardiovascular morbidity in Hong Kong's elderly population.

Method: Interrupted time series with Poisson segmented regression from 2010 to 2016 was used to detect any sudden or gradual changes in emergency hospital admissions for cardiovascular diseases (CVD), after the AQHI policy was implemented. To account for potential confounders, models were adjusted for air pollutants (NO_2, SO_2, PM_{10}, O_3), temperature and humidity. The findings were validated using a negative control and three false policy periods. We also assessed effects on specific subtypes of CVD (hypertensive disease (HPD), acute myocardial infarction (AMI), heart failure, stroke and other CVD) and by sex.

Results: From January 1st 2010 to December 31st, 2016, 375,672 hospital admissions for CVD occurred in Hong Kong's elderly population. Immediately after the policy HPD and AMI dropped by16% (relative risk (RR) 0.84, 95% confidence interval (CI): 0.78–0.91) and 15% (RR 0.85, 95% CI: (0.76–0.97)) respectively. There was no significant change for all CVD or other sub-types and no differences by sex.

Conclusion: Hong Kong's AQHI helped reduced hospital admissions in the elderly for HPD and AMI but had no effect on overall emergency hospitalization for CVD. To maximize health benefits of the policy, at risk groups need to be able to follow the behavioral changes recommended by the AQHI warnings.

1. Introduction

Air pollution causes CVD (Brook et al., 2010; WHO, 2018a). Short term exposure is known to cause CVD including: stroke, heart failure, heart disease and hypertensive disease (Franklin et al., 2015). Ambient air pollution accounts for about 4.2 million deaths per year from CVD, lung cancer and chronic respiratory diseases (WHO, 2018a). Annually, about 17.9 million people die from CVD (WHO, 2018b). To protect the public against air pollution, governments around the world have introduced air quality alert programs to warn people when they should reduce their exposure to air pollution (Cairncross et al., 2007; Chen et al., 2014; Sicard et al., 2011; Stieb et al., 2008; Wong et al., 2013). One of these programs is the air quality health index (AQHI). Specifically, the AQHI provides health advisory messages in real time for the public. These messages provide specific advice for high risk groups — young children and the elderly—concerning the health risks associated with poor air quality and the actions to be taken to reduce their risk, such as: staying indoors and reducing outdoor activity (To et al., 2013).

The AQHI was initially developed by Health Canada and Environment Canada (Chen et al., 2014). The Canadian index is based on estimates of mortality associated with nitrogen dioxide (NO_2), ozone (O_3) and fine particulate matter ($PM \leq 2.5$ μm in aerodynamic diameter; $PM_{2.5}$) (Environment and Climate Change Canada 2019; To et al., 2013). Several studies have been conducted in Canada to show the validity of AQHIs in predicting morbidity and mortality (Chen et al., 2014; Szyszkowicz and Kousha 2014; To et al., 2013, 2015). However, few such studies have been conducted to assess how successful air quality alert programs are at reducing morbidity and mortality.

Hong Kong is a densely populated subtropical coastal city in southern China (Wong et al., 2002b) with living standards and social

---

* Corresponding authors at: School of Public Health, Li Ka Shing Faculty of Medicine, The University of Hong Kong, Patrick Manson Building North Wing, 7 Sassoon Road, Pokfulam, Hong Kong Special Administrative Region.

E-mail addresses: cms1@hku.hk (C. Mary Schooling), linweit@hku.hk (L. Tian).

https://doi.org/10.1016/j.envint.2019.105344
Received 18 July 2019; Received in revised form 31 October 2019; Accepted 17 November 2019

infrastructure similar to North America and Europe, but much higher levels of air pollution (Wong et al., 2002b). Most Hong Kong residents live in very close proximity to major pollutant sources (Wong et al., 2002b) such as: roads and shipping lanes (Mason et al., 2019a). Numerous epidemiological studies from Hong Kong have reported both long and short term exposure to air pollution to be associated with CVD morbidity and mortality (Wong et al., 2002a, 2015; Yang et al., 2018). Air pollution exposure is known to exacerbate adverse health effects in at risk populations— particularly the elderly (Lee et al., 2014; Perez et al., 2011). The elderly account for 16% of the Hong Kong population and is projected to account for a quarter of the population by 2023 (Hong Kong Census and Statistics Department 2017).

On December 30th, 2013, Hong Kong introduced an AQHI to combat the short-term health effects of poor air quality. The index is based on the predicted excess risk of hospital admissions given the 3-hour moving average concentration of NO_2, sulfur dioxide (SO_2), O_3 and PM (including PM $\le$ 10 µm in aerodynamic diameter (PM_{10} and $PM_{2.5}$) whichever has the higher risk). The AQHI information is disseminated to the public via newspapers, radio, television and digital media, such as computer and mobile apps (EPD, 2013a; Mason et al., 2019b). According to a recent survey in the general population in Hong Kong, 79% of the participants were aware of the AQHI: with television as one predominant source of information. Older age and female gender appeared to be associated with higher utilization of the AQHI service (unpublished data).

In a non-Western setting where pollution levels and composition may differ from more commonly studied Western settings, we took advantage of the introduction of Hong Kong's air quality health index (AQHI) alert program on December 30th, 2013 —aimed at the "at risk" population (seniors $\geq$65 years, young children < 5 years and people with preexisting respiratory or cardiovascular diseases (EPD 2013b) —to assess the effect of the policy on emergency hospital admissions for CVD and its sub-types: in the elderly population. Numerous epidemiologic studies have reported short term exposure to air pollution to be associated with emergency hospitalization for CVD (Franklin et al., 2015); with several studies reporting, short term exposure to high levels of air pollution to be associated with increase hospitalization for acute coronary syndrome (Franklin et al., 2015; Mittleman, 2002; Peters et al.), with the strongest associations occurring on same day exposure or in the last 2 days (Bourdrel et al., 2017; Nuvolone et al., 2011). Hence, our a priori hypotheses were: the implementation of the AQHI would reduce overall emergency hospital admissions for CVD for the elderly; with effects more pronounced for specific sub-types such as: acute rather than chronic CVD.

2. Methods

2.1. Data collection

Data on daily mean concentrations of NO_2, SO_2, PM_{10} and O_3 were obtained from the 10 urban background stations in Hong Kong (Fig. 1), which have been in full operation since 2009 (Air Science Group 2011) and represent air pollution exposure for the general population because most of the population resides within 5 km of these stations (Huang et al., 2017). Of the 6 stations omitted: three were road side stations and the remaining three had substantial amounts of missing data. Meteorological information, including daily average temperature and relative humidity, were obtained from the Hong Kong Observatory. The study period was 3 years before and after the introduction of the AQHI policy (December 30th, 2013), i.e., December 31th 2010 to December 31st' 2016 (Fig. 2).

Emergency hospital admissions for CVD for the elderly were obtained from the Hospital Authority which provides all publicly funded hospital beds in Hong Kong covering approximately 90% of all hospital beds for residents (Tian et al., 2017). Hospital discharges are routinely coded using International Classification of Diseases 9th revision (ICD-9). We abstracted emergency hospital admissions for all CVD (ICD-9 390 to 459), and its major sub-types: i.e., stroke (430 to 438), hypertensive disease (HPD) (401 to 405), acute myocardial infarction (AMI) (4 1 0) and heart failure (4 2 8). We also abstracted the ICD 9 codes for all other CVD (ICD-9: 390:400, 406:409, 411:427, 429, 439:459). Emergency hospital admissions for all digestive disease (ICD9 520–579) excluding peptic ulcer bleeding (ICD9 53X.0, 53X.2, 53X.4, 53X.6, where X = 1–3) were used as a control outcome. The AQHI warnings specifically target people with respiratory diseases or CVD, hence people with digestive diseases would not be expected to respond to AQHI warnings. In Hong Kong, as elsewhere, hospital admissions represent serious medical conditions while less severe diseases are treated in primary care (Sun et al., 2016).

2.2. AQHI

Hong Kong's AQHI is calculated hourly at all EPD monitoring stations based on the cumulative percentage excess risk of daily hospital admissions (%AR) associated with the 3 h moving average of 4 criteria pollutants (NO2, SO2, O3, PM_{10} or $PM_{2.5}$ (whichever has the highest pollution record on that day)) (see Fig. 1). The AQHI warnings are low risk, moderate risk, high risk, very high risk and serious (EPD, 2013a). The equation below illustrates how the AQHI is calculated (EPD, 2013a) (see Appendix A for further details):

$$\%AR = \%AR\ \ (NO2) + \%AR\ \ (SO2) + \%AR\ \ (O3) + \%AR\ \ (PM) \qquad (1)$$

2.3. Study design and statistical analyses

Interrupted time series (ITS) with a Quasi-Poisson segmented regression analysis were used to evaluate the policy impact (sudden or gradual) on CVD morbidity in Hong Kong from January 2010-December 2016. Monthly mean hospital admission rates were age-standardized to the WHO standard population (Ahmad et al., 2001) and used as an offset variable in our model (Lopez Bernal et al., 2016). This allowed us to adjust for any potential population change overtime and also convert our count data to rates (Lopez Bernal et al., 2016). The seasonal trend decomposition loess (STL) procedure was used to remove the seasonal trend prior to running the segmented regression analysis (Cleveland et al., 1990; Jassim et al., 2018).

A Quasi-Poisson model specifying sudden changes was selected because it has been shown that short term exposure to air pollution are capable of triggering acute coronary syndromes with the strongest associations occurring on same day exposure or 2 days following exposure (Bourdrel et al., 2017). The AQHI was designed to help reduce the publics short term exposure to air pollution. The outcome variable (Yt)—sequential deseasonalized, age-standardized hospitalizations were regressed on time. Other variables in the model included: the coefficient β0 representing baseline (time = 0) monthly mean hospitalizations; β1 represents the monthly time trend; β2 represents the sudden policy impact, with a value of 0 for the period before the policy and a value of 1 after the policy was implemented; β3 represents the interaction term between policy and time, allowing us to detect gradual (trend) changes after the implementation of the policy; β4 represents all other continuous covariates of interest adjusted for —air pollutants, temperature, humidity—with a natural cubic spline of three degrees of freedom to, control for any non-linearly relationship CVD have with temperature and relative humidity (Cryer and Chan, 2008); εt represents the model error term and residuals were plotted to check for over dispersion.

$$\begin{aligned} Y_t &= \beta 0 + \beta 1 \times \text{time}_t + \beta 2 \times \text{intervention}_t + \beta 3 \times \text{timeafter} \\ &\quad \text{intervention}_t + \beta 4 + \varepsilon_t \end{aligned} \qquad (1)$$

The validity of our results was tested by including digestive diseases

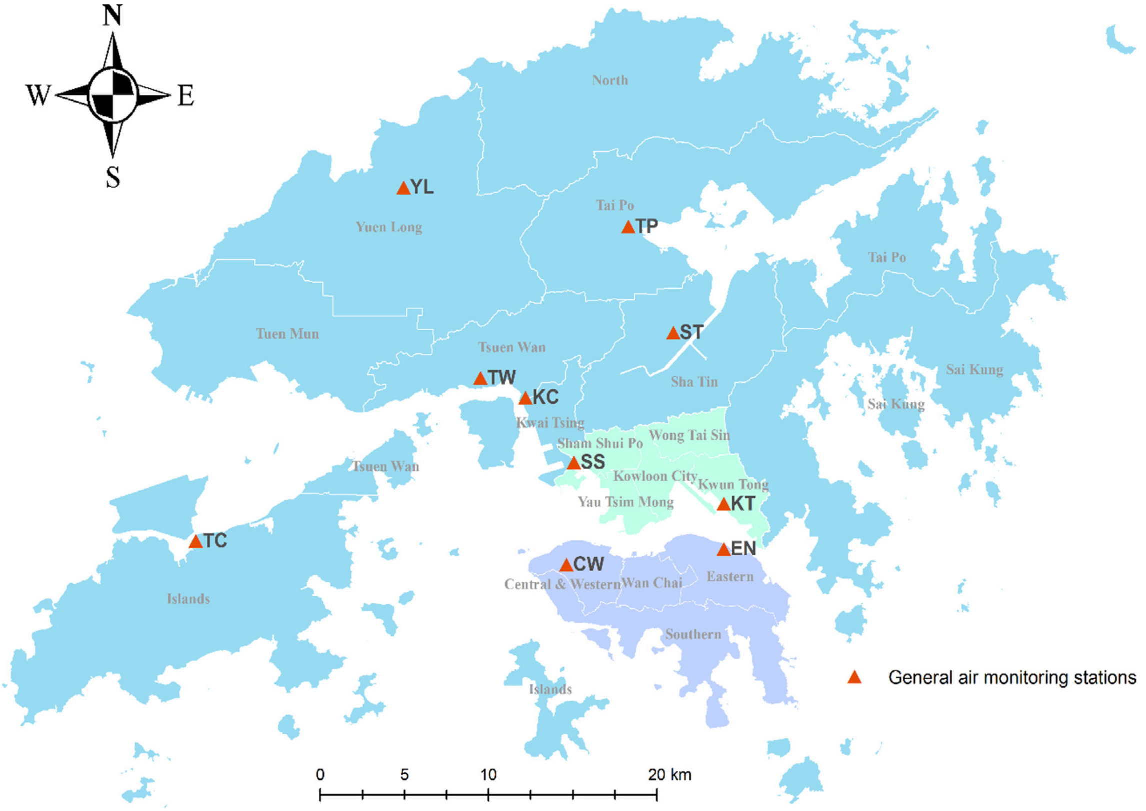

Fig. 1. Spatial map of Hong Kong showing the location of the 10 general air pollution monitoring stations used in the study.

as a negative control to ensure our model was detecting true policy effects. All statistical analyses were conducted using the software package R 3.4.2 (R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/).

3. Results

For the entire study period (2010–2016) there were 375,672 emergency hospital admissions for CVDamong Hong Kong's elderly population accounting for 72% of all CVD emergency hospitalizations in Hong Kong. On average, monthly emergency hospital admissions were 4472.0 with an interquartile range (IQR) of (4035.0, 4903.0) for all CVD, 520.2 (449.0, 576.5) for HPD, 415.1 (357.0, 472.5) for AMI, 1097.0 (866.8, 1298.0) for heart failure, 1025.0 (972.8, 1070.0) for stroke and 1415 (1323, 1484) for all other CVD ((Table 1). For the negative control outcome, the mean monthly emergency hospital admissions for the entire study period were 2272.0 with an IQR of (2122.0, 2415.0). The 4 criteria pollutant daily monthly means were 49.19 μg/m3 for NO$_2$, 11.41 μg/m^3 for SO$_2$, μg/m^3 for PM10 μg/m^3 and the daily 8-hour mean concentration for O3 was 41.4 μg/m3 (Table 1). The monthly mean temperature was 23.7 °C and relative humidity was 78.5.

Table 2 displays the sudden and gradual effects of the policy on emergency hospital admissions for CVD and its subtypes. A declining trend was observed for all emergency hospital admissions for CVD. However, there were no statistically significant sudden (relative risk (RR) 0.98, 95% confidence interval (CI) (0.94–1.02)) or gradual changes (RR 1.00, 95% CI (1.00–1.00)). Immediately after the policy, there was a sudden drop in HPD and AMI, which fell by 16% ((RR) 0.84, 95% (CI) 0.78–0.91) and 15% (RR 0.85, 95% CI (0.76–0.97)) respectively, followed by an insignificant gradual stable trend for both diseases. Stroke, heart failure and all other CVD admissions showed no statistically significant sudden or gradual changes following the policy. Emergency hospital admissions for stroke fell by 2% (RR 0.98, 95% CI (0.95–1.02)) immediately after the policy was implemented and heart failure increased by 1% (RR 1.01, 95% CI (0.93–1.08)). Both diseases showed a gradual stable trend (RR 1.00, 95% CI (1.00–1.00)) after the policy changed. All other CVD had a 5% (RR 1.05, 95% CI (1.00–1.10)) increase in emergency hospital admissions followed by a gradual stable trend (RR 1.00, 95% CI (1.00–1.10)). There was no difference in the policy effect estimates between men and women for all emergency hospital admissions for CVD or its subtypes considered (Table 3).

Our results showed, immediately after the policy, digestive diseases —the negative control— in contrast to CVD, had a 2% increase in emergency hospital admissions (RR 1.02, 95% CI (0.99–1.05) a few months after the policy. This was then followed by a static increasing trend (RR 1.00, 95% CI (1.00–1.00) (Fig. 3).

4. Discussion

In a developed non-Western setting with high levels of air pollution, implementation of the AQHI resulted in a non-significant minor drop in emergency CVD admissions in the elderly. Acute CVD such as: HPD and AMI emergency hospital admissions appeared to be the only CVD that significantly declined immediately after the policy, however, no gradual trend effects for either diseases were observed after implementation of the policy (Fig. 2). The policy had little or no effect onemergency hospital admissions for other types of CVD considered (Fig. 2), with little difference by gender.

To date only a few studies have assessed the effect of air quality alert programs on emergency hospital admissions for CVD (Chen et al., 2018; Mullins and Bharadwaj 2014). In contrast to our findings, a recent study in Canada, found a significant reduction in asthma visits but no reported difference in hospital admissions for any CVD considered as a result of their air quality alert program (Chen et al., 2018). However, this study was conducted in a city with relatively low pollution and only looked at 3 sub-types of CVD (AMI, heart failure and stroke).

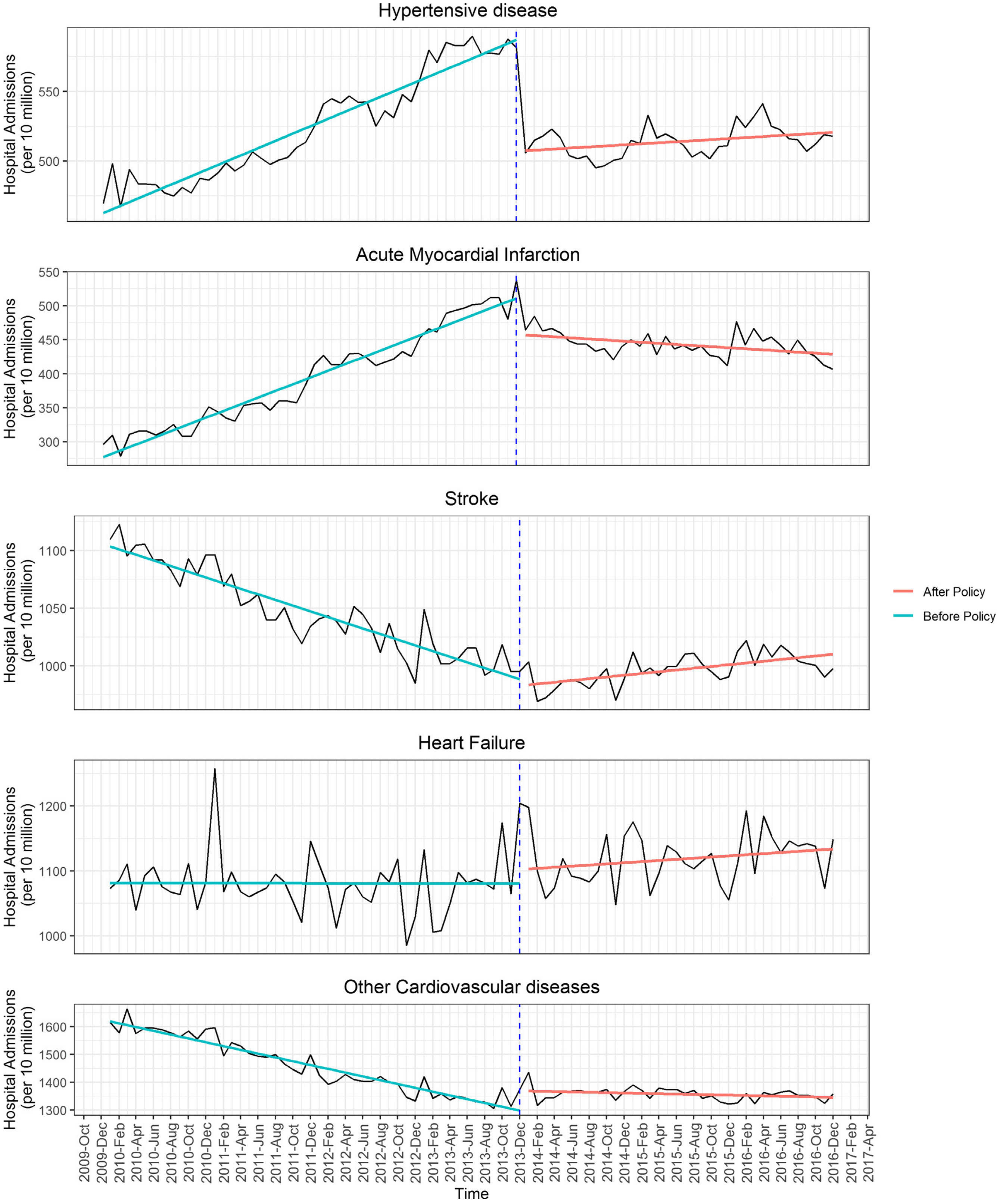

Fig. 2. Time series plots graphically displaying before and after monthly mean emergency hospital admissions for the elderly, adjusted for: seasonality, temperature, humidity, air pollutants and time trend; for cardiovascular sub-types from 2010 to 2016.

Furthermore, the study design — regression discontinuity— was based on days surrounding the alert cut-off without including the overall time trend: which could be another plausible reason for differences in results. In Chile, Mullins and Bharadwaj showed their alert program reduced overall mortality in the elderly but no change in CVD or respiratory mortality (Mullins and Bharadwaj, 2014). Our study included a wide range of CVD sub-types which are a more sensitive measure of cardiovascular health. Health benefits from implementation of the

Table 1
Descriptive statistics for monthly mean hospital admissions (counts per day) for cardiovascular diseases, covariates and meteorological variables; before and after implementation of the AQHI and for the entire study period (2010–2016).

	Before	After	Total
Predicted variables[*]	2010-2013[a]	2013-2016[b]	2010–2016
All Cardiovascular	4505.0 (4114.0, 4926.0)	4429.0 (4016.0, 4824.0)	4472 (4035.0, 4903.0)
Hypertensive	524.9 (456.2, 581.2)	514.0 (436.0, 564.5)	520.2 (449.0, 576.5)
Acute Myocardial Infraction	394.3 (301.8, 447.5)	442.9 (382.0, 498.0)	415.1 (357.0, 472.5)
Heart Failure	1081.0 (864.5, 1275.0)	1118.0 (867.8, 1316.0)	1097.0 (866.8, 1298.0)
Stroke	1046.0 (991.2, 1099.0)	996.8 (951.0, 1039.0)	1025.0 (972.8, 1070.0)
All other Cardiovascular	1459 (1354, 1536)	1357 (1313, 1400)	1415 (1323, 1484)
[‡]Digestive	2156.0 (2066.0, 2230.0)	2427.0 (2368.0, 2479.0)	2272.0 (2122.0, 2415.0)
Covariates			
NO_2(μg/m^3)	53.01 (36.9, 68.8)	44.11 (31.95, 51.7)	49.2 (34.9, 62.9)
SO_2(μg/m^3)	12.9 (8.5, 15.9)	9.42 (6.52, 12.03)	11.4 (6.97, 14.5)
PM_{10}(μg/m^3)	44.8 (27.03, 56.5)	36.92 (21.15, 46.7)	41.4 (24.9, 54.8)
O_3(μg/m^3)	45.3 (24.9, 62.0)	40.01 (23.4, 54.68)	43.01 (23.5, 60.4)
Meteorological variables			
Temperature	23.5 (20.7, 27.8)	24.0 (20.0, 28.8)	23.7 (20.1, 28.2)
Relative humidity	77.3 (73.0, 84.5)	80.0 (76.75, 87.0)	78.5 (73.0, 86.0)

Mean values were presented for each variable followed by their interquartile range (IQR).

[*] Monthly mean concentration of cardiovascular diseases in Hong Kong population per 1000.

[‡] Control disease for study excluding peptic ulcer diseases.

[a] Hong Kong's population at the end of 2013 = 7.2 million.

[b] Hong Kong's population at the end of 2016 = 7.3 million.

Table 2
Approximation of immediate and gradual changes of circulatory diseases after implementation of the AQHI policy in a multivariable analysis.[†]

Diseases	Immediate Effects	Gradual Effects
	RR (95% CI)	RR (95% CI)
All Cardiovascular	0.98 (0.94–1.02)	1.00 (1.00–1.00)
Hypertensive	**0.84 (0.78–0.91)**	0.99 (0.99–1.01)
Acute Myocardial Infarction	**0.85 (0.76–0.97)**	0.99 (0.98–0.99)
Stroke	0.98 (0.95–1.02)	1.00 (1.00–1.00)
Heart Failure	1.01 (0.93–1.08)	1.00 (1.00–1.00)
All other Cardiovascular	1.05 (1.00–1.10)	1.00 (1.00–1.10)
[*]Digestive	1.02 (0.99–1.05)	1.00 (1.00–1.00)

[†] Adjusted for seasonality, temperature, humidity, time trend, SO_2, NO_2, PM_{10}, O_3.

[*] Control disease for study excluding peptic ulcer diseases.

AQHI were mainly apparent in emergency hospitalization for acute CVD, such as HPD and AMI.

Air pollution is known to cause CVD through three mechanistic pathways. First, proinflammatory or oxidative stress mediators created in the lungs by air pollution may spill over into the systemic circulation. Second, air pollution may create an autonomic nervous system imbalance. Third, CVD may be the result of the penetration of certain PMs directly into cardiovascular tissue (Franklin et al., 2015). These mechanistic pathways have recently been elucidated from fairly recent mechanistic studies on how short term and long term exposure to air pollutants— such as PM— can cause acute vasoconstriction and impaired endothelial function (Adar et al., 2010; Franklin et al., 2015; Louwies et al., 2013). A number of epidemiological studies have reported, short term exposure to air pollution can trigger acute CVD, such as AMI (Murad 2015; Shah et al., 2013) and HPD (Brook et al., 2016; Giorgini et al., 2016; Guo et al., 2010). A biologically plausible explanation for AMI could be increased circulation of cytokines and inflammatory factors after short term exposure to air pollution (Bhaskaran et al., 2011; Brook et al., 2016; Eeden et al., 2001; Liu et al., 2017) as well as increased heart rate and heart rate variability (Liu et al., 2017; Liu et al., 2017; Pope et al., 2004). Biological plausibility for HPD involves a biphasic pathway. Exposure to air pollutants can cause an acute response within minutes-to-hours due to an autonomic nervous system imbalance that is caused by lung irritant sensory receptors and afferent nerve stimulation, inducing sympathetic activity; followed by an increase in blood pressure due to an increase arterial vasoconstrictor responsiveness that is caused by a chain of reactions such as: inflammation, endothelial dysfunction and oxidative stress (Giorgini et al., 2016).

Our study raises a question as to whether the AQHI is effective in protecting the public from the effects of air pollution. Although HPD and AMI declined, there was no significant decrease in emergency hospital admissions for overall CVD or other major CVD sub-types (stroke, heart failure and other CVD). Furthermore, our previous study using an interrupted time series to assess the effect of the AQHI on respiratory diseases, showed no significant decline for all respiratory diseases or for most of the specific respiratory diseases. A significant

Table 3
Approximation of immediate and gradual changes for circulatory diseases by sex category post AQHI policy in a multivariable analysis.[†]

Gender	Female		Male	
	Immediate Effects RR (95% CI)	Gradual Effects RR (95% CI)	Immediate Effects RR (95% CI)	Gradual Effects RR (95% CI)
All cardiovascular	0.98 (0.94–1.02)	1.00 (1.00–1.00)	0.98 (0.94–1.02)	1.00 (1.00–1.00)
Hypertensive	0.84 (0.77–0.93)	0.99 (0.99–1.00)	0.84 (0.78–0.92)	1.00 (0.99–1.00)
Acute Myocardial Infarction	0.86 (0.75–0.98)	0.99 (0.98–0.99)	0.85 (0.75–0.97)	0.98 (0.98–0.99)
[*]Digestive	1.02 (0.98–1.07)	1.00 (1.00–1.00)	1.01 (0.98–1.05)	1.00 (1.00–1.00)

[†] Adjusted for seasonality, temperature, humidity, time trend, SO_2, NO_2, PM_{10}, O_3.

[*] Control disease for study excluding peptic ulcer diseases.

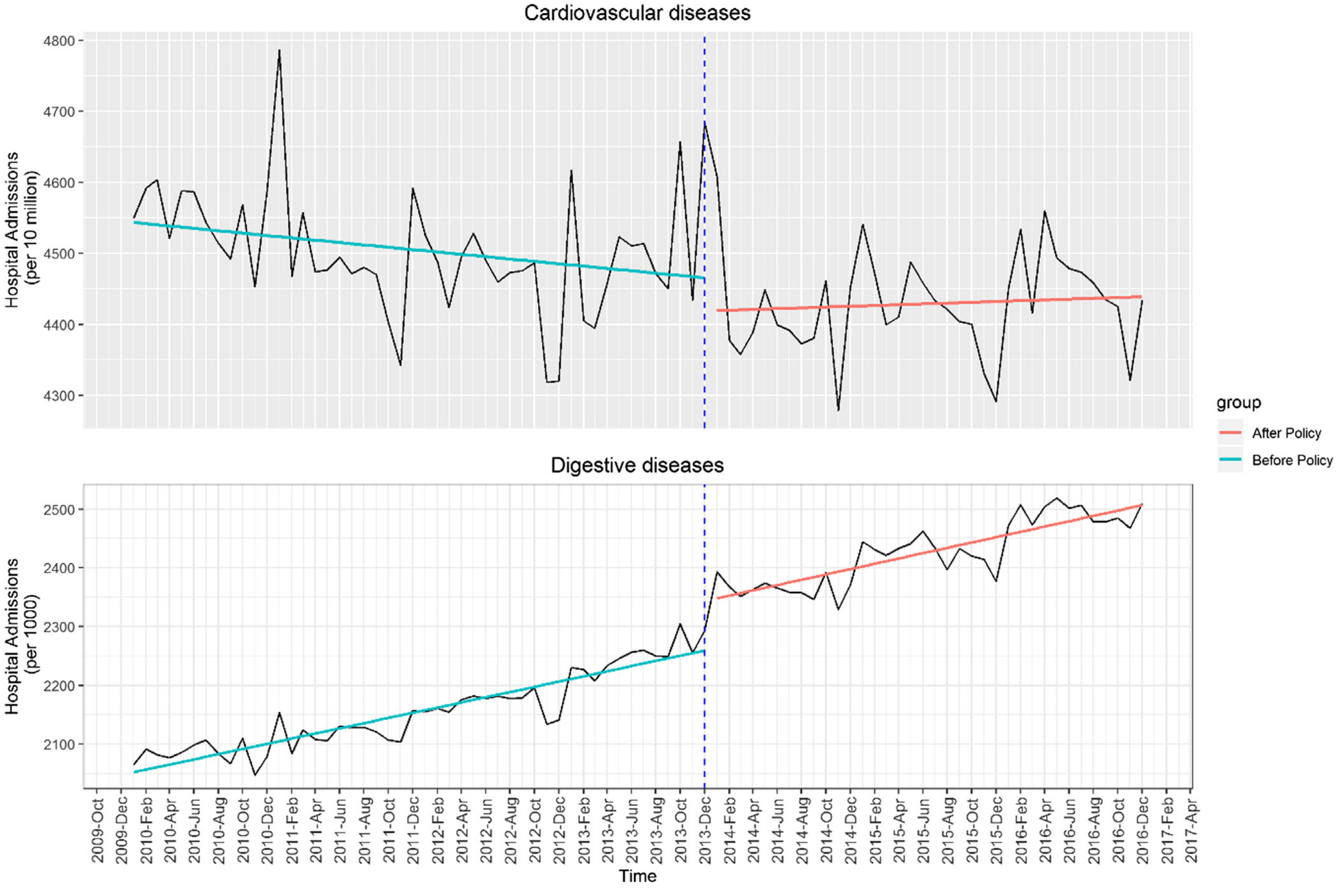

Fig. 3. Time series plots graphically displaying before and after monthly mean emergency hospital admissions for the elderly, adjusted for: seasonality, temperature, humidity, air pollutants and time trend; for all cardiovascular diseases and digestive diseases (control) from 2010 to 2016.

decline was only found for RTI after the AQHI was implemented (Mason et al., 2019b). The AQHI was created as a health education tool to inform the public, particularly the at-risk population, about the short-term effects of air pollution so that they could take action to take to reduce their exposure to harmful air pollution (Chen et al., 2014; Li et al., 2017; To et al., 2015). In Hong Kong, the AQHI readings are available to the public via several communication channels including a free smartphone app available on iTunes (EPD 2013b; To et al., 2015). Alerts are sent out via these communication channels on days of high air pollution. However, the index did not result in any significant decline in overall CVD emergency hospitalization, either because the relevant information was not disseminated effectively or was not acted upon. People may not have been aware of the information, may have ignored it or were not able to act upon it. For example, constraints imposed by employment, family responsibilities or living conditions may mean people cannot follow the recommendations. About 50% of the Hong Kong population lives in public housing which is small compared to private housing (Li et al., 2016), which may mean people still venture out on highly polluted days.

There were a few other air pollution policies contemporaneous with the implementation of the AQHI. Specifically, there were: the shipping emission policy implemented in 2015 and tobacco tax policies implemented in February 2011 and 2014. These policies however, did not coincide with the exact date the AQHI was implemented (December 30th, 2013) and hence do not explain the significant drop in the hospitalizations for certain CVD sub-types (HD, AMI). Smoking rates in Hong Kong are known to be low and the health response from both tobacco policies were minimal and gradual. The shipping emission policy occurred 18 months after the AQHI policy and the most noticeable effect from this policy was emission rates dropping in areas closer the shipping ports (Liu et al., 2018; Mason et al., 2019a). Studies have shown, the further you are inland, the less you are impacted by air pollution from marine sources (Liu et al., 2018; Ng et al., 2013). Hence, this policy cannot explain the drop in emergency CVD hospital admissions for an entire study population.

The main strength of our study is the design. The ITS design is known to be one of the strongest quasi-experimental designs because it is suited for the evaluation of interventions on a population level occurring at defined time periods (Bernal et al., 2017) while automatically controlling for base line and secular trends (Dennis et al., 2013; Mason et al., 2019a). This is also the first study in Hong Kong evaluating the impact of the AQHI on CVD emergency hospital admissions, in a targeted population. Furthermore, our study also contributes to the literature on the evaluation of air quality alert programs, such as the AQHI, for which there is limited evidence. Nevertheless, there are some limitations to our study: First, evaluating a control area, such as an area in mainland China, would have helped strengthen the validity of our study. However, such data were not available during the time period of our study. Secondly, the use of aggregated data rather than individual data means causal inference cannot be made on an individual level. However, our aim was to assess the policy impact on emergency hospitalizations for CVD at a population level. Lastly, information on other health care encounters, such as physician visits were missing.

5. Conclusion

The AQHI alert program in Hong Kong was effective at reducing some types of acute CVD hospitalizations in the elderly. Effects were less marked for all CVD and other major CVD sub-types. Effects were similar in men and women. Future research is warranted on how effective the AQHI communication channels are at reducing exposure to air pollution, and whether structural changes are needed to enable the elderly to properly follow AQHI warnings.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

The AQHI is calculated by using cumulative percentage excess risk for daily cardiorespiratory hospital admissions (%AR) associated with 3 h moving average of the 4 criteria pollutants below. The %AR used in the calculation is determined by local air pollution studies carried to measure the excess risk associated with air pollution and hospital admissions for cardiorespiratory diseases. The %AR is then compared to a scale to obtain the appropriate banding of AQHI. The equations are as follow:

$$\%AR = \%AR\ (NO_2) + \%AR\ (SO_2) + \%AR\ (O_3) + \%AR\ (PM)$$

Note: %AR (PM) = %AR (PM_{10}) or %AR ($PM_{2.5}$), whichever is higher

$$\%AR\ (NO_2) = [\exp\ (\beta(NO_2) \times C\ (NO_2)) - 1] \times 100\%$$

$$\%AR\ (SO_2) = [\exp\ (\beta(SO_2) \times C\ (SO_2)) - 1] \times 100\%$$

$$\%AR\ (O_3) = [\exp\ (\beta(O_3) \times C\ (O_3)) - 1] \times 100\%$$

$$\%AR\ (PM_{10}) = [\exp\ (\beta(PM_{10}) \times C\ (PM_{10})) - 1] \times 100\%$$

$$\%AR\ (PM_{2.5}) = [\exp\ (\beta(PM_{2.5}) \times C\ (PM_{2.5})) - 1] \times 100\%$$

where
%AR represents the added health risk of each pollutant;
C represents the 3-hour moving average concentration of the respective pollutants in microgram per cubic meter (μg/m^3); and
β is the measured regression coefficient associated with each pollutant.

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105344.

References

Adar, S.D., Klein, R., Klein, B.E.K., Szpiro, A.A., Cotch, M.F., Wong, T.Y., et al., 2010. Air pollution and the microvasculature: a cross-sectional assessment of in vivo retinal images in the population-based multi-ethnic study of atherosclerosis (MESA). B.P. Lanphear, ed PLoS Med. 7. https://doi.org/10.1371/journal.pmed.1000372.

Bernal, J.L., Cummins, S., Gasparrini, A., 2017. Interrupted time series regression for the evaluation of public health interventions: a tutorial. Int. J. Epidemiol. 348–355. https://doi.org/10.1093/ije/dyw098.

Bhaskaran, K., Wilkinson, P., Smeeth, L., 2011. Cardiovascular consequences of air pollution: what are the mechanisms? Heart 97, 519–520. https://doi.org/10.1136/hrt.2010.212183.

Bourdrel, T., Bind, M.-A., Béjot, Y., Morel, O., Argacha, J.-F., 2017. Cardiovascular effects of air pollution. Arch. Cardiovasc. Dis. 110, 634–642. https://doi.org/10.1016/J.ACVD.2017.05.003.

Brook, R.D., Rajagopalan, S., Pope, C.A., Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., et al., 2010. Particulate matter air pollution and cardiovascular disease. Circulation 121, 2331–2378. https://doi.org/10.1161/CIR.0b013e3181dbece1.

Brook, R.D., Sun, Z., Brook, J.R., Zhao, X., Ruan, Y., Yan, J., et al., 2016. Extreme air pollution conditions adversely affect blood pressure and insulin resistance: the air pollution and cardiometabolic disease study. Hypertension 67, 77–85. https://doi.org/10.1161/HYPERTENSIONAHA.115.06237.

Cairncross, E.K., John, J., Zunckel, M., 2007. A novel air pollution index based on the relative risk of daily mortality associated with short-term exposure to common air pollutants. Atmos. Environ. 41, 8442–8454. https://doi.org/10.1016/j.atmosenv.2007.07.003.

Chen, H., Li, Q., Kaufman, J.S., Wang, J., Copes, R., Su, Y., et al., 2018. Effect of air quality alerts on human health: a regression discontinuity analysis in Toronto. Canada. Lancet Planet. Heal. 2, e19–e26. https://doi.org/10.1016/S2542-5196(17)30185-7.

Chen, L., Villeneuve, P.J., Rowe, B.H., Liu, L., Stieb, D.M., 2014. The Air Quality Health Index as a predictor of emergency department visits for ischemic stroke in Edmonton, Canada. J. Expo. Sci. Environ. Epidemiol. 24, 358–364. https://doi.org/10.1038/jes.2013.82.

Cleveland, R.B., Cleveland, W.S., McRae, J.E., Terpenning, I., 1990. STL: a seasonal-trend decomposition procedure based on loess. J. Off. Stat. 6 (1), 3–73. http://www.nniiem.ru/file/news/2016/stl-statistical-model.pdf.

Cryer, J.D., Chan, K.-S., 2008. Time Series Analysis. Springer, New York, New York, NY.

Dennis, J., Ramsay, T., Turgeon, A.F., Zarychanski, R., 2013. Helmet legislation and admissions to hospital for cycling related head injuries in Canadian provinces and territories: interrupted time series analysis. BMJ 346, f2674. https://doi.org/10.1136/BMJ.F2674.

Eeden, S.F. Van, Tan, W.A.N.C., Suwa, T., Mukae, H., Terashima, T., Fujii, T., et al., 2001. Circulating Cytokine in PM 10 -exposed Subjects. ATS journals 164, 826–830.

Environment and Climate Change Canada. 2019. Air Quality Health Index. Available: http://www.ec.gc.ca/cas-aqhi/default.asp?lang=En&n=CB0ADB16%961 [accessed 14 January 2019].

EPD. EPD - About AQHI, 2013a.

EPD. EPD - About AQHI. Available: http://www.aqhi.gov.hk/en/what-is-aqhi/about-aqhi.html [accessed 2 July 2018], 2013b.

Franklin, B.A., Brook, R., Arden Pope, C., 2015. Air pollution and cardiovascular disease. Curr. Probl. Cardiol. 40, 207–238. https://doi.org/10.1016/j.cpcardiol.2015.01.003.

Giorgini, P., Di Giosia, P., Grassi, D., Rubenfire, M.D., Brook, R., Ferri, C., 2016. Air pollution exposure and blood pressure: an updated review of the literature. Curr. Pharm. Des. 22, 28–51. https://doi.org/10.2174/1381612822666151109111712.

Guo, Y., Tong, S., Li, S., Barnett, A.G., 2010. Gaseous air pollution and emergency hospital visits for hypertension. Environ. Heal. 9, 57–63. https://doi.org/10.1186/1476-069X-9-57.

Hong Kong Census and Statistics Department, 2017. Census and Statistics Department Hong Kong Special. Administrative Region.

Huang, J.V., Leung, G.M., Schooling, C.M., 2017. The association of air pollution with pubertal development: evidence from hong kong's “children of 1997” birth cohort. Am. J. Epidemiol. 185. https://doi.org/10.1093/aje/kww200.

Jassim, M.S., Gulnur, C., Said, M., 2018. Temporal analysis of air pollution and its relationship with meteorological parameters in Bahrain, 2006–2012. Arab. J. Geosci. 11 (3), 62. https://doi.org/10.1007/s12517-018-3403-z. Springer Berlin Heidelberg.

Lee, B.-J., Kim, B., Lee, K., 2014. Air pollution exposure and cardiovascular disease. Toxicol. Res. 30, 71–75. https://doi.org/10.5487/TR.2014.30.2.71.

Li, C.Z., Hong, J., Xue, F., Shen, G.Q., Xu, X., Luo, L., et al., 2016. SWOT analysis and Internet of Things-enabled platform for prefabrication housing production in Hong Kong. Habitat Int. 57, 74–87. https://doi.org/10.1016/j.habitatint.2016.07.002.

Li, X., Xiao, J., Lin, H., Liu, T., Qian, Z., Zeng, W., et al., 2017. The construction and validity analysis of AQHI based on mortality risk: a case study in Guangzhou, China. Environ. Pollut. 220, 487–494. https://doi.org/10.1016/J.ENVPOL.2016.09.091.

Liu, H., Jin, X., Wu, L., Wang, X., Fu, M., Lv, Z., et al., 2018. The impact of marine shipping and its DECA control on air quality in the Pearl River Delta, China. Sci. Total Environ. 625, 1476–1485. https://doi.org/10.1016/j.scitotenv.2018.01.033.

Liu, H., Tian, Y., Xiang, X., Sun, K., Juan, J., Song, J., et al., 2017. Air Pollution and Hospitalization for Acute Myocardial Infarction in China. Am. J. Cardiol. 120, 753–758. https://doi.org/10.1016/j.amjcard.2017.06.004.

Lopez Bernal, J., Cummins, S., Gasparrini, A., 2016. Interrupted time series regression for the evaluation of public health interventions: a tutorial. Int. J. Epidemiol. 46, 348. https://doi.org/10.1093/ije/dyw098.

Louwies, T., Panis, L.I., Kicinski, M., De Boever, P., Nawrot, T.S., 2013. Retinal microvascular responses to short-term changes in particulate air pollution in healthy adults. Environ. Health Perspect. 121, 1011–1016. https://doi.org/10.1289/ehp.1205721.

Mason, T.G., Chan, K.P., Schooling, C.M., Sun, S., Yang, A., Yang, Y., et al., 2019a. Air quality changes after Hong Kong shipping emission policy: an accountability study. Chemosphere 226, 616–624. https://doi.org/10.1016/j.chemosphere.2019.03.173.

Mason, T.G., Linwei, T., Schooling, C.M., Pan, C.K., 2019b. An evaluation of the Air Quality Health Index Program on respiratory diseases in Hong Kong: an interrupted time series analysis. Atmos. Environ. 211, 151–158. https://doi.org/10.1101/529313.

Mittleman, M.A., 2002. Trigger of acute cardiac events: new insights. Am. J. Med 4, 99–102.

Mullins, J., Bharadwaj, P., 2014. Effect of short-term measures to curb air pollution: evidence from Santiago. Chile. Am. J. Agric. Econ. 97, 1107–1134. https://doi.org/10.1093/ajae/aau081.

Murad, M.H., 2015. Clinician's corner main air pollutants and myocardial infarction. JAMA 307, 713–721.

Ng, S.K.W., Loh, C., Lin, C., Booth, V., Chan, J.W.M., Yip, A.C.K., et al., 2013. Policy change driven by an AIS-assisted marine emission inventory in Hong Kong and the Pearl River Delta. Atmos. Environ. https://doi.org/10.1016/j.atmosenv.2012.07.070.

Nuvolone, D., Balzi, D., Chini, M., Scala, D., Giovannini, F., Barchielli, A., 2011. Short-term association between ambient air pollution and risk of hospitalization for acute myocardial infarction: Results of the Cardiovascular Risk and Air Pollution in Tuscany (RISCAT) Study. Am. J. Epidemiol. 174, 63–71. https://doi.org/10.1093/aje/kwr046.

Perez, L., Nawrot, T.S., Perez, L., Künzli, N., Munters, E., Nemery, B., 2011. Articles Public health importance of triggers of myocardial infarction: a comparative risk assessment. Lancet 377, 732–740. https://doi.org/10.1016/S0140.

Peters, A., Dockery, D., Muller, J., Circulation MM-. 2001 undefined. Increased particulate air pollution and the triggering of myocardial infarction. Am Hear. Assoc.

Pope, C.A., Hansen, M.L., Long, R.W., Nielsen, K.R., Eatough, N.L., Wilson, W.E., et al., 2004. Ambient particulate air pollution, heart rate variability, and blood markers of inflammation in a panel of elderly subjects. Environ. Health Perspect. 112, 339–345. https://doi.org/10.1289/ehp.6588.

Shah, A.S.V., Langrish, J.P., Nair, H., McAllister, D.A., Hunter, A.L., Donaldson, K., et al., 2013. Global association of air pollution and heart failure: A systematic review and meta-analysis. Lancet 382, 1039–1048. https://doi.org/10.1016/S0140-6736(13)60898-3.

Sicard, P., Lesne, O., Alexandre, N., Mangin, A., Collomp, R., 2011. Air quality trends and potential health effects e Development of an aggregate risk index. Atmos. Environ. https://doi.org/10.1016/j.atmosenv.2010.12.052.

Stieb, D.M., Burnett, R.T., Smith-Doiron, M., Brion, O., Shin, H.H., Economou, V., 2008. A new multipollutant, no-threshold air quality health index based on short-term associations observed in daily time-series analyses. J. Air Waste Manage. Assoc. 58, 435–450. https://doi.org/10.3155/1047-3289.58.3.435.

Sun, S., Qiu, H., Ho, K.-F., Tian, L., 2016. Chemical components of respirable particulate matter associated with emergency hospital admissions for type 2 diabetes mellitus in Hong Kong. Environ. Int. 97, 93–99. https://doi.org/10.1016/j.envint.2016.10.022.

Szyszkowicz, M., Kousha, T., 2014. Emergency department visits for asthma in relation to the Air Quality Health Index: A case-crossover study in EWindsor. Canada. Can. J. Public Heal. 105, 336–341.

Tian, L., Qiu, H., Sun, S., Tsang, H., Chan, K.-P., Leung, W.K., 2017. Association between emergency admission for peptic ulcer bleeding and air pollution: a case-crossover analysis in Hong Kong's elderly population. Lancet Planet. Heal. 1, e74–e81. https://doi.org/10.1016/S2542-5196(17)30021-9.

To, T., Feldman, L., Simatovic, J., Gershon, A.S., Dell, S., Su, J., et al., 2015. Health risk of air pollution on people living with major chronic diseases: a Canadian population-based study. BMJ Open 5, e009075. https://doi.org/10.1136/bmjopen-2015-009075.

To, T., Shixin, S., Atenafu, E., Guan, J., 2013. The air quality health index and asthma morbidity: a population-based study. Environ. Health Perspect. 121.

WHO, 2018a. WHO | Ambient air pollution. WHO.

WHO, 2018b. WHO | Cardiovascular diseases (CVDs). WHO.

Wong, C.-M., Atkinson, R.W., Ross Anderson, H., Johnson Hedley, A., Ma, S., Yuen-Kwan Chau, P., et al., 2002a. A tale of two cities: effects of air pollution on hospital admissions in hong kong and london compared. Environ. Heal. Perspect. 110.

Wong, C.M., Lai, H.K., Tsang, H., 2015. Satellite-based estimates of long-term exposure to fine particles and association with mortality in elderly hong kong residents. Environ. Heal. Perspect. 123. https://doi.org/10.1289/ehp.1408264.

Wong, T.W., Tam, W.S., Yu, T.S., 2002b. Associations between daily mortalities from respiratory and cardiovascular diseases and air pollution in Hong Kong. China. Occup. Environ. Med. 59, 30–35. https://doi.org/10.1136/oem.59.1.30.

Wong, T.W., Wai, W., Tam, S., Tak, I., Yu, S., Kai, A., et al., 2013. Developing a risk-based air quality health index. Atmos. Environ. 76, 52–58. https://doi.org/10.1016/j.atmosenv.2012.06.071.

Yang, Y., Tang, R., Qiu, H., Lai, P.-C., Wong, P., Thach, T.-Q., et al., 2018. Long term exposure to air pollution and mortality in an elderly cohort in Hong Kong. Environ. Int. 117, 99–106. https://doi.org/10.1016/j.envint.2018.04.034.