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Thermal stress associated mortality risk and effect modification by sex and obesity in an elderly cohort of Chinese in Hong Kong

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A B S T R A C T

We assessed the effects of apparent temperature (AT) on mortality and the effect modifications attributable to individual characteristics in Hong Kong with subtropical climate conditions. Two datasets are used for analyses: one from mortality data of the general elderly population in 1998–2009; the other from an elderly cohort with 66,820 subjects recruited in 1998–2001 with mortality outcomes followed up until 2009. We found that AT below 20.8 °C was associated with an increase in mortality risk of 1.99% (95% confidence interval: 0.64%, 2.64%) for all causes, 2.48% (0.57%, 4.36%) for cardiovascular disease, and 3.19% (0.59%, 5.73%) for respiratory disease for every 1 °C decrease in AT over the following 3 days. The associations were modified by sex and body mass index, in particular stronger associations were observed for females and for obese subjects.

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1. Introduction

Climate change is one of the biggest threats to health in this century (Costello et al., 2009). It has been suggested that increasing effects of thermal stress could contribute a large number of excess deaths (Basu and Samet, 2002). A substantial body of epidemiological evidence has demonstrated that exposure to temperature exceeding certain comfort limits is associated with increased risks of morbidity and mortality (Mercer, 2003; Basu, 2009). Older people are more susceptible to thermal stress due to their diminished ability to perceive thermal variation (Collins et al., 1981) and the reduction in thermoregulatory response (Kenney and Armstrong, 1996; Keim et al., 2002). Even mild heat or cold exposure may lead to adverse health outcomes among these vulnerable persons. Other factors including sex, lifestyle, health and socioeconomic status of an individual are also potential effect modifiers of thermal stress (Kovats and Hajat, 2008; Basu, 2009). However, the majority of epidemiological reports on health effects of thermal stress are ecological studies using morbidity or mortality of population-based data. Detailed information on individual risk factors is usually not available from aggregate data, which makes it difficult to quantify effect modifications by individual characteristics. Inconsistent findings have been reported in studies on effect modification by sex on thermal stress associated mortality (The Eurowinter Group, 1997; Wilkinson et al., 2001; O’Neill, 2003; Schwartz, 2005; Diaz et al., 2006; Medina-Ramón et al., 2006; Davie et al., 2007).

Several studies using cohort data have been reported in which the effects of thermal stress and the susceptibility of subgroups by individual characteristics on morbidity or mortality were assessed (Wilkinson et al., 2004; Larrieu et al., 2008; Schifano et al., 2009; Matsumoto et al., 2010). All of these studies focused on the assessment of excess risks of heat waves or winter periods, but all were conducted in temperate regions and none has addressed the association between daily exposure to climatic variables and mortality. In Hong Kong, a typical subtropical city, the effects of thermal stress on mortality have only been reported in studies based on population-level data (Yan, 2000; Leung et al., 2008; Chan et al., 2009).
2012). However, the results were not consistent, which may be attributed to the use of different methods and indicators of thermal stress. There remains a need for investigations on the magnitude of effects resulting from exposure to hot and cold weather and on the profile of factors which may affect the vulnerability of different population subgroups in non-temperate climates. Our study aimed to assess the effects of heat and cold stress on mortality and whether individual characteristics modify the association between thermal stress and mortality in a cohort of elderly subjects in Hong Kong.

2. Materials and methods

2.1. Study population

We considered two mortality datasets of elderly populations in Hong Kong; one based on a cohort of 66,820 subjects and the other on the general population aged 65 or older.

2.1.1. Elderly cohort data

The cohort included members aged 65 or older from 18 Elderly Health Centers (EHC) in Hong Kong. There were 66,820 Chinese subjects who enrolled from May 1998 to December 2001. Personal characteristics of the subjects including demographic characteristics, socioeconomic status, lifestyle factors and health status were recorded at baseline period. This cohort has been studied in previous analyses of associations between individual risk factors and mortality (Schooling et al., 2006; Sun et al., 2009). The characteristics of these subjects were similar to the elderly population of Hong Kong in age, smoking status, socioeconomic position and hospital use (Schooling et al., 2006). Vital status, date and cause of death of each subject were obtained through linkage to the death registration database using the unique Hong Kong identity number. Among the 66,820 subjects in the database, 194 (<0.003%) subjects with unknown exact date of death were excluded and 66,626 subjects were used for the analysis, including 14,446 deaths by December 31, 2009, which was the end of follow-up for our study.

2.1.2. Elderly mortality of Hong Kong

Daily mortality data of Hong Kong territory was obtained from the Census and Statistics Department. Among the 334,547 deaths of elders aged 65 or older from 1998 to 2009, 786 deaths (<0.3%) without exact date of death were excluded leaving 333,761 deaths considered for the analysis.

2.2. Mortality outcomes

Causes of death were coded by the Department of Health according to the International Classification of Diseases and Related Health Problems, 9th Revision (ICD-9) before 2001 and 10th Revision (ICD-10) from 2001. Health outcomes in this study were mortality due to all causes, cardiovascular diseases (CVD, ICD-9: 390–459 or ICD-10: 100–199) and respiratory diseases (RD, ICD-9: 460–519 or ICD-10: 100–199). The comparability ratios of ICD-9 and ICD-10 for the leading causes of death from CVD and RD were close to 1 which indicated a high level of agreement.

2.3. Environmental exposure and related factors

2.3.1. Apparent temperature

Apparent temperature (AT) was selected as the indicator of thermal stress in this study as it considered the discomfort feeling from a combination of air temperature, relative humidity and wind speed. Hourly mean air temperature in Celsius (°C), dew point (°C), and wind speed in kilometers per hour (km/h) from 1998 to 2009 were obtained from the Hong Kong Observatory. Hourly mean AT was calculated by the following equation (Steadman, 1984):

\[ AT = -2.7 + 1.047 \times T + 2.0E - 0.65V \]

where \( T \) is air temperature (°C), \( E \) is vapor pressure (kPa) and \( V \) is wind speed in meters per second (m/s). Vapor pressure (\( E \)) was calculated using the following equation (National Weather Service, 2009):

\[ E = 6.11 \times 10^{7.5T / 237.7 - 15} \]

where \( Td \) is dew point (°C).

2.3.2. Air quality and influenza epidemics data

Air pollution data were collected by the Environmental Protection Department of Hong Kong. Daily mean concentrations of particulate matter with aerodynamic diameters less than or equal to 10 μm (PM10) were estimated from the average of hourly concentrations of ten general monitoring stations across Hong Kong. Weekly numbers of positive isolations of influenza A + B virus and the total number of specimens tested were obtained from the Department of Microbiology, Queen Mary Hospital. An influenza epidemic was defined as the days in a year when the weekly number of positive influenza isolates ≥4% of the annual total number of positive isolates for at least two consecutive weeks (Chiu et al., 2002; Thach et al., 2010).

2.4. Statistical methods

Three main analytical steps were adopted in sequence to estimate the excess risks of the association between AT and mortality in a nested case–control study. All analyses were performed using STATA 10 and R 2.12.0.

Step 1: Identifying the best lagged day of AT effects in the elderly cohort

First, we used an incidence density sampling approach to generate risk sets for cases which were defined as subjects who died from all causes, cardiovascular or respiratory diseases (Richardson, 2004). Each risk set included all subjects who were alive with the same length of follow-up as the case. The cases and controls were matched by the same month and year to account for effects of trends and seasonality. We then selected four controls at random from each risk set. The ratio of four controls for each case is recommended as the increase in power diminishes when there are more than four controls (Woodward, 2005).

Second, we quantified associations between mortality and daily mean AT at different lag days by conditional logistic regression adjusting for sex, smoking status, physical activity level, education level, housing type, health status, day of the week, influenza epidemics, and the 2003 severe acute respiratory syndrome (SARS) epidemic as categorical variables and age, body mass index (BMI), and PM10 concentrations as continuous variables.

Finally, we selected the best lagged day based on the model with the lowest Akaike’s information criterion (AIC). The AT of single lag days from the same day (lag 0) to lag 6 days (lag 6) and cumulative lag days from the average AT of lag 0 and 1 days (lag 0–1) to the average of lag 0 to lag 6 days (lag 0–6), and the average of seven days between lag 7 and lag 13 days (lag 7–13) were examined.

Step 2: Determining thresholds of AT for cold and heat effects on elderly mortality in the general population

We used generalized additive Poisson regression allowing for over-dispersion in the model to determine the shape of the AT-mortality relationship in the general elderly population of Hong Kong (Wood, 2006). Variations in trends and seasonality were fitted with natural cubic splines. We chose 5 degrees of freedom (df) per year for smoothing function of the time trends and 3 df for AT. Dummy variables were used to control the variations for days of the week, holidays, influenza epidemics and SARS epidemic. PM10 concentrations were controlled for using a linear term in the model.

The model which had the lowest AIC in Step 1 was selected to obtain the best lag to describe the AT-mortality relationship. We examined models with different lag days to identify thresholds for detecting effects of cold and heat stress due to their distinct patterns of the lag effects. The use of different lags to identify thresholds for cold and heat effects according to their distinct lag patterns could help to avoid underestimation of thermal stress effects (Braga et al., 2001; O’Neil, 2003). Days with AT below the threshold for cold effects were identified as cool days and days above the threshold for heat effects were classified as hot days.

Step 3: Assessing effects of AT on cool and hot days in the elderly cohort

After identifying the thresholds of AT for cool and hot days obtained in Step 2, we divided cases and controls into two groups for cool and hot days, with cases defined as those who died on days in which mean AT exceeded the thresholds. We fitted conditional logistic regression models to estimate the effects on all-cause, CVD and RD mortality associated with every 1°C change in daily mean AT for each group. Dummy variables were used to control the variations for days of the week, holidays, influenza epidemics and SARS epidemic. PM10 concentrations were controlled for using a linear term in the model.

To examine whether sex and BMI acted as effect modifiers in the association between AT and mortality, the dataset was further stratified according to categories of these factors. BMI of the subjects were categorized into three levels (kg/m²): underweight (less than 18.5), normal weight (18.5–24.9) and obesity (equal to or higher than 25.0) for the stratified analysis based on the classification of weight by BMI for Asians (World Health Organization, 2000). We estimated the excess risk of mortality for every 1°C change in AT for each subgroup separately.

To enhance the accuracy and reliability of the estimates, we generated 100 different sets of controls for analysis of each model. Mean of estimated excess risks from the 100 samples were reported as the final results.

Ethics approval for our study was obtained from the ethics committee of the University of Hong Kong and Hospital Authority Hong Kong West Cluster.
3. Results

3.1. Summary statistics of data

During our study period, a total of 66,626 subjects were available for analyses in our cohort, of whom, 66.1% were females. A larger proportion of females were uneducated (20.3%) or illiterate (40.2%) compared with males, of whom 18.1% were uneducated or illiterate. Most females (88.2%) had never smoked while most males (61.8%) were current or ex-smokers. The prevalence of obesity was higher for females (42.4%) compared with males (36.6%). The mortality rate for males was higher than that of females (Table 1). The daily mean AT ranged from 4.4 °C to 35.9 °C with an average of 24.9 °C.

3.2. Thresholds for cold and heat effects in the general elderly population

Models with 3 lag days and lag 0–1 days for AT on all-cause mortality were selected to characterize the AT-mortality relationship and to identify the threshold for cold and heat effects, respectively. From model for AT measured at lag 3 days, we found a reversed J-shape relationship between AT and mortality. For AT below 20.8 °C, decreasing daily mean AT was associated with increasing mortality and to identify the threshold for cold and heat effects, respective.

Fig. 1. Exposure–response relationships for daily mean apparent temperature in Celsius (°C) of lag 3 day and all-cause mortality in the general elderly population (65 years) in Hong Kong, 1998–2009. The density of the vertical bars on the x-axis shows the distribution of apparent temperature.

AT measured at lag 0–1 days, a U-shape relationship was observed with the threshold of AT for heat effects estimated at 28.2 °C, above which increasing mortality was found (Fig. 2).

With the above-determined thresholds for cold and heat effects, 1274 days (30% of the study period) were classified into cool days with daily mean AT ranging from 4.4 °C to 20.8 °C (average of 16.5 °C), and 1480 days (34.8%) classified as hot days with daily mean AT ranging from 25.2 °C to 35.9 °C (average of 31.2 °C).

3.3. Effects on cool days in the elderly cohort

Significant associations between daily mean AT and mortality were observed with the largest cold effect estimates shown at lag 0–6 days. Estimated excess risks of mortality for every 1 °C decrease of AT with different lags from 0 up to 13 days ranged from 0.99% (0.22%, 1.76%) to 1.95% (0.91%, 2.98%) for all causes, 1.52% (0.03%, 2.99%) to 2.82% (0.82%, 4.78%) for CVD, and 1.65% (–0.38%, 3.63%) to 3.98% (1.28%, 6.60%) for RD mortality (Appendix Table A1).

Fig. 2. Exposure–response relationships for average of daily mean apparent temperatures in Celsius (°C) of lag 0 and 1 days and all-cause mortality in the general elderly population (≥65 years) in Hong Kong, 1998–2009. The density of the vertical bars on the x-axis shows the distribution of apparent temperature.

Table 1. Characteristics of male and female subjects and mortality in the Elderly Health Center cohort.

| Characteristics                        | Male          | Female        |
|----------------------------------------|---------------|---------------|
|                                        | Number | %    | Number | %    |
| Age (years)                            |         |      |         |      |
| 65–74                                  | 16,147  | 71.5 | 31,097  | 70.6 |
| 75–84                                  | 5824    | 25.8 | 11,398  | 25.9 |
| ≥85                                    | 613     | 2.7  | 1547    | 3.5  |
| Education level                        |         |      |         |      |
| Post-secondary                         | 1611    | 7.1  | 861     | 2.0  |
| Secondary                              | 5329    | 23.6 | 3631    | 8.2  |
| Primary                                | 11,559  | 51.2 | 12,906  | 29.3 |
| Uneducated                             | 2396    | 10.6 | 8951    | 20.3 |
| Illiterate                             | 1687    | 7.5  | 17,693  | 40.2 |
| Housing type                           |         |      |         |      |
| Public and aided housing               | 8895    | 39.4 | 17,569  | 39.9 |
| Rented private housing                 | 1221    | 5.4  | 2073    | 4.7  |
| Self-owned flat                        | 11,212  | 49.7 | 21,181  | 48.1 |
| Others                                 | 1255    | 5.6  | 3218    | 7.3  |
| Smoking status                         |         |      |         |      |
| Never-smoker                           | 8633    | 38.2 | 38,844  | 88.2 |
| Ex-smoker                              | 9347    | 41.4 | 3429    | 7.8  |
| Current smoker                         | 4602    | 20.4 | 1768    | 4.0  |
| Physical activity level                |         |      |         |      |
| Low                                    | 3749    | 16.6 | 6483    | 14.7 |
| Moderate                               | 6472    | 28.7 | 13,736  | 31.2 |
| High                                   | 12,361  | 54.7 | 23,822  | 54.1 |
| Body mass index (kg/m2)                |         |      |         |      |
| <18.5                                  | 1317    | 5.8  | 2217    | 5.1  |
| 18.5–24.9                              | 12,964  | 57.5 | 23,101  | 52.6 |
| ≥25                                    | 8260    | 36.6 | 18,625  | 42.4 |
| Times of hospitalization for the last 12 months | | | | |
| 0                                      | 19,415  | 86.0 | 38,496  | 87.4 |
| 1–2                                    | 2909    | 12.9 | 5132    | 11.7 |
| 3–4                                    | 199     | 0.9  | 338     | 0.8  |
| >4                                     | 61      | 0.3  | 76      | 0.2  |
| Mortality                              |         |      |         |      |
| All causes                             | 6433    | 28.5 | 8013    | 18.2 |
| Cardiovascular                         | 1601    | 7.1  | 2459    | 5.6  |
| Respiratory                            | 1448    | 6.4  | 1307    | 3.0  |
mortality risk estimates stratified by BMI level were found in obese subjects for all-cause and CVD mortality, and in subjects with normal weight for RD mortality (Table 2).

3.4. Effects on hot days in the elderly cohort

No significant association was found between AT and mortality with lags of current and the following day (Appendix Table A2). The excess risks for every 1 °C increase in AT at lag 0–1 days were
\[-0.07% (95% CI: \,-1.80%, 1.69%), \,-2.73% (\,-6.17%, 0.84%)\] and 0.97% (\,-3.78%, 5.95%) for all causes, CVD and RD mortality, respectively.

4. Discussion

4.1. Thresholds for cold and heat effects in the general elderly population

In our study, we identified the thresholds of AT to be 20.8 °C at lag 3 day for cold effects and 28.2 °C at lag 0–1 days for heat effects. Previous reports suggested that effects of heat stress are immediate and restricted to current and the following day (Braga et al., 2001; O’Neill, 2003; Stafoggia et al., 2006), and in most studies the strongest heat effects occurred in very short lag periods (Busu et al., 2005; Anderson and Bell, 2009). However, cold effects usually occur after an interval and are more persistent through time (The Eurowinter Group, 1997; Mercer, 2003; Anderson and Bell, 2009). The use of different lags to identify thresholds for cold and heat effects according to their distinct lag patterns could help to avoid underestimation of thermal stress effects. Therefore, we chose the conservative threshold with lag 3 day instead of lag 0–1 days to identify the effects of cool days. A previous study from Hong Kong also reported that the greatest correlation coefficients between minimum net effective temperature (NET) and mortality from all causes, CVD and RD occurred at lag 3 or 4 days in winter (November–March) (Leung et al., 2008). Our results support the phenomenon that cold effects are associated with long lags as positive associations between cold exposure and mortality could be observed for lags up to 30 days (Appendix Table A3). This effect of cold stress on mortality may be attributed to the mechanism of cold effects which are more likely to be indirectly mediated through changes in blood composition and blood pressure or infection with a longer time elapsed before death (The Eurowinter Group, 1997; Cheng and Su, 2010).

The identified threshold of AT at 28.2 °C for heat effects was lower than that reported in a study in Hong Kong which observed a summer (May–October) threshold of air temperature of 28.2 °C, which is equivalent to about 31 °C of AT, for heat effects (Chan et al., 2012). The difference in the thresholds may be due to the inclusion of relative humidity and wind speed factors in the derivation of AT.

In addition, because the threshold defined in our study was based on data from mortality of an elderly population, which has been demonstrated to be more vulnerable to thermal stress (Ballester et al., 1997; Gouveia, 2003; O’Neill et al., 2005a; Hajat et al., 2007; Baccini et al., 2008; Ishigami et al., 2008; Anderson and Bell, 2009), the threshold of temperature for detectable heat effects in older populations is known to be lower than that for the general population.

4.2. Cold and heat effects in the elderly cohort

We found statistically significant effects of cold stress during cool days but not of heat effect during hot days for exposure at the same or previous day before death. We were able to identify a threshold for heat effects in the general elderly population but no heat effect for our cohort subjects was observed. It may be that the subjects of the cohort were self selected to be enrolled in the Elderly Health Service and were generally more health conscious. Our results are consistent with previous findings from another Hong Kong study, which reported 1.0%–2.0% increase in all-cause, cardiovascular and respiratory mortality in winter but no significant increased risk for a unit change of NET in summer (May–September) (Leung et al., 2008). However, these results do not concur with those of Chan et al. (2012) who reported that heat effects on excess mortality from natural causes, were associated with daily mean air temperature above 28.2 °C in summer. There are two possible explanations for these differences. First, there may be important differences between our cohort subjects and the general elderly population. Second, the thermal indices used in the three Hong Kong studies are different. Both AT and NET take into account the effects of humidity and wind speed. AT was developed based on the principles of human physiology and clothing (Steadman, 1979) and widely used in studies on health effects of thermal stress (O’Neill et al., 2005b; Stafoggia et al., 2006; Analitis et al., 2008; Basu and Ostro, 2008; Anderson and Bell, 2009). It has been recognized that changes of relative humidity and wind speed could affect the capacity of sweat vaporization and alter heat exchange between human body and the environment (Gaffin and Moran, 2001; Keim et al., 2002). A local study also documented wind speed as one of the factors that impact on the thermal comfort of people in Hong Kong (Cheng et al., 2012). Therefore, AT is considered to be a better thermal stress measure than air temperature alone.

Our findings on cold effects are consistent with the existing literature from other regions in which higher risks for cold-related mortality were generally present in areas with milder winter climates (The Eurowinter Group, 1997; Yan, 2000; Näyhä, 2002; Healy, 2003; Mercer, 2003; Analitis et al., 2008). Lower or absent heat effects in warmer cities were observed in most multi-city studies (Anderson and Bell, 2009; Hajat and Kosatky, 2010). So the absence of a strong heat effect might be expected in a subtropical city like Hong Kong. An important environmental factor may be air conditioning which is commonly used in summer. The excess consumption of electricity in summer is mainly attributed to air conditioning which accounts for 59.1% of the power consumed, whereas in winter only 2.6% of the electricity consumed is dedicated for space heating (Yee et al., 2004). Acclimatization of the residents and frequent public warnings on the potential adverse health effects of heat exposure may also contribute to the reduction of heat effects (Chau et al., 2009).

On cool days, excess risks of mortality from cardiovascular and respiratory diseases were larger than that for all-causes mortality. Cold exposure has an impact on the respiratory tract and leads to bronchoconstriction (Koskela, 2007) and also suppresses the immune responses which causes reduction of resistance to infections.

Table 2

| Characteristics | All causes | Cardiovascular | Respiratory |
|----------------|-----------|----------------|-------------|
|                | ERS (%)   | 95% CI         | ERS (%)     | 95% CI         | ERS (%)     | 95% CI         |
| Total stratification by Sex |           |                |             |                |             |                |
| Male           | 1.19      | 0.32, 2.67     | 1.27        | 1.77, 4.22     | 0.84        | -2.74, 4.29   |
| Female         | 2.14      | 0.87, 3.40     | 3.35        | 1.09, 5.55     | 5.23        | 1.95, 8.40    |
| Body mass index (kg/m²) |           |                |             |                |             |                |
| <18.5          | 0.09      | -0.03, 4.34    | 1.33        | -14.98, 15.32  | 1.78        | -9.64, 12.01  |
| 18.5–24.9      | 1.77      | 0.48, 3.04     | 2.26        | -0.10, 4.56    | 3.99        | 0.89, 6.99    |
| ≥25            | 2.19      | 0.50, 3.85     | 3.33        | 0.21, 6.35     | 1.88        | -3.17, 6.69   |
The physiological effects of cold exposure can also explain the observed higher risk of cardiovascular deaths in obese subjects. In our cohort, higher rates of pre-existing hypertension, heart diseases, hypercholesterolemia and diabetes mellitus were recorded among subjects with the highest BMI level (Appendix Table A4). Increases in blood pressure, plasma cholesterol and plasma fibrinogen levels under cold exposure would aggravate these comorbidities by increasing the risks of cardiovascular events. On the other hand, significant excess risk was not observed inobese subjects for respiratory mortality. It is possibly related to the smaller sample size as well as the lower prevalence of chronic obstructive Airways diseases and asthma in obese subjects compared with normal weight range subjects in the cohort.

We found females were more susceptible to cold effects than males. This finding agrees with previous ecological studies on cold stress which reported a higher risk in females (The Eurowinter Group, 1997; Wilkinson et al., 2001; Schwartz, 2005; Diaz et al., 2006; Davie et al., 2007). An investigation on the thermal comfort of a Chinese population also confirmed that females preferred a warmer environment than males with a comfortable operative temperature of 26.2 °C for females and 25.3 °C for males (Jan et al., 2008), but the mechanisms underlying sex differences in temperature preferences and physiological responses to thermal stress were not fully explained. Several potential modifiers of thermal stress have been suggested including the sexual dimorphism of body fatness (Hardy and Bois, 1940; Burse, 1979), the higher thermal-metabolic threshold for females (Cunningham et al., 1978) and differences in the endocrine milieu between males and females (Graham et al., 1989). It is possible that the larger body surface to mass ratios and lower resting metabolic rates of females contribute to the higher susceptibility to cold stress (Arciero et al., 1993).

4.3. Effect modification

The physiological effects of cold exposure can also explain the observed higher risk of cardiovascular deaths in obese subjects. In our cohort, higher rates of pre-existing hypertension, heart diseases, hypercholesterolemia and diabetes mellitus were recorded among subjects with the highest BMI level (Appendix Table A4). Increases in blood pressure, plasma cholesterol and plasma fibrinogen levels under cold exposure would aggravate these comorbidities by increasing the risks of cardiovascular events. On the other hand, significant excess risk was not observed in obese subjects for respiratory mortality. It is possibly related to the smaller sample size as well as the lower prevalence of chronic obstructive Airways diseases and asthma in obese subjects compared with normal weight range subjects in the cohort.

We found females were more susceptible to cold effects than males. This finding agrees with previous ecological studies on cold stress which reported a higher risk in females (The Eurowinter Group, 1997; Wilkinson et al., 2001; Schwartz, 2005; Diaz et al., 2006; Davie et al., 2007). An investigation on the thermal comfort of a Chinese population also confirmed that females preferred a warmer environment than males with a comfortable operative temperature of 26.2 °C for females and 25.3 °C for males (Jan et al., 2008), but the mechanisms underlying sex differences in temperature preferences and physiological responses to thermal stress were not fully explained. Several potential modifiers of thermal stress have been suggested including the sexual dimorphism of body fatness (Hardy and Bois, 1940; Burse, 1979), the higher thermal-metabolic threshold for females (Cunningham et al., 1978) and differences in the endocrine milieu between males and females (Graham et al., 1989). It is possible that the larger body surface to mass ratios and lower resting metabolic rates of females contribute to the higher susceptibility to cold stress (Arciero et al., 1993).

4.4. Strengths and limitations

Our study is the first attempt to assess the association between daily exposure of apparent temperature and mortality utilizing data from a cohort. It is also one of the few studies which have identified the effect modifications of individual characteristics on temperature—mortality associations in contrast to aggregate population data. We adopted conditional logistic regression models with matching on time of follow-up, which yielded comparable estimates to those from Cox proportional hazards regression models with time-dependent covariates (Richardson, 2004; Essebag et al., 2005). The use of these models reduces the requirement for high computing power and running time (Essebag et al., 2005).

Our study demonstrated that cold exposure contributed to significant increases in mortality in Hong Kong despite the relatively mild winter climate in a subtropical latitude. As cold-related mortality can be reduced or even avoided by simple protective measures (The Eurowinter Group, 1997), it is important to promote awareness of the risk of cold exposure through carefully designed public health messages, especially for susceptible groups including elders, females and obese people.

Some limitations are associated with our study. First, the female to male ratio was high and subjects in our cohort are likely to be more health conscious compared with the general elderly population which may result in selection bias. Second, all the meteorological variables used in our study were recorded from the Hong Kong Observatory, so the apparent temperature could be different from the actual individual exposures, especially for subjects living in suburban areas. Third, as the number of cases in each stratum is not large enough, it is unlikely to have sufficient statistical power for assessment with further stratification, like for obese or non-obese female groups. We suggest that further investigations on effect modifications attributable to individual characteristics of associations between thermal stress and mortality should be conducted in subtropical regions to confirm the findings and inform public health authorities of the harm associated with cold stress.

Ethical approval

Our study has been approved by the Institutional Review Board of the University of Hong Kong and Hospital Authority Hong Kong West Cluster. It ensures that the research complies with the Declaration of Helsinki and acts in accordance to ICH GCP guidelines, local regulations and Hospital Authority and the University policies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2013.03.020.

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