Community planning for a "healthy built environment" via a human-environment nexus? A multifactorial assessment of environmental characteristics and age-specific stroke mortality in Hong Kong

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- Evaluated socio-environmental impacts on age-specific stroke mortality
- Female and older age contributed to higher stroke mortality
- daily PM_{10} also contributed to higher stroke mortality
- regional-level air pollution were associated with non-hemorrhagic stroke deaths
- These associations varied by age

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Abstract

With the prevalence of stroke rising due to both aging societies and more people getting strokes at a younger age, a comprehensive investigation into the relationship between urban characteristics and age-specific stroke mortality for the development of a healthy built environment is necessary. Specifically, assessment of various dimensions of urban characteristics (e.g. short-term environmental change, long-term environmental conditions) is needed for healthy built environment designs and protocols.

A multifactorial assessment was conducted to evaluate associations between environmental and sociodemographic characteristics with age-stroke mortality in Hong Kong. We found that short-term (and temporally varying) daily PM_{10}, older age and being female were more strongly associated with all types of stroke deaths compared to all-cause deaths in general. Colder days, being employed and being married were more strongly associated with hemorrhagic stroke deaths in general. Long-term (and spatially varying) regional-level air pollution were more strongly associated with non-hemorrhagic stroke deaths in general. These associations varied by age. Employment (manual workers) and low education were risk factors for stroke mortality at younger ages (age < 65). Greenness and open space did not have a significant association with stroke mortality. Since a significant connection was expected, this leads to questions about the health-inducing efficacy of Hong Kong's compact open spaces (natural greenery being limited to steep slopes, and extensive impervious surfaces on public open spaces). In conclusion, urban plans and designs for stroke mortality prevention should implement age-specific health care to neighborhoods with particular population segments.

Keywords: stroke; mortality; urban characteristics; age-specific; high-density; Asia

Introduction

Stroke is a common disorder of older adults and its population incidence is associated with demographic characteristics (Arnold et al., 2008; Graham et al., 2010). It is also important to note that strokes are one of the leading causes of death in high-density cities (Kaup et al., 2015; Wang et al., 2007). Specifically, stroke is related to cerebrovascular accidents (CVA), a type of acquired brain injury resulting from low blood supply. Multiple strokes, particularly lacuna infarction, can also cause vascular dementia. Older adults can be vulnerable, especially those who are frail or have lower quality of life (Haley et al., 2011; Nicholson et al., 2013). For example, 6.4% of male deaths and 7.5% of female deaths in 2016 were from cerebrovascular diseases in Hong Kong (https://www.healthyhk.gov.hk). Stroke was recorded as the second leading cause of death in China (Wang et al., 2007). In South America, stroke has also been recorded as a leading cause of death in Brazil (Lotufo & Bensenor, 2009) and shown to be associated with urban living. For example, although the mean standardized stroke mortality has been dropping in São Paulo, one of Brazil's highest density cities, the standardized stroke mortality remained 46.7 per 100 000 inhabitants in 2010, with significant spatial disparity due to urban settlement and urban characteristics (Kaup et al., 2015).

To turn such knowledge into health promotion and urban planning interventions, more studies of environment-stroke relationship are needed, in order to provide community protocols that can improve the wellbeing of these older adults. Evidence also points to environmental factors having moderating and exacerbating influence.

Previous studies have shown the relationships between urban environment (e.g. geophysical environment, built environment, and social environment) and stroke (Hong et al., 2002, Ho et al., 2003; Hu et al., 2008; Katz et al., 2016; Martinez et al., 2003; Rostand et al., 2016; Wellenius et al., 2012). The above studies have found that living environment may be associated with stroke in a number of ways. For example, green space, socioeconomic disparity, racial problems, and long-term air pollution are factors associated with stroke (Hu et al., 2008; Katz et al., 2016; Martinez et al., 2003; Rostand et al., 2016). Studies have also found an association between short-term risk of extreme weather or temporal variability of air quality and stroke (Hong et al., 2002, Ho et al., 2003; Wellenius et al., 2012). Regrettably, most of the previous studies isolated exposure to a single environmental variable to evaluate its relationship with one health outcome (Paul et al., 2020; Wilker et al., 2014). Understanding how different components of the built environment are associated with stroke is particularly important in a high-density Asian city such as Hong Kong, where older adults live in a compact environment that strongly shapes their daily lives.

Since there are more people having strokes at a younger age these days due to workstyle and daily behaviors (Jamrozik et al., 19994; Galimanis et al., 2009; von Sarnowski et al., 2013), it is also important to understand the impact of environmental characteristics over urban areas across an age-range. Additionally, environmental factors may also be important as it can influence cardiovascular issues of an individual (Miller et al., 2007; Phung et al., 2016; Chi et al., 2016) and further induce cerebrovascular issues (Wilker et al., 2014).

Therefore, we conducted a register-based study to evaluate the association of multifactorial environmental characteristics on age-specific stroke mortality in Hong Kong. Particularly, we followed previous studies to divide urban environment into three dimensions: built environment, natural environment, and social environment (Sarkar and Webster, 2017). A register-based study is a common epidemiological design using nationwide or territory-wide epidemiological data registered with an authority (e.g. death records or birth records) for statistical analysis (Erlangsen et al., 2017; Rahman et al., 2018). This approach makes it possible to include the entire relevant population, which minimizes sampling bias. Using data from Hong Kong Census Department, our study sought to address the following overarching questions:

1) Which types of environmental elements might influence stroke mortality in a high-density city?
2) How do environmental element(s) influence stroke mortality among subpopulations by age groups?
3) If environmental influences vary by age, what may be the driving factors?

Methods

Health measures

Mortality data from 2007 through 2014 were obtained from the Hong Kong Census and Statistics Department. The following mortality data were captured: 1) date of death; 2) age; 3) gender; 4) occupation; 5) marital status; 6) cause of death; and 7) location of residence. Specifically, cause of death was based on the 10th version of the International

Statistical Classification of Diseases and Related Health Problems (ICD-10), and location of residence was based on "tertiary planning units" (TPU). TPU is a fine-scale planning unit and is the finest spatial information for vital statistics in Hong Kong, and there are 287 TPUs within 1,100 km^2 of land across Hong Kong.

In this study, we grouped decedents with stroke into two groups, hemorrhagic stroke and non-hemorrhagic stroke, as these two groups have strokes associated with different pathology. Hemorrhagic stroke included decedents with ICD-10 I60-I62 recorded causes of death; and the non-hemorrhagic stroke group was defined by ICD-10 I63 and ICD-10 I64 (individuals dying from ischemic stroke or cerebral infarction or other non-hemorrhagic issues). Excluding decedents with a missing death date or TPU residence location, the analytic dataset included 8,697 hemorrhagic stroke deaths and 10,270 non-hemorrhagic stroke deaths.

Individual-level social measures

Considering individual-level social factors related to stroke (Hu et al., 2008; Katz et al., 2016), a binary measure of gender was used (1=male, 0=female). A binary measure of unemployment represented pre-mortem socioeconomic status, based on a reclassification of occupation, with "economically inactive" coded as 1 and others as 0. Marital status was coded as 1 for "unmarried" and 0 for "married" and taken as an index of social isolation (Ho et al., 2020), although it could also indicate social stress in some circumstances (Ho et al., 2018). A continuous variable of age was used.

Community-level social measures

Based on previous studies (Martinez et al., 2003; Rostand et al., 2016), we used the following community-level social measures associated with stroke (Figure 1): 1) % of population with low-education (*Low education %*), and 2) % of population whose native language not Cantonese (*Not Cantonese %*). *Low education %* was measured as the percentage of population whose highest level of education was primary school or below. This is commonly taken as a social indicator of low health preparedness (Guo et al., 2020). *Not Cantonese %* indicates a neighbourhood with mixed cultures. Mixed culture may be associated with community health problems in Hong Kong, because of social isolation and cultural conflicts (Guo et al., 2020; Mok & Ho, 2020). These measures were retrieved from the 2006 Hong Kong census data at the TPU level.

Measures of long-term environmental impacts

Based on previous studies (Hu et al., 2008), four spatially varying measures related to stroke were investigated (Figure 1): 1) percentage of open spaces (*Open space %*), 2) greenness; 3) regional air pollution, and 4) traffic-related air pollution.

Open space % was obtained from land utilization map of Hong Kong Planning Department (Ho et al., 2019; Shi et al., 2018b), and re-sampled to the TPU-level. Open spaces in Hong Kong may be defined as public open-access areas, with or without greenery. These typically comprise planned spaces of impervious surfaces, which are mainly used for leisure, social and physical activities. In this study, the average for each TPU was used as the measure for each of these variables. An average increase of 10%

across a sub-district were used as the unit of change.

We treated greenness as a binary measure calculated based on the average normalized difference vegetation index (NDVI) of each TPU. NDVI is a spectral index ranging from –1 to 1 (Tucker, 1979), with lower values indicating an area with less greenness, and high values meaning more greenness. Therefore, “greenness” in this study is linked to density of vegetation of a neighborhood even though the vegetation itself may not be accessible. In Hong Kong, natural vegetation is typically found on steep slopes of the hillsides that bound the built-up areas (70% of HK is natural park, mainly in the form of steep hills and river systems). Green-space is thus less likely to be accessible to local populations, especially older adults. We used a resampled spatial dataset at 15m resolution from an IKONOS multispectral image to estimate average NDVI (Ho et al., 2017). Based on the relationship between NDVI and local vegetation noted in previous studies (Yu et al., 2018), the average NDVI of 0.1 was used as the threshold, with average NDVI > = 0.1 grouped as “1” to represent TPU with higher greenness, and NDVI < 0.1 grouped as “0” to demonstrate areas with lower greenness. Particularly, using NDVI of 0.1 as the threshold has been validated for local scenario (Nichol & Wong, 2007) and was commonly used in previous health research in Hong Kong (Wang et al., 2017; Yu et al., 2018).

Regional air pollution was measured from a map of fine particulate matter. Traffic-related air pollution measures came from a black carbon map. Air and traffic pollution maps were produced based on land use regression and air quality data of a campaign operated by the Hong Kong Environmental Protection Department (EPD) as recorded in previous studies (Barratt et al., 2018; Lee et al., 2017). Spatial resolution of these air quality maps is 10 meters and we resampled to create an average for each TPU., An average increase of 10 μg/m^3 in each air pollutant across a sub-district were used as the unit of change.

Measures of short-term environmental impacts

The following six temporally-varying measures have been shown in past studies to have short-term impacts on stroke mortality (Hong et al., 2002; Hong et al., 2003; Wellenius et al., 2012): 1) influence of hot weather (*Hot day*); 2) influence of cold weather (*Cold day*); 3) daily variation of respirable suspended particulates (*daily PM_{10}*); 4) daily variation of nitrogen oxides (*daily NO_x*); 5) daily variation of tropospheric ozone (*daily O_3*); and 6) daily variation of humidity (*daily humidity*).

In our study, we define *Hot day* as a binary measure based on the daily average temperature at the headquarters of HK Observatory, in which "1" is a day with temperature >= 29.72°C (95th percentile based on long-term weather records from January 1st 1971 through Aug. 31, 2015) and "0" is the other days. *Cold day* codes days with temperature <= 14.25°C (5th percentile) as "1" and the other days as "0". By using long-term weather records, both *Hot day* and *Cold day* allow us to speculate on the impact of climate change. *Daily humidity* is the daily average humidity.

Daily PM_{10}, *daily NO_x*, and *daily O_3* are the daily average of coarse particulate matters, nitrogen oxides and ozone. We followed previous studies (Ho et al., 2018; Ho & Wong 2019) to retrieve temporally varying air quality data from seven EPD stations

(Central Western, Sham Shui Po, Sha Tin, Tai Po, Tsuen Wan, Kwai Chung, and Tap Mun). A 10 $\mu g/m^3$ increase in each air pollutant for a day was used as the unit of change.

Register-based study

In order to evaluate which type(s) of urban element are associated with stroke mortality, we first selected all stroke deaths as "cases" and all-cause deaths as "controls" for comparison. We used all-cause deaths as a control to standardize, so that our models indicate whether associations between stroke and environmental exposure vary from a more general association (based on all-cause deaths). We then applied binomial logistic regressions to separately estimate the influences of urban characteristics on hemorrhagic and non-hemorrhagic stroke mortality, based on odds ratios (OR) and 95% confidence intervals (CI). Particularly, all significant results had p-value < 0.05. A preliminary analysis of variance inflation factor (VIF) was applied to test for multicollinearity. Based on the preliminary analyses, the above models had VIF < 3 for all variables, indicating the model itself did not involve significant issues of multicollinearity.

To determine whether urban elements influence stroke mortality in decedents in different age groups, subgroup analysis was applied as follows: 1) all ages; 2) "old-old" aged >= 89, 3); "young-old" aged between 65 and 79' and 4) "not-old" aged < 65. For each subgroup, we repeated the binomial logistic regressions. R software was used to perform all statistical analyses.

Results

Data summary

Among the 8,697 hemorrhagic stroke deaths, 3565 were old-old, 2932 were young-old, and 2,200 were not-old (Table 1); and among the 10,270 non-hemorrhagic stroke deaths, 6111 were old-old, 3721 were young-old, and 888 were not-old (Table 2). Our analytical dataset showed a higher ratio of hemorrhagic stroke deaths at younger ages compared to non-hemorrhagic stroke deaths.

Tables 1 and 2 show that both hemorrhagic and non-hemorrhagic stroke decedents lived in areas with long-term exposure to fine particulate matter three times more than the threshold defined by the World Health Organization (WHO). They also experienced PM_{10} and O_3 reaching the threshold of the daily mean on an almost daily basis. In addition, stroke decedents had not tended to live in areas with more or less greenery or open spaces. Although the majority of stroke decedents were old and unemployed or retired at the time of death, we note that approximately 34% of “not-old” hemorrhagic stroke decedents and 45 % of “not-old” non-hemorrhagic stroke decedents were employed. This evidences the widening socio-demographic profile of stroke mortality in this high-density Asian city.

Urban characteristics and age-specific hemorrhagic stroke mortality

Among all decedents, days with low temperature were positively associated with hemorrhagic stroke mortality (OR: 1.101 [1.008, 1.202]), while days with high temperature were negatively associated with hemorrhagic stroke mortality, when compared with all-cause mortality, controlling for other social and environmental factors (Table 4). In addition, being male, older, unemployed, and unmarried were factors negatively associated with higher hemorrhagic stroke mortality. Furthermore, a 10 μg/m^3 increase in *daily* PM_{10} was positively associated with higher hemorrhagic stroke mortality (OR: 1.015 [1.005, 1.027]).

From our age-specific models, short-term environmental measures only had significant associations with hemorrhagic stroke mortality among the young-old group. Specifically, days with high temperature were negatively associated with hemorrhagic stroke mortality among the young-old decedents; and a 10 μg/m^3 increase in *daily* PM_{10} was positively associated with higher hemorrhagic stroke mortality among young-old decedents (OR: 1.022 [1.005, 1.040]).

Individual-level social measures showed some significant associations with hemorrhagic stroke decedents in age-specific groups. Among old-old decedents, being male and being older were negatively associated with higher hemorrhagic stroke mortality. Among the mid-old decedents, being male was the only individual-level social measure negatively associated with higher hemorrhagic stroke mortality. Among the not-old decedents, older age was positively associated with higher hemorrhagic stroke mortality, with OR of 1.005 [1.001, 1.009]. However, being unemployed was negatively associated with hemorrhagic stroke mortality (OR: 0.575 [0.527, 0.628]). None of the measures of long-term environmental impacts or of community-level social measures were significantly associated with hemorrhagic stroke mortality, including open space and greenness.

Urban characteristics and age-specific non-hemorrhagic stroke mortality

For all decedents, long-term exposure to regional air pollution had a stronger positive association with non-hemorrhagic stroke mortality (OR: 1.077 [1.003, 1.157]) when compared with all-cause mortality, controlling for other social and environmental factors (Table 5). Being male was negatively associated with higher non-hemorrhagic stroke mortality, while being older was positively associated with higher stroke mortality. In addition, a 10 μg/m^3 increase in *daily* PM_{10} was positively associated with higher non-hemorrhagic stroke mortality (OR: 1.014 [1.004, 1.025]).

From our age-specific models, measures of long-term environmental measures only had significant associations with non-hemorrhagic stroke mortality among the young-old group. Specifically, long-term exposure to regional air pollution was more strongly related to non-hemorrhagic stroke mortality (OR: 1.139 [1.004, 1.292]) compared with all-cause mortality among young-old decedents, controlling for other social and environmental factors.

Individual-level social measures showed a number of significant associations with non-hemorrhagic stroke decedents in age-specific groups. Among both old-old decedents and young-old decedents, being male was a factor negatively associated with non-hemorrhagic stroke mortality. Non-hemorrhagic stroke deaths tended to occur at a younger age among the old-old group compared with all-cause deaths (OR: 0.986 [0.981, 0.991]). In comparison, non-hemorrhagic stroke deaths tended to occur at an older age among the young-old group compared with all-cause deaths (OR: 1.027 [1.018, 1.036]). More importantly, older age and a neighborhood with higher percentage of lower education were positively associated with higher non-hemorrhagic stroke mortality, with OR of 1.048 [1.039, 1.058] and 1.018 [1.007, 1.029] respectively. However, being unemployed was negatively linked to non-hemorrhagic stroke mortality compared to being employed (OR: 0.820 [0.710, 0.948]).

Discussion

Summary of the results

This study suggests various stroke fatality patterns associated with urban characteristics in the high density city of Hong Kong. In general, short-term (and temporally varying) daily PM_{10}, older age and being female were more strongly associated with all types of stroke deaths compared to all-cause deaths. Colder days, being employed and being married were more strongly associated with hemorrhagic stroke deaths. Long-term (and spatially varying) regional air pollution was more strongly associated with non-hemorrhagic stroke deaths than all-cause deaths. However, the only factor that was consistent across all age-subgroups of decedents was gender, with females being more vulnerable to stroke mortality. This result is inconsistent with previous studies showing that incidence of stroke was higher in men than in women (Poorthuis et al., 2017). This may be due to a high prevalence of frailty and osteoporosis among females in Hong Kong, which affected their social behavior and commuting modes including usage of spaces (Ho et al., 1999; Yu et al., 2018).

Interpretation and implications from the environmental impacts

For the non-hemorrhagic stroke decedents, the air pollution results imply that dust particles inhaled into lungs may produce higher risk of non-hemorrhagic stroke mortality, consistent with previous studies regarding impacts of low air quality on community health (Ho et al., 2018b; Wang et al., 2020; Zhou et al., 2020). Our results suggest that the short-term effect of dust particles on non-hemorrhagic stroke mortality is not age-specific, so protection of the entire population is needed. In contrast, the association between regional air pollution and non-hemorrhagic stroke mortality for all ages and for the young-old group were found. It showed that the young-old group may be particularly vulnerable for non-hemorrhagic stroke mortality. The negative effect of an increase in daily PM_{10} levels and days with lower temperature for all ages in general and for the young-old population among the hemorrhagic stroke decedents in particular, suggests that the need for protection from pollution due to its short-term impact rather than long-term impact on hemorrhagic stroke mortality.

The above results are important, as the young-old could be older people with frailty and chronic disease, but with less health care and support than the old-old. Therefore, these young-old people may not be well protected from the short- and long-term impacts that influence various types of stroke mortality.

The insignificant results of greenness and open space are of interest. Greenness and open space have been found to be associated with various chronic diseases, both globally and in high density cities, including Hong Kong (Paul et al., 2020; Yu et al., 2018). These factors have also been reported as significant in stroke mortality models elsewhere (Wilker et al., 2014).

The lack of correlation in our study may indicate mixed health effects from high-density living (Guo et al., 2019; Guo et al., 2021; Lin et al, 2021), suggesting that this type of urban design presents residents with a high density of walkable destinations which induces more walking and outdoor socializing (Guo et al., 2021). Physical activity conducted in local greenspace may reduce health problems (Hu et al., 2008) and for seniors who do not participate in sport, walking to green space may yield health benefits (Sarkar et al., 2013). The urban greenery in Hong Kong, however, is often inaccessible, being the land-cover on the city's many steep slopes that abut and punctuate built up areas. In contrast, public open spaces located, by design, within the urban fabric of Hong Kong, is predominately impervious surfaces without greenery. Other studies have indicated beneficial effects of greenness and open space as independent urban design attributes (Mennis, Mason and Ambrus, 2018; Orioli et al., 2019; Rojas-Rueda et al., 2019). Our study is the first to find that neither urban greenery nor designed urban open spaces do not significantly influence stroke mortality among the local population. As we say, this could be the result of countervailing environmental influences in Hong Kong's mixed land-use neighborhoods or the irrelevance of greenery to walking when it is on an inaccessible slope (Frank et al., 2004; Brown et al., 2009; Alves et al., 2020; Manzi et al., 2020). Senior populations may even walk away from green areas to better enjoy a mountain landscape view of the greenery. The null effect for non-greened open spaces may be due to a lack of interest in such spaces among seniors. However, this does not tally with studies on Hong Kong's open spaces, which suggest that they are well used, particularly by the seniors (Lo and Jim, 2010;

Xue, Gou and Lau, 2017; Garrett et al., 2019). We are more inclined to think that the lack of association may be due to a lack of heterogeneity of such spaces. Urban areas are very well planned and access to open spaces 'sitting out spaces' in Hong Kong, is much the same across the territory.

Interpretation and implications from the socio-demographic impacts

The degree of access to health care might also help explain another intriguing other age-relate findings. Our results showed that younger decedents among the old-old suffered from higher non-hemorrhagic stroke mortality, in contrast to the overall results that older people have higher non-hemorrhagic stroke mortality in general. The results for hemorrhagic mortality were even more extreme, in which we found 1) overall results as well as age-specific results for the old-old group showing that younger people have higher hemorrhagic stroke mortality in general; 2) no significant result of an age effect was found among the young-old decedents; and 3) older decedents among the not-old suffered from higher hemorrhagic stroke mortality. This indicated that non-hemorrhagic stroke mortality might be more commonly found among the mid-old (age approximately to 80), while hemorrhagic stroke mortality could be more common for the young-old. This partially indicates that the younger old need more health care to protect them from the fatal effects of stroke. More importantly, the association between higher hemorrhagic stroke mortality and being married for all ages could also be because of the needs of health care, as previous studies have already noted the health burdens caused by supporting one's closest family members who may be frail and have chronic diseases (Martire et al., 2004).

The negative effects of a community's percentage of low education as well as employment among not-old decedents could imply a critically missing part in health care. Specifically, these results may indicate that less-well-educated workers (e.g. construction workers and other manual laborers) have a high risk of stroke mortality. More health education and support should be delivered to these vulnerable subpopulations.

Recommendations for urban and community planning

First, our findings provide no evidence for suggesting that greenness and ungreened open spaces influence the risk of stroke death. This is interesting in terms of healthy city design since it is well established that access to green and to other open spaces has a beneficial effect on adiposity (Sarkar et al., 2013; Sarkar, 2017; Persson et al ., 2018). Why might there be an effect of open space and green on obesity but not stroke death? Additionally, our results were somewhat aligned with some local studies, which have found that natural greenness in Hong Kong might not be able to benefit community health across the cities (Guo et al., 2021; Lin et al., 2021). Particularly, Lin et al. (2021) found that natural greenery might actually worsen bone mineral density and increase fall risks among older adults in Hong Kong. Guo et al. (2021) found that open spaces could improve mental health and subjective wellbeing but natural greenery might reduce subjective wellbeing through sense of community. We note that our outcome measure is stroke mortality not stroke incidence. It may be that the environmentally-shaped habits of urban walking do in fact impact on incidence of obesity, stroke and other sedentary diseases, but not on mortality (at least in stroke). Second, we show that urban ventilation is potentially a protector against stroke mortality, especially in the young-old group. Urban design that improves air quality, by ventilation or filtering, provides multiple health benefits (Goggins et al., 2013). Vertical greening on high-rise buildings can help filter more urban air (Perini et al., 2011; Pugh et al., 2012), as can the design of ventilation corridors in high density high rise cities (Ng, 2009; Yuan and Ng, 2012;Yuan, Ng and Norford, 2014).

Furthermore, those with less education (e.g. manual laborers) who are younger (< 65) also tend to have low awareness and preparedness due to socioeconomic deprivation and a lack of social engagement. Therefore, urban design with multifunctional spaces may better suit these subpopulations, who can participate in social or physical activities in social facilities, while at the same time health promotion through community programs can be delivered to the individuals to enhance their awareness for stroke prevention.

Limitation and future directions

There are several limitations in this study. First of all, the register-based dataset did not have information on spatial mobility. This may reduce the explanatory power of a spatiotemporal effect of urban characteristics on stroke mortality. However, since older people usually have less mobility, we think we are justified in modelling local environmental exposures of age-specific stroke mortality. A second limitation is a lack of information on co-morbidities from the register-based study. While we were able to draw out a statistical association to imply potential causality, we were unable to investigate path analysis that requires information related to co-morbidities. For future study, as the data might be hierarchical due to multiple levels of variables existed, further analyses by using mixed effect models with the TPU as the mixed effect item might be more appropriate. Thirdly, we used binary measure to indicate social support (married/unmarried); overlooking the fact that many unmarried live with relatives in Hong Kong because of the high cost of homes.

Fourthly, this was an ecological study conducted at the TPU level, and thus suffers from all the normal caveats. One in particular that we should note is the unmeasured possible interaction of greenness as an inducement to walking and greenness as an air filter. Our air quality measures were spatially interpolated from point sources from land use regression modelling. That means that our vegetation measure simultaneously indicates the attractiveness of a TPU environment for walking and its performance in filtering polluted air. Because of limitation related to spatial unit, we are unlikely to have captured important local variations in filtering effects of vegetation, which would have in reality moderated the modelled pollution measures.

Finally, as an extension of investigating the effects of environmental factors in the present study, future studies can further determine the effects of the spikes of environmental elements to gain an in-depth understanding of environmental effects (Ebenstein et al., 2017; Pope & Dockery, 2006; Yin et al., 2017; Zhao et al., 2020), which thus provides the support for the healthy built environment designs and protocols.

Conclusions

In this study, we evaluate which type(s) of urban element may influence stroke mortality in a high-density city. Based on a register-based study, we found various factors linked to stroke mortality among different age groups in Hong Kong.

1) Linking to the research question regarding which type(s) of urban element may influence stroke mortality in a high-density city, we found that dust pollution and females should receive greater attention in general.
2) In addition, less well-educated workers younger than 65 and living in more polluted areas should be protected against their higher odds of stroke mortality at younger ages.
3) We found no evidence for a moderating effect of greenness or non-green public open spaces on stroke mortality in HK, which is seldom reported in previous studies. The insignificant association of stroke with these two green-associated factors may be due to the high homogeneity in access to open space in Hong Kong. However, we note that the insignificant effects of greenness observed in the present study do not rule out an influence of greenness on stroke incidence, as would be expected from other studies of urban design and chronic disease.

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	Hemorrhagic stroke decedents							
	All ages [n = 8697 (100%)]		Old-old [n = 3565 (41.0%)]		Young-old [n=2932 (33.7%)]		Not-old [n=2200 (25.3%)]	
	Avg	**SD**	**Avg**	**SD**	**Avg**	**SD**	**Avg**	**SD**
Regional air pollution (μg/m^3)	**32.6**	**3.7**	**32.5**	**3.7**	**32.7**	**3.7**	**32.6**	**3.7**
Traffic-related air pollution (μg/m^3)	**9.3**	**3.2**	**9.3**	**3.2**	**9.4**	**3.2**	**9.4**	**3.4**
High temp days (%)	**6.8**	**25.2**	**6.5**	**24.6**	**7.4**	**26.2**	**6.9**	**25.3**
Low temp day (%)	**6.4**	**24.5**	**6.6**	**24.8**	**6.4**	**24.5**	**5.3**	**22.4**
Daily PM_{10} (μg/m^3)	**48.3**	**24.1**	**48.2**	**23.4**	**48.4**	**25.6**	**48.4**	**23.4**
Daily NO_x (μg/m^3)	**93.6**	**33.9**	**93.6**	**33.5**	**93.7**	**34.4**	**93.8**	**34.2**
Daily O_3 (μg/m^3)	**41.4**	**20.7**	**41.6**	**20.8**	**41.3**	**20.7**	**41.0**	**20.6**
RH	**77.9**	**10.9**	**77.9**	**10.9**	**77.9**	**10.8**	**77.5**	**11.1**
% open space (%)	**33.7**	**22.0**	**33.4**	**22.1**	**33.6**	**22.0**	**35.4**	**21.6**
High greenness (%)	**27.9**	**44.8**	**27.8**	**44.8**	**27.7**	**44.8**	**28.7**	**45.3**
low education (%)	**26.9**	**7.5**	**26.6**	**7.7**	**27.4**	**7.3**	**27.3**	**7.2**
Non-Cantonese native tongue (%)	**11.7**	**5.7**	**11.9**	**6.0**	**11.4**	**5.1**	**11.3**	**5.2**
Unemployed (%)	**91.5**	**27.9**	**94.4**	**22.9**	**92.9**	**25.7**	**66.0**	**47.4**
Unmarried (%)	**61.1**	**48.8**	**70.7**	**45.5**	**47.4**	**49.9**	**45.5**	**49.8**
Age	**80.3**	**10.8**	**87.2**	**5.1**	**74.0**	**3.9**	**56.1**	**7.6**
Male (%)	**47.9**	**50.0**	**38.2**	**48.6**	**60.8**	**48.8**	**67.0**	**47.0**

Table 2 – Data summary of non-hemorrhagic stroke decedents

	Non-hemorrhagic stroke decedents							
	All ages [n=10270 (100%)]		Old-old [n=6111 (59.5%)]		Young-old [n=3271 (31.9%)]		Not-old [n=888 (8.6%)]	
	Avg	**SD**	**Avg**	**SD**	**Avg**	**SD**	**Avg**	**SD**
Regional air pollution (μg/m^3)	**32.5**	**3.6**	**32.4**	**3.5**	**32.5**	**3.6**	**32.5**	**3.6**
Traffic-related air pollution (μg/m^3)	**9.2**	**3.3**	**9.1**	**3.3**	**9.4**	**3.3**	**9.3**	**3.4**
High temp days (%)	**6.4**	**24.4**	**6.6**	**24.8**	**5.8**	**23.3**	**6.9**	**25.3**
Low temp day (%)	**7.1**	**25.7**	**7.5**	**26.3**	**7.0**	**25.6**	**6.7**	**25.1**
Daily PM_{10} (μg/m^3)	**49.0**	**25.0**	**48.9**	**24.9**	**49.9**	**26.7**	**48.0**	**22.9**
Daily NO_x (μg/m^3)	**93.5**	**34.0**	**94.1**	**35.0**	**94.2**	**34.1**	**91.6**	**32.1**
Daily O_3 (μg/m^3)	**42.0**	**21.0**	**41.8**	**20.9**	**42.1**	**20.8**	**42.3**	**21.2**
RH	**77.4**	**11.2**	**77.4**	**11.4**	**77.2**	**11.1**	**77.7**	**11.1**
% open space (%)	**34.1**	**21.9**	**33.5**	**21.8**	**34.2**	**21.9**	**34.8**	**22.2**
High greenness (%)	**27.7**	**44.8**	**27.4**	**44.6**	**28.0**	**44.9**	**27.9**	**44.9**
low education (%)	**26.9**	**7.5**	**26.8**	**7.8**	**27.2**	**7.3**	**26.5**	**7.0**
Non-Cantonese native tongue (%)	**11.6**	**5.8**	**11.9**	**6.1**	**11.4**	**5.4**	**11.4**	**5.7**
Unemployed (%)	**83.8**	**36.9**	**94.8**	**22.2**	**92.0**	**27.2**	**55.0**	**49.8**
Unmarried (%)	**54.1**	**49.8**	**66.4**	**47.2**	**46.2**	**49.9**	**44.6**	**49.7**
Age	**73.4**	**14.7**	**86.2**	**4.8**	**73.5**	**4.2**	**52.5**	**9.5**
Male (%)	**55.1**	**49.7**	**43.6**	**49.6**	**61.8**	**48.6**	**65.0**	**47.7**

Table 3 – Data summary of all-cause deaths

	All-cause deaths							
	All ages [n=284443 (100%)]		Old-old [n=141613 (49.8%)]		Young-old [n=86987 (30.6%)]		Not-old [n=55843 (19.6%)]	
	Avg	**SD**	**Avg**	**SD**	**Avg**	**SD**	**Avg**	**SD**
Regional air pollution (µg/m^3)	**32.4**	**3.7**	**32.4**	**3.6**	**32.5**	**3.7**	**32.4**	**3.7**
Traffic-related air pollution (µg/m^3)	**9.2**	**3.3**	**9.2**	**3.2**	**9.3**	**3.3**	**9.3**	**3.4**
High temp days (%)	**7.1**	**25.7**	**7.0**	**25.6**	**7.1**	**25.6**	**7.3**	**26.0**
Low temp day (%)	**6.3**	**24.3**	**6.6**	**24.9**	**6.2**	**24.0**	**5.7**	**23.2**
Daily PM_{10} (µg/m^3)	**47.8**	**24.7**	**47.8**	**24.6**	**48.0**	**25.0**	**47.4**	**24.4**
Daily NO_x (µg/m^3)	**93.0**	**33.6**	**93.1**	**33.8**	**93.0**	**33.4**	**92.6**	**33.2**
Daily O_3 (µg/m^3)	**41.7**	**21.0**	**41.8**	**21.0**	**41.6**	**21.1**	**41.5**	**21.1**
RH	**77.9**	**10.9**	**77.9**	**10.9**	**77.8**	**10.9**	**77.9**	**10.8**
% open space (%)	**34.0**	**21.8**	**33.3**	**21.9**	**34.2**	**21.6**	**35.6**	**21.9**
High greenness (%)	**28.0**	**44.9**	**27.8**	**44.8**	**28.0**	**44.9**	**28.9**	**45.3**
low education (%)	**26.8**	**7.5**	**26.6**	**7.8**	**27.3**	**7.4**	**26.6**	**7.2**
Non-Cantonese native tongue (%)	**11.7**	**5.7**	**12.0**	**6.0**	**11.5**	**5.2**	**11.3**	**5.4**
Unemployed (%)	**88.8**	**31.6**	**94.7**	**22.4**	**92.6**	**26.2**	**67.7**	**46.7**
Unmarried (%)	**56.7**	**8.2**	**68.1**	**46.6**	**44.8**	**49.7**	**46.1**	**49.8**
Age	**76.2**	**15.0**	**87.4**	**5.3**	**73.5**	**4.1**	**52.0**	**11.9**
Male (%)	**55.2**	**49.7**	**45.6**	**49.8**	**65.9**	**47.4**	**62.7**	**48.4**

Table 4 – Odds ratio (OR) and 95% confidence interval (CI) for evaluating the associations between urban characteristics and age-specific hemorrhagic stroke mortality. Based on each regression, the OR was used to evaluate the difference between stroke and all-cause mortality.

	Odds ratio											
	All decedents			Old-old			Young-old			Not-old		
	OR	LUI	UCI	OR	LUI	UCI	OR	LUI	UCI	OR	LUI	UCI
Regional air pollution (in 10 μg/m^3)	1.008	0.932	1.090	0.995	0.880	1.124	1.034	0.904	1.183	1.011	0.863	1.183
Traffic-related air pollution (in 10 μg/m^3)	0.972	0.890	1.062	0.919	0.800	1.057	1.037	0.890	1.209	0.967	0.812	1.151
Day with high temperature	**0.903**	**0.825**	**0.988**	0.933	0.812	1.072	**0.825**	**0.702**	**0.970**	0.949	0.797	1.130
Day with low temperature	**1.101**	**1.008**	**1.202**	1.085	0.948	1.241	1.082	0.929	1.261	1.192	0.994	1.430
Daily PM_{10} (in 10 μg/m^3)	**1.016**	**1.005**	**1.027**	1.012	0.994	1.030	**1.022**	**1.005**	**1.040**	1.009	0.984	1.035
Daily NO_x (in 10 μg/m^3)	1.000	0.993	1.008	1.004	0.992	1.015	1.003	0.990	1.016	0.991	0.975	1.007
Daily O_3 (in 10 μg/m^3)	0.993	0.979	1.007	0.989	0.967	1.011	0.990	0.966	1.014	1.007	0.978	1.037
Relative humidity	0.998	0.995	1.000	0.997	0.993	1.001	0.997	0.993	1.001	1.000	0.995	1.005
Percent of open space	1.003	0.988	1.019	1.016	0.992	1.040	1.004	0.978	1.031	0.987	0.958	1.016
Vegetation	0.961	0.890	1.037	0.903	0.801	1.017	1.006	0.882	1.148	0.983	0.844	1.145
Percent of low education	1.000	0.997	1.004	1.000	0.995	1.006	0.997	0.991	1.003	1.001	0.994	1.008
Percent of non-Cantonese	0.997	0.992	1.002	0.997	0.990	1.004	0.995	0.986	1.003	1.003	0.994	1.013
Unemployed	**0.731**	**0.687**	**0.778**	1.012	0.870	1.176	0.904	0.787	1.038	**0.575**	**0.527**	**0.628**
Unmarried	**0.911**	**0.871**	**0.953**	0.965	0.894	1.041	1.021	0.945	1.102	0.944	0.864	1.031
Age	**0.991**	**0.990**	**0.992**	**0.953**	**0.946**	**0.959**	0.999	0.990	1.008	**1.005**	**1.001**	**1.009**
Male	**0.915**	**0.874**	**0.956**	**0.827**	**0.769**	**0.888**	**0.836**	**0.773**	**0.903**	1.010	0.922	1.106

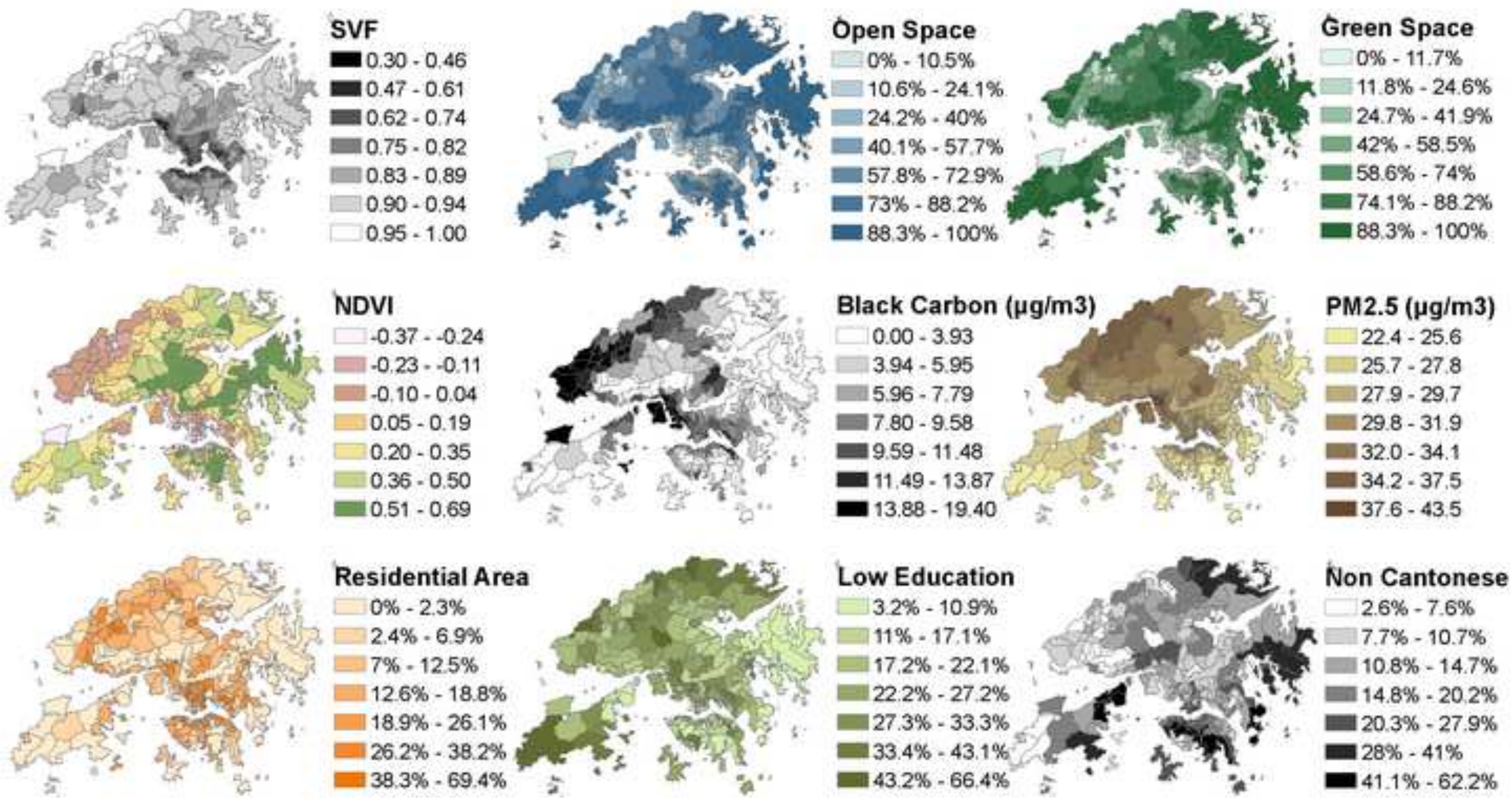
Table 5 – Odds ratio (OR) and 95% confidence interval (CI) for evaluating the associations between urban characteristics and age-specific non-hemorrhagic stroke mortality. Based on each regression, the OR was used to evaluate the difference between stroke and all-cause mortality.

	Odds ratio											
	All decedents			Old-old			Young-old			Not-old		
	OR	LUI	UCI	OR	LUI	UCI	OR	LUI	UCI	OR	LUI	UCI
Regional air pollution (in 10 $\mu g/m^3$)	**1.077**	**1.003**	**1.157**	1.037	0.945	1.139	**1.139**	**1.004**	**1.292**	1.103	0.865	1.406
Traffic-related air pollution (in 10 $\mu g/m^3$)	1.077	0.992	1.169	1.092	0.981	1.215	1.024	0.885	1.185	1.131	0.862	1.483
Day with high temperature	0.970	0.894	1.052	0.920	0.826	1.024	1.082	0.942	1.243	0.909	0.692	1.192
Day with low temperature	0.982	0.903	1.070	0.980	0.879	1.093	1.051	0.904	1.221	0.822	0.603	1.121
Daily PM_{10} (in 10 $\mu g/m^3$)	**1.014**	**1.004**	**1.025**	1.012	0.998	1.026	1.012	0.994	1.031	1.029	0.996	1.064
Daily NO_x (in 10 $\mu g/m^3$)	1.000	0.993	1.007	0.999	0.990	1.008	1.003	0.991	1.016	0.998	0.975	1.021
Daily O_3 (in 10 $\mu g/m^3$)	**0.985**	**0.972**	**0.999**	0.988	0.971	1.005	0.993	0.970	1.016	**0.955**	**0.913**	**0.998**
Relative humidity	1.000	0.998	1.003	1.000	0.997	1.003	1.002	0.998	1.006	0.995	0.988	1.002
Percent of open space	0.995	0.981	1.009	1.003	0.985	1.022	0.986	0.961	1.011	0.997	0.952	1.044
Vegetation	1.066	0.993	1.145	1.031	0.940	1.132	1.091	0.962	1.237	1.101	0.871	1.391
Percent of low education	1.003	0.9999	1.006	1.000	0.996	1.005	1.001	0.995	1.006	**1.018**	**1.007**	**1.029**
Percent of non-Cantonese	0.999	0.994	1.003	0.997	0.992	1.003	0.998	0.990	1.007	1.013	0.999	1.028
Unemployed	1.026	0.953	1.104	0.949	0.848	1.063	1.008	0.878	1.158	**0.820**	**0.710**	**0.948**
Unmarried	1.011	0.968	1.056	1.031	0.970	1.096	1.052	0.979	1.132	1.131	0.988	1.294
Age	**1.020**	**1.019**	**1.022**	**0.986**	**0.981**	**0.991**	**1.027**	**1.018**	**1.036**	**1.048**	**1.039**	**1.058**
Male	**0.831**	**0.796**	**0.866**	**0.723**	**0.684**	**0.766**	**0.822**	**0.764**	**0.884**	1.093	0.947	1.262

Captions of Figures

Figure 1 – Spatial variability of long-term environmental conditions and community-level socioeconomic disparity

Figure 1


SVF
0.30 - 0.46
0.47 - 0.61
0.62 - 0.74
0.75 - 0.82
0.83 - 0.89
0.90 - 0.94
0.95 - 1.00
Open Space
0% - 10.5%
10.6% - 24.1%
24.2% - 40%
40.1% - 57.7%
57.8% - 72.9%
73% - 88.2%
88.3% - 100%
Green Space
0% - 11.7%
11.8% - 24.6%
24.7% - 41.9%
42% - 58.5%
58.6% - 74%
74.1% - 88.2%
88.3% - 100%
NDVI
-0.37 - -0.24
-0.23 - -0.11
-0.10 - 0.04
0.05 - 0.19
0.20 - 0.35
0.36 - 0.50
0.51 - 0.69
Black Carbon (μg/m3)
0.00 - 3.93
3.94 - 5.95
5.96 - 7.79
7.80 - 9.58
9.59 - 11.48
11.49 - 13.87
13.88 - 19.40
PM2.5 (μg/m3)
22.4 - 25.6
25.7 - 27.8
27.9 - 29.7
29.8 - 31.9
32.0 - 34.1
34.2 - 37.5
37.6 - 43.5
Residential Area
0% - 2.3%
2.4% - 6.9%
7% - 12.5%
12.6% - 18.8%
18.9% - 26.1%
26.2% - 38.2%
38.3% - 69.4%
Low Education
3.2% - 10.9%
11% - 17.1%
17.2% - 22.1%
22.2% - 27.2%
27.3% - 33.3%
33.4% - 43.1%
43.2% - 66.4%
Non Cantonese
2.6% - 7.6%
7.7% - 10.7%
10.8% - 14.7%
14.8% - 20.2%
20.3% - 27.9%
28% - 41%
41.1% - 62.2%

H.C. Ho and K. Fong conceived the study. H.C. Ho and H. Guo conducted the data analysis. H.C. Ho prepared the draft of the manuscript. Y. Shi prepared the data collection. Y. Shi, C. Webster and T.C. Chan provided comments on environmental health implications. All authors provided critical feedback on all versions of the manuscript.