Objectives: Recently, studies have shown a positive relationship between air pollutants and suicide. But, the previous studies did not take other significant factors into consideration. The present study was intended to explore the relationship between the air pollutant concentrations and suicide rate by cross-sectional time series analysis considering other significant factors simultaneously.

Methods: I gathered the annual suicide rates, socioeconomic parameters, meteorological data, and concentrations of five air pollutants -- sulfur dioxide (SO₂), nitrogen dioxide (NO₂), ozone (O₃), carbon monoxide (CO), particulate matter (PM₁₀) -- in Taiwan during 1994-2009. Then, I did a pooled cross-sectional time series analysis. Results: Random effect model was identified as the final model, indicating the spouseless population having the most significant risk factor for suicide (z = 4.27, p < 0.001). PM₁₀ was also found to play a significant role in suicide (z = 2.56, p < 0.05); while SO₂, NO₂, O₃, and CO were found to be nonsignificant. Conclusion: The results identify PM₁₀ as a possible risk factor for suicide. The present findings complement previous studies by providing the viewpoint from a longer aspect as well as a broader cross-sectional distribution, with the consideration of some more potential confounders.

Key words: air pollutants, cross-sectional time series analysis, PM₁₀, suicide


Introduction

Suicide is a major worldwide mental health threat. The complicated causes of suicide have been the focus of numerous studies. Various socioeconomic factors associated with suicide include marital status, old age, unemployment, low-income, being a laborer [1, 2], and meteorological causes [3]. Recent studies have revealed a positive relationship between air pollutants and suicide. An increased risk of suicide has been found to be related to ambient particulate matter less than 10 μm in diameter (PM₁₀) exposure [4]. Yang et al. found that increased PM₁₀ has also shown to be associated with seasonal increases in suicide, and that concentrations of sulfur dioxide (SO₂), and increased ozone (O₃) have been found to be associated with a longer-term increased suicide [5]. But Kim et al. [4] did not study well-recognized...
socioeconomic factors because they only focused on a short-term exposure to air pollutants [4]. Yang et al. in their study [5] only controlled for the unemployment rate, which is a less significant economic factor [1]. If the research focus is limited, the results may be deviant.

The study by Yang et al. [5] was conducted only in one city, focusing that environmental factors contributing to suicide risk may vary in distinct geographic regions. Hsiao [6] asserted that panel data analysis comprising both longitudinal and cross-sectional data can provide a better model to study complexities of human behavior compared with single cross-section or time series data.

The aim of the present study was to explore the relationship between the annual average air pollutant concentrations and suicide rates across different cities and counties in Taiwan from 1994 to 2009. With a cross-sectional time series analysis, I in this study took both significant socioeconomic factors and meteorological parameters into consideration, to obtain a more comprehensive understanding for suicide.

Methods

Study design

In this study, I analyzed 17 cities and counties in Taiwan. I analyzed complete data of air pollutant concentrations, socioeconomic factors, meteorological parameters, and suicide rates from 1994 to 2009 in 17 cities and counties in Taiwan. Locations included the Keelung city, the Taipei city, the Taipei county, the Hsinchu city, the Hsinchu county, the Yilan county, the Taichung county, the Taichung city, the Hualien county, the Chiayi city, the Chiayi county, the Tainan county, the Tainan city, the Taitung county, the Kaohsiung county, the Kaohsiung city, and the Pingtung county. The study began from 1994 when complete air pollution data started to be available. Overall, I used 272 pieces of data from 17 regions over 16 years.

Data collections

I obtained the annual suicide death rates (per 100,000 inhabitants) of the total population in the study regions from 1994 to 2009 from a population-based database (ICD-9 classification E950-959) of the Department of Health of Taiwan (www.doh.gov.tw). Because all deaths must be registered, Taiwan’s vital event statistics are highly comprehensive and accurate. I also got the monthly air pollutant concentrations in the 17 cities and counties during the study period from Environmental Protection Administration, Executive Yuan of Taiwan (taqm.epa.gov.tw/taqm/zh-tw/). The collection methods were uniform across time and space. Measurements included SO2 (Model 9850, Ecotech Inc., Knoxfield, Australia), nitrogen dioxide (NO2) (Model 9841, Ecotech Inc.), O3 (Model 9810, Ecotech Inc.), carbon monoxide (CO) (Model APMA-370, Horiba Inc., Kyoto, Japan), and PM10 (Mode F701, Verewa, Hamburg, Germany). Then, I calculated the annual mean concentrations of the air pollutants for each region in each year with the consideration of the calendar effect. Namely, the annual mean was average of weighted monthly concentrations according to the days in each month.

I gathered the annual data of five widely recognized relevant significant socioeconomic factors (percentage of spouseless population including single/divorced/widowed, percentage of population aged over 65 years, unemployment rate, labor force participation rate, low-income population with aid per 10,000 inhabitants) in the 17 areas during the study period, from Directorate-General of Budget, Accounting and Statistics,
Executive Yuan of Taiwan (ebas1.ebas.gov.tw/px-web/Dialog/statfile9L.asp). Monthly data may provide more detailed information regarding the relationship between air pollution and suicide. But unfortunately, the socioeconomic data for each areas in Taiwan are released yearly by the Directorate-General of Budget, Accounting and Statistics, Executive Yuan of Taiwan. To take the important socioeconomic variables into consideration is desirable in the study, but only yearly data were used for the analyses.

I calculated three meteorological parameters (mean annual ambient temperature (°C), total rainfall (mm) and sunshine (hours) from the database of the Central Weather Bureau in Taiwan (www.cwb.gov.tw).

**Statistical analyses**

Descriptive statistics were used to present the characteristics of suicide rates, air pollutant concentrations, socioeconomic factors, and meteorological parameters. I used a pooled data matrix that comprised cross-sectional data regarding the 17 cities and counties as well as time series for 16 years to produce a data set of 17 × 16 observations. The regression models with fixed and random effects were specified as follows, respectively:

\[ Y_{NT} = \beta_k X_{kNT} + \alpha_N + \epsilon_{NT} \]
\[ Y_{NT} = \beta_k X_{kNT} + \alpha_N + u_{NT} + \epsilon_{NT} \]

Where

- \( N \) = 1...17 cities/counties (refers to a cross-sectional entity)
- \( T \) = 1...16 years (refers to calendar year 1994-2009)
- \( k \) = 1...13; number of independent variables (refers to concentrations of 5 air pollutants, 5 socioeconomic and 3 meteorological factors)
- \( Y_{NT} \) = suicide rate of Nth city/county in year T

\( X_{kNT} \) = independent variables of Nth city/county in year T
\( \beta_k \) = pooled regression estimates of the effect for each independent variable
\( \alpha_N \) = intercept
\( u_{NT} \) = between entity error
\( \epsilon_{NT} \) = within entity error

I did pooled cross-sectional time series analyses with STATA 10.0 (College Station, Texas, USA) to obtain the estimates of the fixed and random effects, with the option “robust” used to overcome repeated measure biases, correlated errors and heteroskedasticity. Then, I conducted Hausman test to decide the final model, fixed or random effect, and finally, the diagnostic test (dss.princeton.edu/training/Panel101.pdf) to confirm the final model. The differences between groups were considered significantly if \( p \)-values were less than 0.05.

**Results**

The 17 regions in the study consisted of 72.9% (30,472 km²) of the territory and about 18 million (80%) of the population of Taiwan, locating in the subtropical areas. From 1994 to 2009, the total number of death by suicide in the 17 areas was 35,935 (23,871 males and 12,064 females). The mean yearly suicide rates are ranged from 1.8 to 29.6 per 100,000 inhabitants. The annual mean concentrations of SO₂, NO₂, O₃, CO and PM₁₀ varied between 0.34 and 14.4 parts per billion (ppb), 5.67 and 31.8 ppb, 15.3 and 34.9 ppb, 0.35 and 1.33 parts per million (ppm), and 28.17 and 103.4 μg/m³, respectively. Figure 1 shows the suicide rates and the concentrations of these 5 air pollutants in the 17 areas from 1994 to 2009. The percentages of the spouseless population were between 39.0% and 52.6%. The elderly
Figure 1. The panel data of suicide rate (1/100,000) and the concentrations of five air pollutants, sulfur dioxide (SO$_2$, ppb), nitrogen dioxide (NO$_2$, ppb), ozone (O$_3$, ppb), carbon monoxide (CO, ppm), particulate matter < 10 μm in diameter (PM$_{10}$, μg/m$^3$) in 17 cities/counties (A01-A17) in Taiwan during the 1994-2009 period.
proportions ranged from 5.6% to 15.0%. Labor force participation rates varied from 48.4% to 63.2%. The unemployment rates were between 1.0% and 5.9%. The registered low-income population with aid varied from 12 to 531 per 10,000 inhabitants. The mean annual temperatures were between 19.3 and 26.0 °C. The mean annual rainfalls were as dry as 878 mm, and as wet as 5438 mm. The mean annual hours of sunshine were as little as 983 h, and as much as 2574 h. Since obvious trends were manifested in the time series data as shown in Figure 1, de-trend procedure was applied to each variable using STATA 10.0 before the subsequent cross-sectional time series analysis.

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Table 1 lists the estimates of the cross-sectional time series analysis in the models of fixed and random effects. The fixed effect model identified the spouseless population percentage as the most significant risk factor for suicide ($\beta = 1.152 \pm 0.230$, $t = 5.01, p < 0.001$). Another possible risk factor for suicide was PM$_{10}$ exposure ($\beta = 0.076 \pm 0.032$, $t = 2.39, p < 0.05$). SO$_2$, NO$_2$, O$_3$ and CO were not significantly associated with suicide. The random effect model, again, identified the spouseless population as the most significant risk factor for suicide ($\beta = 1.212 \pm 0.284$, $t = 4.27, p < 0.001$). PM$_{10}$ concentration was significantly positively associated with suicide ($\beta = 0.072 \pm 0.028$, $z = 2.56, p < 0.05$). SO$_2$, NO$_2$, O$_3$ and CO were all still nonsignificant. The result of Hausman test identified random effect model as the final model ($\chi^2(1) = 1.63$, nonsignificantly different). Lagrangian multiplier test further confirmed the random effect model ($\chi^2(1) = 8.52, p < 0.01$).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fixed effect</th>
<th>Random effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\beta$ (S.E.)</td>
<td>$t$</td>
</tr>
<tr>
<td>Spouseless</td>
<td>1.152 (0.230)</td>
<td>5.01***</td>
</tr>
<tr>
<td>Aged</td>
<td>0.223 (0.155)</td>
<td>1.44</td>
</tr>
<tr>
<td>Labor participation</td>
<td>-0.131 (0.190)</td>
<td>-0.69</td>
</tr>
<tr>
<td>Unemployment</td>
<td>0.303 (0.283)</td>
<td>1.07</td>
</tr>
<tr>
<td>Poor</td>
<td>-0.137 (0.603)</td>
<td>-0.23</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.317 (0.509)</td>
<td>0.62</td>
</tr>
<tr>
<td>Rainfall</td>
<td>0.0001 (0.0003)</td>
<td>0.37</td>
</tr>
<tr>
<td>Sunlight</td>
<td>-0.001 (0.001)</td>
<td>-1.11</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>-0.196 (0.197)</td>
<td>-0.99</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>-0.032 (0.140)</td>
<td>-0.23</td>
</tr>
<tr>
<td>O$_3$</td>
<td>0.066 (0.109)</td>
<td>0.61</td>
</tr>
<tr>
<td>CO</td>
<td>-5.195 (3.398)</td>
<td>-1.53</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>0.076 (0.032)</td>
<td>2.39*</td>
</tr>
</tbody>
</table>

$R^2$ (Overall)  | 0.6252*** | 0.6314*** |

*p < 0.05; **p < 0.01; ***p < 0.001
S.E., standard error
Discussion

In this study, I explored the relationship between various air pollutants and the suicide death rate in Taiwan during the 1994-2009 period, with cross-sectional time series analysis on major socioeconomic factors and meteorological variables. As shown in Table 1, the results showed that of the five air pollutants examined, only PM$_{10}$ concentration exhibited a significant positive association with suicide death rates ($p < 0.05$). By contrast, the associations of suicide with SO$_2$, NO$_2$, O$_3$ and CO were nonsignificant.

Although the socioeconomic factors and meteorological parameters are not discussed further because they are outside the scope of this study, I would like to highlight the significant association of the spouseless population percentage with suicide risk. As shown in Table 1, spouseless population was shown to be a significant risk factor ($p < 0.001$).

The finding that exposure to PM$_{10}$ was a significant potential risk factor for suicide in this study is consistent with that reported in previous studies [4, 5]. But, Kim et al. [4] asserted that there may be confounding factors associated with individual susceptibility were not considered in their study, and that a long-term study is necessary to investigate the neurotoxic effects of particulate matter. Because important socioeconomic factors were considered, study duration was spanned over 16 years, and population-based data were used to analyze, I suggested that this current study complements the previous studies by providing a long-term viewpoint, broad cross-sectional distribution, and considering additional potential confounders.

Particulate matter, including PM$_{10}$, has been found to pose a considerable health risk, particularly in the cardiovascular system. Exposure to particulate air pollutants reduces heart rate variability [7], and increases the risk of coronary heart disease [4, 7, 8]. These factors are associated with the risk of depression [9-11], resulting in playing a major rôle in suicide [12, 13]. In an animal study, male mice have been found to exhibit more depressive-like responses following exposure to particulate matter for 10 months [14]. The investigators [14] suggested that long-term exposure to particulate air pollution exposure in major cities around the globe can alter affective responses. Lim et al. [15] showed that Geriatric Depression Scale score is positively associated with increased concentration of PM$_{10}$. Banerjee et al. [16] also reported that Indian households exposed to high PM$_{10}$ concentration after using biomass fuel, showing a relatively higher prevalence of depression, depleted platelet serotonin, and altered serotonergic activity in the brain, which are related to suicide [17]. Yackerson et al. [18] stated that the natural air-suspended particulates may be a source of atmospheric ionization, and that platelet serotonin is altered according to the sign and density of charges.

Unlike the data in previous studies [5, 15], the remaining air pollutants SO$_2$, NO$_2$, O$_3$, and CO of this study showed nonsignificant associations with suicide. The differences between these findings and those reported by previous results may be two fold. First, Lim et al. [15] focused on the effect of short-term exposure to air pollutants, and therefore the relatively time-invariant socioeconomic factors were not considered. Especially, the most significant potential risk factor identified in this study, the percentage of the spouseless population, was not considered in the previous studies. Although Lim et al. [15] and Szyszkowicz et al. [19] suggested that SO$_2$, NO$_2$, O$_3$, and CO are positively related to the symptoms of depression, the
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...spouseless population, including the divorced, is recognized as having higher prevalence of major depression [20]. I speculate that depression may be a common confounder, whereas the effect of spouseless population percentage is competitive with that of air pollutant concentrations when selecting significant variables for inclusion in the final regression model. Unfortunately, depression was not included in this study because the official data about the local prevalence of depression were not readily available. Second, the investigators of previous studies did not consider the cross-sectional aspects of suicide etiologies. Yang et al. [5] stated that environmental factors contributing to suicide risks may vary in distinct geographic regions, implying between-entity errors. This further explains why the random effects, rather than the fixed effects which concerning time series alone, were selected as the final model in this study.

The study complements previous research in several aspects. First, I took more socioeconomic factors into consideration, and addresses the importance. Second, being similar to the findings in previous studies [4, 15], the results of this study confirm the potential risk of PM_{10} in the long-term and in wide geographic regions. Because the association between suicide and concentrations of particulate matter has been recognized, population health experts may recommend reducing the production of ambient particulate matter, avoiding outdoor exposure during warning of elevated particulate matter concentrations, and using devices to reduce the indoor concentration of particulate matter.

**Study limitations**

The readers are cautioned not to over-interpret the study findings which might have the potential risk of causing an ecological fallacy because it has four major limitations:

- I did not include well-recognized suicidal crucial risk factors, such as depression in this study, and the association between the air-pollutant concentrations and the prevalence of depression was not further explored.
- I used annual rather than monthly data in the analyses. This choice of data prevented detailed explorations of the relationship between air pollution and suicide.
- Because no official data of PM_{2.5} concentrations for the study period was available, further analysis of the relationship between PM_{2.5} and suicide was impossible.
- The factors associated with individual susceptibility were not considered in this study.

**Summary of the study**

This study was to explore the relationship between five air pollutants and suicide using both longitudinal and cross-sectional aspects and considering the crucial socioeconomic factors and meteorological parameters. The results of the study indicate that PM_{10}, but not the other air pollutants, is a potential risk factor for suicide. The findings of this research complement previous studies by providing a viewpoint based on an extended time scale and broad cross-sectional distribution, as well as considering additional potential confounders.

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