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Developing a risk-based air quality health index

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HIGHLIGHTS

► We developed an air quality health index based on excess risk of morbidities.
► Excess risks were derived from time series analyses of data on hospital admissions.
► Risk categories were constructed based on the WHO Air Quality Guidelines.
► Advisory messages were developed for the general public including high-risk groups.
► This index has a short lag time and reflects health risk from multiple pollutants.

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ABSTRACT

We developed a risk-based, multi-pollutant air quality health index (AQHI) reporting system in Hong Kong, based on the Canadian approach. We performed time series studies to obtain the relative risks of hospital admissions for respiratory and cardiovascular diseases associated with four air pollutants: sulphur dioxide, nitrogen dioxide, ozone, and particulate matter with an aerodynamic diameter less than 10 μm (PM_{10}). We then calculated the sum of excess risks of the hospital admissions associated with these air pollutants. The cut-off points of the summed excess risk, for the issuance of different health warnings, were based on the concentrations of these pollutants recommended as short-term Air Quality Guidelines by the World Health Organization. The excess risks were adjusted downwards for young children and the elderly. Health risk was grouped into five categories and sub-divided into eleven bands, with equal increments in excess risk from band 1 up to band 10 (the 11th band is 'band 10+'). We developed health warning messages for the general public, including at-risk groups: young children, the elderly, and people with pre-existing cardiac or respiratory diseases. The new system addressed two major shortcomings of the current standard-based system; namely, the time lag between a sudden rise in air pollutant concentrations and the issue of a health warning, and the reliance on one dominant pollutant to calculate the index. Hence, the AQHI represents an improvement over Hong Kong's existing air pollution index.

1. Introduction

1.1. Objective

The objective of this study is to develop an air quality health index (AQHI) reporting system for Hong Kong that uses locally derived relative risk estimates of air pollutants on health outcomes. It should provide timely and risk-based information to the public on the short-term health risks of air pollution, and advise them of the appropriate behavioural responses to each situation.

1.2. The air pollution index reporting system

The air pollution index (API) reporting system currently used in Hong Kong is a risk communication tool that informs the public of the local level of ambient air pollution, and the potential health risk it would impose, particularly on vulnerable groups such as children, the elderly, and those with existing cardiovascular and respiratory diseases. People use the API to help them make decisions on

Abbreviations: API, Air Pollution Index; AQG, Air Quality Guideline(s); AQHI, Air Quality Health Index; AQO, Air Quality Objective(s); d.f., Degrees of freedom; ER(s), Excess risk(s); ICD, International Classification of Diseases; PM_{10}, Particulate matter with an aerodynamic diameter less than 10 μm; RR (s), Relative risk(s); US EPA, United States Environmental Protection Agency; WHO, World Health Organization.

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outdoor physical activities. In Hong Kong, schools and sports organisations may check the latest API figures to decide whether physical education lessons or outdoor sporting events should be conducted on a certain day. The API systems in many Asian countries, including China, Taiwan, Singapore, Malaysia, Thailand, South Korea, Macau, and Hong Kong, are based on the model advocated by the United States Environmental Protection Agency (US EPA). In the US system, pollutant concentrations for each pollutant, measured in a network of monitoring stations, are transformed to a normalised numerical scale of 0–500. The key reference point is the index value of 100, which is reported whenever any of the monitored pollutants reaches the level set by its respective primary National Ambient Air Quality Standard (US EPA, 1999, 2006). Hong Kong has adopted the US method, but uses its own Air Quality Objectives (AQO) for four 'criteria' air pollutants – particulate matter with an aerodynamic diameter less than 10 μm (PM_{10}), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and ozone (O_3). These AQO were first established in 1987, for the derivation of the Hong Kong API. The index value of 50 is anchored to Hong Kong's long-term AQO.

A major shortcoming of the US-based system is that the calculation of the index depends on whichever air pollutant deviates the most from its reference standard, without regard to the concentrations of the other pollutants. This implies that the joint effect of air pollutants is not considered. Moreover, even though the API is calculated on an hourly basis, the choice of averaging times used as reference standards will affect the timeliness of the reporting system. In Hong Kong, where the 24-h average concentrations of PM_{10} are used as a reference, there is considerable time lag between a sudden, rapid increase in PM_{10} concentration and a rise in API above the warning level, as the latter is derived from the average PM_{10} concentrations over the past 24 h. To address these shortcomings, several researchers have proposed alternative approaches. The Canadian AQHI adopted a multi-pollutant approach that summed up the health risk posed by individual pollutants (Stieb et al., 2008). In the South African system, Cairncross also used a multi-pollutant approach, but anchored the health risk to the World Health Organization (WHO) guideline concentration for O_3 as a reference level for the other pollutants (Cairncross et al., 2007). A similar approach was adopted by Sicard et al. (2011), using $PM_{2.5}$ as a reference instead. An aggregate index using five air pollutants ($PM_{2.5}$, PM_{10}, NO_2, O_3 and SO_2) was further developed for European cities (Sicard et al., 2012).

2. Methods

2.1. Summary of procedures

Using time series analyses, we derived relative risks (RRs) of emergency hospital admissions for respiratory and cardiovascular diseases, associated with four major air pollutants routinely monitored in Hong Kong. With these RRs, we calculated the excess risk (ER, which equals RR – 1) of daily hospital admissions associated with each of these air pollutants, expressed as a percentage (%ER), and summed the %ERs of all four pollutants. The reference of the RR (where RR = 1) was set at zero concentrations of all air pollutants. We then grouped them into categories and bands, and developed advisory messages to the public, including specific advice for outdoor workers (included in response to strong community demand) and for susceptible groups (i.e. children, the elderly, and people with existing illnesses).

2.2. Time series analyses

Hospital data from 2001 to 2005 were obtained from all public hospitals under the Hospital Authority that had accident and emergency services. The Hospital Authority is a government-funded organisation which provides over 90% of all hospital beds in Hong Kong, and thus provides us with a sampling frame that has a wide coverage throughout the city. Diagnoses were coded using the International Classification of Diseases (ICD), 9th Revision (WHO, 1977). The following codes were used: 'all diseases of the respiratory system' (ICD 460–519), and 'all diseases of the cardiovascular system' (ICD 390–459). Daily meteorological variables – namely, mean temperature and humidity – were obtained from the Hong Kong Observatory. Hourly air pollutant concentrations were provided by the Environmental Protection Department of Hong Kong.

We performed the Poisson regression on daily emergency hospital admissions for respiratory and cardiovascular diseases combined (the dependent variable), using a generalised additive model. Smoothing for the time variable was done using smoothing splines, with varying degrees of freedom (d.f.). We chose the model with 70 d.f., in which the RRs of the air pollutants were at or near their peak values.[1] The rationale for our model choice was to estimate the highest levels of risk associated with the air pollutants, while maintaining a balanced contribution of %ERs among the four pollutants.[2] The model was adjusted for potential confounders, including daily mean temperature and relative humidity, a 'day of the week' indicator, a holiday indicator, and a season indicator. Over-dispersion was adjusted by the quasi-likelihood method and auto-correlation was adjusted by adding auto-regressive terms into the core model. Residuals plots and partial autocorrelation function (PACF) plots were used to examine the model's goodness of fit.

Following the Canadian methodology, we added the maximum of the 3-hourly moving average concentrations of the pollutants on each day in the model (Stieb et al., 2008). This represented a compromise between the timeliness of air pollutant data and the stability of the air quality health index (AQHI), which would be reported hourly, though based on calculations using the 3-h moving average concentrations of the constituent pollutants. The model was tested for the lag effect of air pollution, using air pollutant concentrations on the same day (lag day 0), the previous day (lag day 1) and two days previously (lag day 2). The 'best lag day' (i.e. one when the RR was statistically most significant) for each air pollutant was chosen according to the maximum t-value, calculated using the gam.exact function of S-PLUS (iHAPSS, 2002; Dominici et al., 2004).

The core model (before the air pollutant concentrations were added) is shown as follows:

Log (resp card 0) = resp card 1 to 7 + s (day, d.f. = 70) + s (humidity, d.f. = 15) + s (temperature, d.f. = 15) + day of week indicator + season indicator + holiday indicator.

2.2.1. Explanatory notes

The dependent (outcome) variable, resp card 0, is the daily number of emergency hospital admissions for respiratory diseases and cardiovascular diseases.

[1] In the generalised additive model, the degrees of freedom (d.f.) for the smoothing parameter tested were: 0, 10, 20, … up to 160. RR estimates varied with varying d.f., and peaked at different d.f. The model with 70 degrees of freedom was chosen because the RRs of the air pollutants were near their maximum values.

[2] At d.f. = 70, the relative weights of the RRs of all pollutants in their contribution to the %ER were much more balanced than when using RRs derived from the statistically 'best-fit' model, where the minimum Akaike information criterion (AIC) appeared at d.f. = 147. At d.f. = 70, the ratio of the regression coefficient (β) values for NO_2, O_3, SO_2, and PM_{10} were: 3:4:1:2. At d.f. = 147, where the RR of O_3 was much higher than the others, the corresponding ratios were: 5:10:1:3. This implied that the %ER will be dominated by O_3 concentrations while other pollutants' contributions to the %ER would be much smaller.

The independent variables are:

Resp card 1 to 7 = resp card 1 + resp card 2 + resp card 3 + resp card 4 + resp card 5 + resp card 6 + resp card 7. These are the numbers of emergency hospital admissions for respiratory and cardiovascular diseases from lag day 1, day 2, … to day 7. They are also called auto-regressive terms. s (day, d.f. = 70) is the time (or day) variable, smoothed with 70 degrees of freedom.s (humidity, d.f. = 15) is the daily mean humidity, smoothed with 15 degrees of freedom.s (temperature, d.f. = 15) is the daily mean temperature (in Celsius), smoothed with 15 degrees of freedom.

Day of week indicator shows the day of the week variable (Monday, Tuesday, …, Sunday).

(Cold) season indicator takes the value 1 from December to February, and 0 during the period from March to November.

Holiday indicator takes the value of 1 on public holidays, and 0 on all other days.

3. Calculations

3.1. Excess risk of hospital admissions for respiratory and cardiovascular diseases

The percentage of excess risk of hospital admissions for respiratory and cardiovascular diseases associated with air pollutants (%ER) was expressed as: $\Sigma_{i=1,\ldots p}\ (e^{\beta_i x_{ij}}-1) \times 100\%$. β_i was the regression coefficient of pollutant i from the time series analysis, and x_{ij} was the concentration of pollutant i at time j, for a total of p pollutants. The %ER was calculated using the concentrations of four pollutants, NO_2, O_3, PM_{10}, and SO_2, for each day over the five-year period. An equal weight was assumed for each pollutant.

Similar models were constructed using the hospital admissions for children below 5 years of age and for adults aged 65 years and above, and their corresponding %ERs were estimated using the respective regression coefficients (β) for the pollutants obtained from these models, as described above.

3.2. Banding of the risk of hospital admissions associated with air pollution

The %ERs were grouped into five categories, according to the risk level from short-term exposure to air pollution: low risk, moderate risk, high risk, very high risk, and serious risk. We used the short-term exposure limits of the four air pollutants, as recommended by the WHO (2005) in their Air Quality Guidelines (AQG), to calculate a summed %ER. This figure formed the lower cut-off point of the 'very high risk' category, where the general public is at a significant health risk. The recommended short-term exposure limit values of the WHO AQG for our four pollutants were: 129.8 μg m^{-3} for NO_2 (adjusted downwards from 200 μg m^{-3}, the one-hour mean)[3]; 100 μg m^{-3} for O_3 (8-h mean), 50 μg m^{-3} for PM_{10} (24-h mean), and 20 μg m^{-3} for SO_2 (24-h mean). A %ER that was at least 50% higher than this %ER value is labelled as 'serious risk'. To address the health risk to the vulnerable groups – children aged under 5, and the elderly aged 65 years and above – the reference point for the %ER of these groups was further adjusted. An adjustment factor was derived from the ratio of the median %ER for children under 5 or those aged 65 years and above (using the larger value of the two) to that for all ages. The adjusted %ER, defined as the maximum allowable risk for short-term exposure to air pollutants by the vulnerable groups, was obtained by dividing the % ER for all ages by this adjustment factor. This new cut-off point formed the upper boundary of the 'high risk' category. Half of this adjusted %ER was arbitrarily used as a dividing line between the 'low risk' category ($\leq$0.5 × adjusted %ER) and the 'moderate risk' category (>0.5 × adjusted %ER to $\leq$ adjusted %ER).

Three of the categories – low risk, moderate risk, and very high risk – were further sub-divided into equal thirds, forming nine bands. These, together with the 'high risk' category (containing only one band), made a total of ten bands. These ranged from band 1 at the lower end of the 'low risk' category, to band 10 at the upper limit of the 'very high risk' category. A %ER beyond band 10 was labelled as 'band 10+' and indicated a 'serious risk' to health.

[3] The WHO AQG for short-term exposure are: 200 μg for NO_2 (1-h), 100 μg for O_3 (8-h mean), 50 μg for PM_{10} (24-h) and 20 μg for SO_2 (24-h). Since the averaging time for NO_2 was one hour, we calculated the corresponding value of the NO_2 concentration for a 3-h moving average, by regressing the hourly concentrations with the 3-h moving average in a linear regression model using NO_2 data in our study period. The corresponding value was 184.45 μg m^{-3} with a lower 95% confidence limit of 129.8 μg m^{-3}. The lower 95% confidence limit of 129.8 μg m^{-3} was used as the concentration in our calculation of %ER for NO_2.

4. Results

4.1. Relative risks of emergency hospital admissions for cardio-respiratory diseases

All four air pollutants (NO_2, O_3, PM_{10} and SO_2) had significantly raised RRs of emergency hospital admissions for respiratory and cardiovascular diseases for all age groups combined (Table 1). The RRs were significant at $p < 0.0001$ for the first three pollutants. For SO_2, p was 0.013. The 'best' lag day was lag day 0 (same day) for all pollutants except O_3 (where lag day 1 was the 'best' lag day).

4.2. Sensitivity analysis

To examine the effect of influenza on hospital admissions, we added an indicator variable to the model using an arbitrary definition of an influenza week, as one during which the number of influenza hospital admissions exceeded the 75th percentile for the year (Wong et al., 2002). The differences in RR from that in our original model ranged from −0.0013% to −0.0131%, which had little effect on our calculation of % excess risks. There was little change in the statistical significance of the RRs. To test the stability of the model, we split the time series into two periods (2001–2003 and 2004–2005) and ran the models separately. All the RRs were very similar to that in the original model, with differences ranging from −0.0061% to 0.144%, for the 2-year model, and from −0.0195% to 0.0796% for the 3-year model. The 95% confidence intervals of the RRs in the split models were wider, but remained statistically significant, except for SO_2 in the 3-year model.

4.3. Excess risks of hospital admissions associated with air pollution

The excess risk of hospital admissions associated with air pollution, expressed as a percentage (%ER), ranged from 2.64% to 31.51% in the 5-year study period, with a median of 9.04% and a mean of 9.50%.

4.4. Excess risks of hospital admissions among high-risk groups

Using RRs derived separately from the time series models for children and for those aged 65 and above, we calculated the respective %ERs for hospital admissions for cardiovascular and respiratory diseases. For those aged 65 and above, the minimum, median, mean and maximum %ERs were: 3.02%, 10.34%, 10.86% and 36.25% respectively. For children under 5 years of age, the minimum, median, mean and maximum %ERs were: 2.59%, 9.44%, 10.01% and 33.32% respectively.

Table 1
Relative risk of hospital admissions for cardiovascular and respiratory diseases per 10 μg m^{-3} increase in air pollutant concentrations.

RR (95% CI) per 10 μg m^{-3} increase in air pollutant concentration (single pollutant model)				
Emergency hospital admissions	NO_2	O_3	PM_{10}	SO_2
Cardiovascular and respiratory (all ages)	1.0045[d] (1.0044–1.0046) (lag day 0)	1.0051[d] (1.0050–1.0052) (lag day 1)	1.0028[d] (1.0027–1.0029) (lag day 0)	1.0014[b] (1.0013–1.0015) (lag day 0)
Cardiovascular and respiratory (≥65 years)[a]	1.0051[d] (1.0039–1.0063) (lag day 0)	1.0057[d] (1.0045–1.0069) (lag day 1)	1.0033[d] (1.0028–1.0044) (lag day 0)	1.0017[b] (1.0003–1.0030) (lag day 0)
Cardiovascular and respiratory (<5 years)	1.0034[c] (1.0032–1.0037) (lag day 2)	1.0074[d] (1.0072–1.0077) (lag day 0)	1.0025[b] (1.0003–1.0048) (lag day 2)	1.0019 (NS) (0.9991–1.0046) (lag day 1)

[a]The ≥65 years age group constituted about 80% of all respiratory and cardiovascular admissions; [b]$p < 0.05$, [c]$p < 0.001$, [d]$p < 0.0001$; NS = not significant at $p = 0.05$.

4.5. Health risk categories and AQHI bands

The %ERs that constituted the cut-off points for the five categories of risk are shown in Table 2 and Fig. 1. A summed %ER of 12.91% was obtained for the general public (all ages). This became the upper cut-off point for the 'high risk' category. For the vulnerable groups – comprising both children aged below 5 years, and the elderly aged 65 years and above – the %ER of 12.91% was adjusted downwards to 11.29%.[4] This formed the lower cut-off for the 'high risk' category. Half of this (5.64%) was taken to be the lower cut-off point of the 'moderate risk' category, while the %ER at 5.64% or below was labelled as 'low risk'. The 'serious risk' category refers to a %ER of 19.37% (50% higher than 12.91%).

4.6. Health advice

The health advice for different population groups corresponding to each band is shown in Table 3.[5]

4.7. Interaction of air pollutants with the cold season

We further examined the interaction between the cold season and the effects of air pollutants by adding interaction terms (season × air pollutant concentration) into the model. Only O_3 had significant interaction with season, with the RR being higher in the cold season (December to March). Accordingly, the contribution by O_3 to %ER was greater in the winter months than in other months. We also tested for interaction between different air pollutants by adding interaction terms. All were statistically insignificant and were excluded in the final model.

5. Discussion

5.1. Assumptions of the AQHI system

Based on the Canadian methodology, we calculated the excess risks of hospital admissions for cardiovascular and respiratory diseases that are associated with air pollution. There are several important assumptions. First, we have assumed that the risk is linear and without a threshold. There is much epidemiological evidence in support of this assumption, especially for the effects of particulates and ozone (WHO, 2005). We have also assumed that each air pollutant contributes independently to health risk, derived from the RR obtained in a single pollutant model. Owing to the collinearity of some air pollutants which share common sources, their individual RRs cannot be reliably estimated in a multi-pollutant model. We also explored the potential synergistic effects of air pollutants. All interaction terms in the model were statistically insignificant and have little effect on our risk estimate. The use of all four air pollutants in the AQHI calculation is an improvement from the current Hong Kong API, where only one air pollutant – whichever happens to exceed the AQO the most – is considered at any given time.

The concept of additive health risk was also used in the development of air pollution indices by Cairncross et al. (2007) and Sicard et al. (2011, 2012). In these studies, the cut-off points between two indices or bands were arbitrarily chosen, using the concentration of one air pollutant as a reference. The concentrations that would put the other pollutants, with their respective RRs, in the same 'index' or band as the reference pollutant were then calculated. In Cairncross's study, the UK standard of 100 μg m^{-3} for 1-h O_3 was chosen as the cut-off point between the index values of 2 and 3 (the latter being the highest index value of the 'low' band.). In Sicard's study (2011), the WHO AQG for 24-h PM_{10} of 50 μg m^{-3} was used as the cut-off point between the index values of 3 (low) and 4 (moderate).

5.2. Strengths and weaknesses of the AQHI system

A major strength of the AQHI is that our health risk estimates are derived from RRs using local health statistics and air pollution data, instead of relying on RRs published elsewhere. Time series

Table 2
Distribution of percentage excess risk (%ER) of hospital admissions for cardiovascular and respiratory diseases by health risk category and AQHI band.

Recommended health risk category	AQHI band	%ER	No. of days	Frequency (%)
Low	1	0–1.88	0	0.0
	2	>1.88–3.76	36	2.0
	3	>3.76–5.64	333	18.2
Moderate	4	>5.64–7.52	277	15.2
	5	>7.52–9.41	339	18.6
	6	>9.41–11.29	306	16.8
High	7	>11.29–12.91	194	10.6
Very high	8	>12.91–15.07	172	9.4
	9	>15.07–17.22	93	5.1
	10	>17.22–19.37	27	1.5
Serious	10+	>19.37	49	2.7
Total			1826	100.00

[4] The median %ER for the elderly (at 10.34%) was higher than that for the children (at 9.44%) and for all ages (9.04%). The ratio of the median %ER for the elderly to that for all ages was 10.34/9.04, or 1.144. Hence, we scaled down the %ER of 12.91% for people of all ages by a factor of 1.144 to obtain a figure for the elderly: 12.91/1.144 = 11.29. Using this %ER as a cut-off point should protect the children as well as the elderly.

[5] In response to demand from different sectors of the community, the health advice included persons with cardiovascular and/or respiratory diseases and outdoor workers, in addition to children and the elderly, and the general public. It should be noted that the advice was not based directly on the risk estimates from the results of this study. Advice for persons with cardiovascular/respiratory diseases generally follows that for children and the elderly, whereas outdoor workers were assumed to be healthy, non-elderly adults. 1.

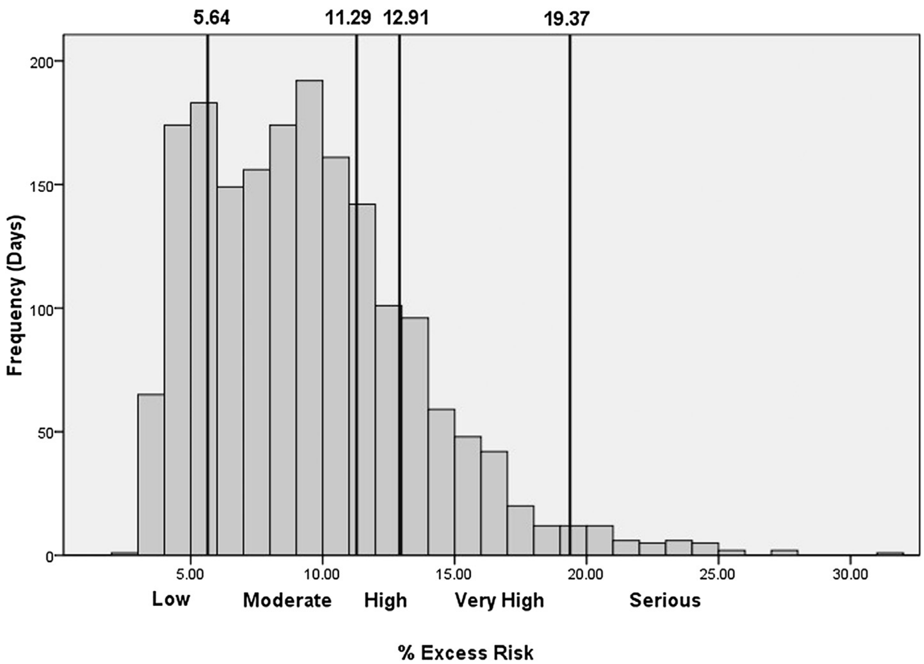

Fig. 1. Distribution of percentage excess risk (%ER) and the categories of health risk.

models have been extensively used for estimating RRs of short-term exposure to air pollutants on health. An important feature of this approach is that risk factors that do not change on a daily basis, for example smoking prevalence, need not be adjusted, even though smoking is a strong personal risk factor for cardio-respiratory diseases (Schwartz et al., 1996). Our model has been tested by splitting the series into two periods, and by adding an indicator for influenza. Sensitivity analyses have shown that our model is robust – the RRs are similar with or without adjustment for influenza, and whether or not the models are split.

However, the RRs in our study cannot be compared with RRs reported in other studies, owing to the differences in the averaging time of the air pollutants used in model building. While most studies use the 24-h mean concentration of air pollutants, we followed the Canadian approach in using the 3-h moving mean concentration (Stieb et al., 2008). The RRs obtained are 50%–70% of their corresponding RRs derived from using 24-h means (data not shown). Our findings are similar to that reported by Stieb et al. (2008). We have used emergency hospital admissions for cardiovascular and respiratory diseases as the health outcomes of air pollution, instead of mortality, as in the Canadian approach (Stieb et al., 2008). Mortality represents only the 'top of the pyramid' in the spectrum of health outcomes and is dominated by the elderly population. By contrast, hospitalisation affects a greater number of people of different ages, including children, who are highly susceptible to air pollution. Our hospital data are of high quality, and covered more than 90% of emergency hospital admissions in Hong Kong. Although the RR of SO_2 is comparatively low, we included it in our AQHI calculations – in contrast to the Canadian system by Stieb et al. (2008) – to safeguard against any future increase in SO_2 concentrations from whatever sources.

PM is an important cause of mortality and the effects of long-term exposure have been quantified (COMEAP, 2010). Using $PM_{2.5}$ instead of PM_{10} in our model, we found that the RR of hospital admissions for cardiovascular and respiratory diseases was 1.0022 (per 10 $\mu g\ m^{-3}$ increase of $PM_{2.5}$), which was slightly lower than 1.0028 for PM_{10}. The %ERs worked out to be fairly similar. However, we opted for PM_{10} in our model as $PM_{2.5}$ measurements are available in only a few air pollutant monitoring stations in Hong Kong. Moreover, the AQHI derived from PM_{10} provided a better estimate of health risk during dust storms (caused by wind-blown dust from China), where the predominant pollutant is PM_{10} instead of $PM_{2.5}$.

The use of a single RR for O_3, regardless of the season, is a simplified approach in the calculation of the %ER. Ozone is known to exert different effects in warm and cold weather (Dear et al., 2005; Ren et al., 2008a, 2008b; Zhang et al., 2006; Kan et al., 2008). Although the addition of an interaction term (O_3 concentration × seasonal indicator) in the model should have better reflected the health risk, the inclusion of a seasonal indicator might cause an abrupt change when reporting %ER values during the two transitional days between the 'warm' and 'cold' seasons. We consider that this disadvantage outweighs its advantage.

Because of chemical reactions between O_3 and oxides of nitrogen (NO_x), roadside levels of O_3 are not high and therefore have not been monitored in Hong Kong until recently. The derivation of the roadside AQHI can be performed in the same way if roadside O_3 concentrations are available in roadside stations.

To reduce the time lag between a rise in air pollutant levels and the reporting of a raised AQHI, we used the 3-h moving average of the concentrations of air pollutants in calculating the AQHI on an hourly basis, in accordance with the Canadian approach. The present API system, which depends on a 24-h mean concentration of PM_{10}, would inevitably suffer from a much longer time lag. As the RRs for air pollutants vary between communities, the use of local health and air pollutant data in deriving the RRs and %ERs for the AQHI provided more realistic and timely estimates of health risk from short-term exposure to air pollution.

The banding system of the Canadian approach is related neither to its national air quality standards, nor to the WHO AQG. Instead, the categories of air quality are grouped to form ten equal bands throughout the entire range of %ERs. If we adopted this banding system, Hong Kong might have a similar proportion of days with 'low risk', 'moderate risk', 'high risk', and 'very high risk' categories as in Canadian cities, even though Hong Kong has poorer air quality compared to Canada. To overcome the lack of reference to any air quality standards, we calculated the %ERs based on the WHO

Table 3
The air quality health index and associated health advice.

Health risk category	AQHI band	%ER	(i) People who are sensitive to air pollution		(ii) Outdoor workers[a]	(iii) General public
			(a) People with existing heart or respiratory illnesses	(b) Children and the elderly		
Low	1 2 3	0–1.88 >1.88–3.76 >3.76–5.64	No response action is required.	No response action is required.	No response action is required.	No response action is required.
Moderate	4 5 6	>5.64–7.52 >7.52–9.41 >9.41–11.29	No response action is normally required. Individuals who are experiencing symptoms are advised to **consider reducing** outdoor physical exertion.	No response action is required.	No response action is required.	No response action is required.
High	7	>11.29–12.91	People with existing heart or respiratory illnesses (such as coronary heart disease and other cardiovascular diseases, asthma and chronic obstructive airways diseases including chronic bronchitis and emphysema) are advised to **reduce** outdoor physical exertion, and to **reduce** the time of their stay outdoors, especially in areas with heavy traffic. They should also seek advice from a medical doctor before participating in sport activities and take more breaks during physical activities.	Children and the elderly are advised to **reduce** outdoor physical exertion, and to **reduce** the time of their stay outdoors, especially in areas with heavy traffic.	No response action is required.	No response action is required.
Very high	8 9 10	>12.91–15.07 >15.07–17.22 >17.22–19.37	People with existing heart or respiratory illnesses are advised to **restrict** outdoor physical exertion, and to **restrict** the time of their stay outdoors, especially in areas with heavy traffic.	Children and the elderly are advised to **restrict** outdoor physical exertion, and to **restrict** the time of their stay outdoors, especially in areas with heavy traffic.	Outdoor workers are advised to **reduce** outdoor physical exertion, and to **reduce** the time of their stay outdoors, especially in areas with heavy traffic. Employers are advised to assess the risk of outdoor work, and take appropriate preventive measures to protect the health of their employees.	The general public is advised to **reduce** outdoor physical exertion, and to **reduce** the time of their stay outdoors, especially in areas with heavy traffic.
Serious	10+	>19.37	People with existing heart or respiratory illnesses are advised to **avoid** outdoor physical exertion, and to **avoid** staying outdoors, especially in areas with heavy traffic.	Children and the elderly are advised to **avoid** outdoor physical exertion, and to **avoid** staying outdoors, especially in areas with heavy traffic.	Outdoor workers are advised to **restrict** outdoor physical exertion, and to **restrict** the time of their stay outdoors, especially in areas with heavy traffic. Employers are advised to assess the risk of outdoor work, and take appropriate preventive measures to protect the health of their employees.	The general public is advised to **restrict** outdoor physical exertion, and to **restrict** the time of their stay outdoors, especially in areas with heavy traffic.

Additional health advice:
1. As the health effects on individuals may vary, you should seek advice from a medical doctor if you are in doubt or feel uncomfortable. If you are suffering from existing heart or respiratory illnesses (such as coronary heart disease and other cardiovascular diseases, or asthma and chronic obstructive airway diseases, including chronic bronchitis and emphysema), you should follow your doctor's advice on the amount of physical exercise and the management of your illness under different air quality health index bands. If you are a smoker, you should quit smoking now!
2. Outdoor workers need to be aware of the potential impact on their health at times when the AQHI reaches 'very high' or 'serious' health risk, and seek advice from a medical doctor if they are in doubt of their health condition or suffer from any chest or breathing discomfort. They should inform their employers of the medical advice so that suitable work arrangements can be made.
3. The amount of physical exercise that should be performed differs according to the individual's physical capacity, and should be tailored to one's own physical condition. Ask your doctor for advice.

[a] Advice in this column applies to outdoor workers who do not belong to group (i), people who are sensitive to air pollution.

short-term AQG (with a downward adjustment of the WHO 1-h AQG for NO_2). One criticism against the summation of %ERs based on the WHO AQG is that they are meant to protect against health risk for a breach in any one of the four pollutants. Our rationale for advocating the summed %ER as the cut-off point for 'very high risk' is based on the assumption that, on a day when all four pollutants are at or above their WHO AQG levels, the health risk should be considered unacceptably high to the general public and would require the issue of a health warning. Setting the cut-off point for 'very high risk' by the %ER value of only one pollutant at the WHO AQG level would imply the issue of health warnings on most days of the year. This will lead to 'information fatigue' by the public and defeats the purpose of this risk communication system. We emphasise that the %ER refers to short-term risk. For the assessment of long-term health risk, the public is advised to make reference to the long-term Air Quality Index, which compares the annual concentrations of the four pollutants relative to the long-term WHO AQG.

To further reduce the %ER to the elderly and children, who are more vulnerable to air pollution-related illnesses, we adjusted the %ER for the general population downwards by an adjustment factor. This reduced %ER, the cut-off point for 'high risk', implies that the elderly and children can tolerate a lower level of risk compared to the general public. We arbitrarily designated, as the 'low health risk' category, one that causes less than 50% of the %ER at the WHO short-term AQG risk levels, adjusted for the elderly. We acknowledge that if the concentration of one pollutant is much higher than its WHO AQG while others are much lower, the health risk might still be categorised as 'low' or 'moderate'. In other words, even on a 'low risk' day one cannot assume that all four target pollutants are within the WHO AQG risk levels. However, as PM_{10} and NO_2 are strongly correlated, it is unlikely for the concentration of PM_{10} to be high while NO_2 is low, or vice versa. O_3 is much less correlated with the other three pollutants. The relatively high RR of O_3 makes it unlikely for a day with high O_3 concentration to fall into the 'low risk' category. The %ERs used as cut-off points for various bands used in our system are similar to those used by Cairncross et al. (2007) and Sicard et al. (2011).

5.3. Health advice

The health advice given to the general population, and to the high risk groups, generally follows the Canadian approach. The only difference is in the way the health risk categories and bands are constructed, as described before. The aim is to inform and advise those at higher risk on their outdoor activities and physical exercise, including those with cardiovascular and respiratory diseases, as well as outdoor workers. When the air quality is good, they can enjoy their daily outdoor activities freely; but at various poorer levels of air quality, they should be informed on the appropriate actions to take, and protect themselves from excessive exposure to outdoor air. One limitation in our health advisory is that the AQHI was not derived separately for those with and without existing cardiovascular and respiratory health problems. Hence, the %ERs for these groups are set at the same levels as for children and the elderly. Furthermore, it is not possible to tailor specific health advice to individual persons with health problems. The health advice given for each health risk category should therefore be interpreted as general advice. People with existing cardiovascular and respiratory illnesses, and those who experience chest discomfort or respiratory symptoms such as cough or breathing difficulties, are asked to seek advice from their doctors. The division of the health risk categories into 11 bands (bands 1–10 and 10+), with equal increments in %ER, provides more detailed information on the air quality and its associated health risk. The linearity of the banding facilitates a better understanding of the health risk by the public, so that they can adjust their physical activities accordingly.

6. Conclusions

This AQHI system reports the additional risk of hospital admissions for cardiovascular and respiratory diseases arising from short-term exposure to air pollutants. With its many advantages and improvements, this risk-based system should be considered as a suitable replacement for the present standard-based API in Hong Kong.

Disclaimer

The content of this paper does not necessarily reflect the views and policies of the Hong Kong SAR Government.

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References

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. Atmospheric Environment 41, 8442–8454.

COMEAP, 2010. The Mortality Effects of Long-term Exposure to Particulate Air Pollution in the United Kingdom. In: A Report by the Committee on the Medical Effects of Air Pollution. Health Protection Agency, United Kingdom.

Dear, K., Ranmuthugala, G., Kjellström, T., Skinner, C., Hanigan, I., 2005. Effects of temperature and ozone on daily mortality during the August 2003 heat wave in France. Archives of Environmental and Occupational Health 60, 205–212.

Dominici, F., McDermott, A., Hastie, T.J., 2004. Improved semi-parametric time series models of air pollution and mortality. Journal of American Statistical Association 468, 938–948.

Internet-based Health & Air Pollution Surveillance System (iHAPSS), 2002. Software for Computing the Asymptotically Exact Standard Errors in GAM. Biostatistics Department, Bloomberg School of Public Health, Johns Hopkins University. http://www.ihapss.jhsph.edu/software/gam.exact/gam.exact.htm (Last accessed Feb 2012).

Kan, H., London, S.J., Chen, G., Zhang, Y., Song, G., Zhao, N., Jiang, L., Chen, B., 2008. Season, sex, age, and education as modifiers of the effects of outdoor air pollution on daily mortality in Shanghai, China: the Public Health and Air Pollution in Asia (PAPA) study. Environmental Health Perspectives 116 (9), 1183–1188.

Ren, C., Williams, G.M., Mengersen, K., Morawska, L., Tong, S., 2008a. Does temperature modify short-term effects of ozone on total mortality in 60 large eastern US communities? An assessment using the NMMAPS data. Environment International 34, 451–458.

Ren, C., Williams, G.M., Morawska, L., Mengersen, K., Tong, S., 2008b. Ozone modifies associations between temperature and cardiovascular mortality: analysis of the NMMAPS data. Occupational and Environmental Medicine 65, 255–260.

Schwartz, J., Spix, C., Touloumi, G., et al., 1996. Methodological issues in studies of air pollution and daily counts of deaths or hospital admissions. Journal of Epidemiology and Community Health 50 (S1), S3–S11.

Sicard, P., Lesne, O., Alexandre, N., Mangin, A., Collomp, R., 2011. Air quality trends and potential health effects – development of an aggregate risk index. Atmospheric Environment 45, 1145–1153.

Sicard, P., Talbot, C., Lesne, O., Mangin, A., Alexandre, N., Collomp, R., 2012. The Aggregate Risk Index: an intuitive tool providing the health risks of air pollution to health care community and public. Atmospheric Environment 46, 11–16.

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. Journal of Air and Waste Management Association 58, 435–450.

US EPA, 1999. Air quality index reporting (40 CFR Part 58). Federal Register Environmental Documents 64 (149), 42529–42549.

US EPA, 2006. Guideline for Reporting of Daily Air Quality – Air Quality Index (AQI). In: Office of Air Quality Planning and Standards. US Environmental Protection Agency.

Wong, C.M., Atkinson, R.W., Anderson, H.R., Hedley, A.J., Ma, S., Chau, P.Y.K., Lam, T.H., 2002. A tale of two cities: effects of air pollution on hospital admissions in Hong Kong and London compared. Environmental Health Perspectives 110, 67–77.

World Heath Organization, 1977. International Classification of Diseases, 9th Revision. World Health Organization, Geneva.

World Heath Organization, 2005. WHO Air Quality Guidelines Global Update 2005: Report of a Working Group Meeting, Bonn, Germany, 18–20 October 2005. World Health Organization, Geneva.

Zhang, Y., Hwang, W., London, S.J., Song, G., Chen, G., Jiang, L., Zhao, N., Chen, B., Kan, H., 2006. Ozone and daily mortality in Shanghai. Environmental Health Perspectives 114, 1227–1232.