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# Estimating the Acute Health Effects of Smoke Exposure from an Urban Factory Fire Accident: A Case Study of a Tire Factory Fire in Korea

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**BACKGROUND:** A major industrial fire accident occurred in a tire manufacturing factory in Daejeon, Korea, on 12 March 2023 and lasted for 3 d, generating air pollutant emissions. Although evidence regarding the health effects of urban fires is limited, residents near tire factory may have experienced health hazards due to smoke exposure from fire plumes.

**OBJECTIVES:** Capitalizing on the timing of this fire incident as a natural experiment, we estimated the attributable excess air pollution exposure and associated disease development among residents living near the tire factory.

**METHODS:** We used the generalized synthetic control method to estimate air pollution exposure and health burden attributable to the accident among residents living in smoke-exposed districts. Based on satellite images and air pollution monitoring results, three administrative districts (within 1.2 km from the factory) were defined as smoke-exposed, and the other 79 districts of Daejeon were defined as controls. Among the 11 monitoring stations in Daejeon, the station located 500 m from the factory was used to estimate excess air pollution exposure (PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub>, O<sub>3</sub>, SO<sub>2</sub>, and CO) for residents in the exposed districts. The number of daily district-level disease-specific incidence cases were acquired from the National Health Insurance Database and used to estimate excess health burden resulting from the fire.

**RESULTS:** During the first week following the factory fire, residents of exposed districts had an estimated excess exposure to 125.2 [95% confidence interval (CI): 44.9, 156.7] µg/m<sup>3</sup> of PM<sub>10</sub>, 50.4 (95% CI: 12.7, 99.8) ppb of NO<sub>2</sub>, and 32.0 (95% CI: 21.0, 35.9) ppb of SO<sub>2</sub>. We also found an average increase in the incidence cases of other diseases of upper respiratory tract [20.6 persons (95% CI: 6.2, 37.4)], lung disease due to external agents [2.5 persons (95% CI: 2.1, 3.3)], urticaria and erythema [5.9 persons (95% CI: –0.6, 11.2)], and episodic and paroxysmal disorders [8.5 persons (95% CI: 3.7, 13.4)] in exposed districts.

**DISCUSSION:** Excessive air pollution exposure and disease incidence were identified among residents living close to the tire factory. Preventive measures, such as a warning system, to avoid health impacts to people breathing fire-related pollution may be beneficial for communities impacted by such events. <https://doi.org/10.1289/EHP14115>

## Introduction

A sudden fire occurred at a tire manufacturing factory in Daejeon, Korea, on 12 March 2023. The fire lasted for 58 h, burning 200,000 stored tires and causing a property loss of USD \$140 million. Tire combustion is known to produce harmful pollutants, including particulate matter (PM), elemental carbon (EC), carbon monoxide (CO), sulfur dioxide (SO<sub>2</sub>), polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), and heavy metals.<sup>1–3</sup> Previous studies on landfill tires and tire factory fires have reported increases in the air concentrations of such substances.<sup>4–7</sup> Therefore, communities residing near the tire factory in Daejeon may have experienced adverse health effects due to the toxic pollutants that originated from the tire fire.<sup>7</sup>

However, only a few studies have reported on the public health effects of tire fire smoke. Residents exposed to the Westley tire fire

in California in 1999 reported headaches, coughing, difficulty breathing, and burning eyes.<sup>8</sup> The prevalence of eye and nose irritation was higher in children exposed to smoke from a tire fire that occurred in Bogotá, Colombia, in 2014, compared with unexposed children.<sup>9</sup> A tire fire in Amberley, New Zealand, in 2021, resulted in reports of difficulty breathing and throat irritation in patients within 3 d of the initial fire.<sup>10</sup> Although several exposure assessment studies have indicated possible links between tire fire plumes and adverse health outcomes in residents near fire sites,<sup>11,12</sup> epidemiological evidence is still lacking.

Few studies have documented the acute health effects of urban fires on local residents.<sup>13</sup> An increase in respiratory disease-related hospital visits was reported in residents exposed to warehouse and scrapyard fires.<sup>14,15</sup> Residents exposed to a fireworks facility explosion in Enschede, Netherlands, in 2000 reported acute respiratory symptoms within a day after the first explosion and physical and mental problems 2–3 wk after the incident.<sup>16</sup> A pilot study involving 13 residents reported an increase in respiratory and post-traumatic stress symptoms after the Intercontinental Terminals Company fire, which occurred in Deer Park, Texas, in 2019.<sup>17</sup> However, these previous studies on urban and industrial fires were prone to multiple sources of bias related to the lack of information on environmental exposure and health risks monitored before and after the disastrous event.<sup>13</sup> Most disaster studies used post-only designs with a small number of convenience samples, without an accurate assessment of baseline health status or environmental exposure levels.<sup>18</sup> On the other hand, the randomness of the timing of disasters provides a unique opportunity to conduct quasi-experimental studies by using data from such events as natural experiments.<sup>19,20</sup>

In our previous studies, nationwide health insurance data and difference-in-differences analyses were applied to evaluate the

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mental health effects of major earthquakes in Korea.<sup>21,22</sup> A unique health insurance system with universal coverage tracks the hospital usage information of each Korean.<sup>23</sup> By using insurance data, the baseline health status before the event and exact timing of disease onset can be estimated. A difference-in-differences analysis minimizes unmeasured confounding as long as the parallel trend assumption between the exposed individuals (e.g., a group living in an earthquake area) and control individuals (e.g., a group living in a region away from the earthquake area) holds.<sup>24</sup> Recent developments in this literature have offered more flexible methods that provide weights across multiple control groups to generate a synthetic control, aiming to minimize the difference between the exposed and control units.<sup>25</sup> Building on the difference-in-differences and synthetic control methods, a generalized synthetic control method allows for the control of time-varying confounders and has been shown to be suitable for analyzing the acute health effects of disasters having multiple exposure groups.<sup>26</sup>

In this study, we aimed to estimate excess air pollution exposure and health burden in residents living near the massive tire factory fire in Daejeon using National Health Insurance and air pollution monitoring data collected in Korea. Our objective was to apply a generalized synthetic control approach to assess the short-term temporal changes in both air pollution exposure and factory fire-related disease incidence burden.

## Methods

### Study Location

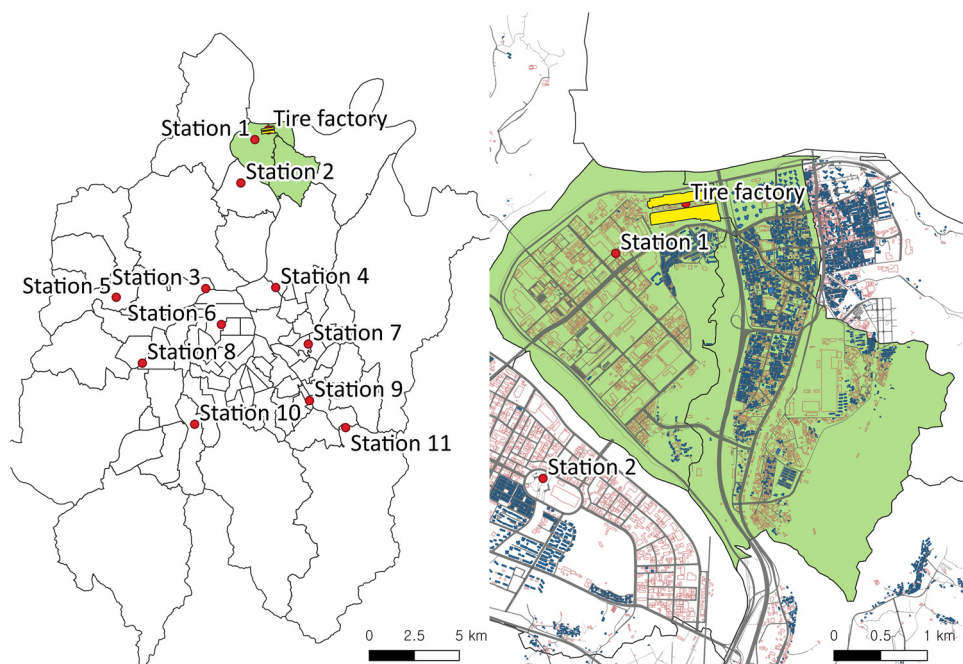
Daejeon city comprises 5 municipalities and 82 small districts (Figure 1; Figure S1). The tire factory is located in Moksang-district of Dae-deok municipality in the northern part of Daejeon. Dae-deok municipality contains a high concentration of industrial complexes (Figure 1, outlined buildings), but there are also residential areas located throughout Dae-deok municipality, including near the tire factory site (Figure 1, shaded buildings).

Figure S2 shows satellite images of the tire factory fire smoke plume captured on 13 and 14 March, 2023. Satellite images were obtained from PlanetScope-SuperDove (3-m resolution) and through Skywatch. During the fire, the plume spread from the factory in the southeast direction, consistent with wind direction at the time of the event. The wind rose diagram for Daejeon shows strong northwesterly winds during the 10 d following the initial fire event (Figure S3).

There are 11 fixed governmental air pollution monitoring stations in Daejeon, operated by the Ministry of Environment. The closest station to the tire factory, Munpyeong station (herein “Station 1”), is located only 500 m away (Figure 1).<sup>28</sup> The hourly air pollution levels [particulate matter with aerodynamic diameters of  $\leq 10$  (PM<sub>10</sub>) and 2.5  $\mu\text{m}$  (PM<sub>2.5</sub>), nitrogen dioxide (NO<sub>2</sub>), and ozone (O<sub>3</sub>), SO<sub>2</sub>, CO] monitored at each governmental station in Daejeon 10 d before and after the initial fire are summarized in Table S1 and Figure S4. The number of high-pollution hours (defined as hours over the World Health Organization 24-h air pollution guidelines interim target 1) for PM increased at Station 1 after the fire, but not at other stations in Daejeon (Table S1). Station 1 showed a distinct increased hourly air pollution concentration pattern after the fire event (Figure S4), which suggests that air pollution exposure from the fire affected a localized region near the tire factory.

Based on satellite images, wind patterns, and the monitoring results (described above) from fixed air pollution stations in Daejeon during the fire, three districts near the tire factory (Moksang-dong, Deogam-dong, and Seokbong-dong) were defined as factory fire plume-exposed regions (Figure 1). These three fire plume-exposed districts are also where residential buildings are concentrated near the factory (Figure S3). All 12 districts of Dae-deok were set as exposed regions in the sensitivity analysis by applying different exposure definitions, which included all the districts located southeast of the factory (Figure S1).

Since the factory opened in 1979, it has produced tires for use in passenger vehicles and small trucks. The factory manufactures ~40,000 to 45,000 units of tires per day, which represents



**Figure 1.** The map of Daejeon city with 82 districts and 11 air pollution monitoring stations. Shaded districts represent three smoke-exposed districts located close to the tire factory. In the zoomed-in area, shaded buildings represent residential houses, and outlined buildings represent industrial facilities. The geographic information systems layers were acquired from the Ministry of Interior and Safety of the Korean government.<sup>27</sup>



~ 16.4% of the company's daily production volume. Of the two factory buildings, the second building burned down entirely, and >200,000 tires were destroyed by the fire.

The fire started at 2200 hours on Sunday, 12 March 2023, and lasted until 0800 hours on Wednesday, 15 March 2023. Because the fire started late at night on 12 March, we assumed that the health effects of air pollution from the fire may not have been reflected by hospital visit information recorded on 12 March. Therefore, we defined 13 March 2023, as the first day of treatment (the effect of fire smoke on disease incidence), and the study period was divided into pretreatment (1 January–12 March 2023: 71 d) and posttreatment (13–22 March 2023: 10 d, 3 d of active fire plus 1 wk after the fire's extinction) periods.

## Data Collection

**Air pollution monitoring data.** The concentrations of hourly monitored air pollutants (PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub>, O<sub>3</sub>, SO<sub>2</sub>, and CO) were gathered from the Airkorea website (<https://www.airkorea.or.kr>). The missing hourly observations, attributed to maintenance, quality control, and extremely high concentrations of air pollution, were excluded when calculating the daily averages (Table S1). PM levels (in micrograms per meter cubed) were measured using the  $\beta$ -ray absorption method, NO<sub>2</sub> levels (in parts per billion) were measured using chemiluminescent methods, O<sub>3</sub> levels (in parts per billion) were measured using ultraviolet (UV) photometric methods in fixed monitoring station in Korea,<sup>29</sup> SO<sub>2</sub> levels (in parts per billion) were measured via the pulse UV fluorescence method, and CO levels (in parts per million) were measured using nondispersive infrared methods.

There are 11 fixed air pollution monitoring stations in Daejeon operated by the Ministry of Environment, Korea. Data from the Munpyeong station, located within 500 m of the factory (Station 1 in Figure 1), were used as the surrogate exposure levels representing the level of air pollution experienced by the residents in the fire plume-exposed districts. To match the results of the exposure analysis with hospital-use data, the starting point of treatment (the effect of fire smoke on air pollution) was defined as 0000 hours on 13 March 2023. The pretreatment (1 January–12 March 2023: 71 d) and posttreatment (13–22 March 2023: 10 d, 3 d of active fire plus 1 wk after the fire's extinction) periods are the same periods as used for the hospital-use data.

**Hospital-use data.** National Health Insurance data were used to define the daily disease incidence cases at the district level. In Korea, the medical usage information of each individual within the country's single-payer universal health insurance system is registered in a single database (the National Health Insurance Database, or NHID).<sup>23</sup> The NHID contains comprehensive information on hospital usage, including types of use (inpatient, outpatient, and emergency department visits), usage dates, diagnosis codes, and details of prescriptions and treatments, as well as personal information such as birth year, sex, residential address, and household insurance premiums. To objectively evaluate the district-level health status before and after the factory fire, we obtained access to the entire hospital usage information of all Daejeon residents registered with NHID for the years 2022–2023 through collaboration with the National Health Insurance Service (NHIS) of Korea.

The number of residents maintaining health insurance eligibility for each district of Daejeon in year 2023 is summarized in Table S2. Previous work has demonstrated that nearly 100% of the actual population is covered by NHIS.<sup>30</sup> The number of residents ( $n$ ) with health insurance eligibility in the three exposed districts were as follows: Moksang 6,682; Deogam 13,596; and Seokbong 16,414.

Based on previous studies,<sup>8,9,15,17</sup> four disease categories—*a*) respiratory disease, *b*) psychological disease, *c*) dermatological disease, and *d*) disease of eye, ear, and vertiginous syndrome—that might be related to acute tire fire smoke and urban fire disaster exposure, were evaluated using the primary diagnosis information of each hospital visit. The diseases and their *International Classification of Diseases, 10th Revision* (ICD-10) codes<sup>31</sup> are as follows: for respiratory disease, acute upper respiratory infections (codes J00–J06), influenza and pneumonia (codes J09–J18), other acute lower respiratory infections (codes J20–J22), other diseases of upper respiratory tract (codes J30–J39), chronic lower respiratory diseases (codes J40–J47), lung diseases due to external agents (codes J60–J70), other respiratory diseases principally affecting the interstitium (codes J80–J84), other diseases of pleura (codes J90–J94), and other diseases of the respiratory system (codes J95–J99); for psychological disease, mood disorders (codes F30–F39), neurotic, stress-related and somatoform disorders (codes F40–F48), and behavioral syndromes associated with physiological disturbances and physical factors (codes F50–F59); for dermatological disease, infections of the skin and subcutaneous tissue (codes L00–L08), dermatitis and eczema (codes L20–L30), papulosquamous disorders (codes L40–L45), and urticaria and erythema (codes L50–L59); for disease of eye, ear, and vertiginous syndrome, disorders of eyelid, lacrimal system and orbit (codes H00–H06), diseases of middle ear and mastoid (codes H65–H75), diseases of inner ear (codes H80–H83), and episodic and paroxysmal disorders (codes G40–G47).

For the negative control analyses, four specific disease outcomes [intestinal infectious diseases (codes A00–A09); diseases of external ear (codes H60–H62); diseases of esophagus, stomach, and duodenum (codes K20–K31); and injuries to the wrist and hand (codes S60–S69)] that might be irrelevant to tire fire smoke exposure were selected with expectation of null results.

The term “incidence case” in this study was used to define new onsets of disease that had not been diagnosed in an individual for a year before the factory fire. From the NHID, we initially extracted all hospital visits of Daejeon residents diagnosed with the above disease categories from January 2022 to March 2023 by using the primary diagnostic code (total 9,246,119 hospital visits extracted). Extracting all hospital visits results in data for multiple visits from the same individual for the same disease.

To determine the “incident case,” we subsequently identified the date of the first hospital visit for each individual and disease category (which is unique for each individual and disease category). Given that our study period spanned from January to March 2023, if an individual's first visit with a specific disease diagnosis occurred between January and March 2023, it confirmed that the individual was not diagnosed with that disease for at least 1 y prior to the study period.

For example, if a person's initial hospital visit for “other diseases of the upper respiratory tract” (J30–J39) was observed on 13 March 2023, this indicates that the person had not visited the hospital for that specific disease from 1 January 2022 to 12 March 2023. This definition of disease incidence has been widely used in epidemiological studies based on the National Health Insurance data of Korea.<sup>21,22,32</sup> Daily times-series of incidence cases of Dajeon for each disease category was generated based on the incidence counts. This study was exempt from review by the institutional review board of Chungnam National University (IRB no. 202307-SB-096-01) because it used de-identified secondary data from the NHIS.

## Statistical Analysis

In this study, we used the flexible and data-adaptive generalized synthetic control (GSC) method to estimate the excess air

pollution exposure and disease incidence of residents in the fire plume-exposed districts (treated).<sup>33</sup> The daily disease incidence counts among the residents of the three fire plume-exposed districts was compared with that of those in the other 79 districts in the analysis.

Because the fire occurred late at night, the first day of treatment was defined as 13 March 2023, and the study period was divided into pretreatment (1 January–12 March 2023: 71 d) and posttreatment (13–22 March 2023: 10 d, 3 d of active fire plus 1 wk after the fire was extinguished) periods. The time point of 1 wk after the fire extinguishment was selected based on the air pollution monitoring results, which showed that the elevation in the levels of air pollutants lasted for a week after the fire was extinguished (Figure S4). The pretreatment period of 71 d was assumed to capture the disease incidence trends before the factory fire.

The GSC model and analysis steps used in this study can be summarized as follows:

$$Y_{it} = \delta_{it}D_{it} + \lambda_i f_i + \epsilon_{it},$$

where  $Y_{it}$  refers to daily disease incidence counts for district  $i$  at date  $t$ ;  $D_{it}$  represents treatment (if district  $i$  is exposed district and date  $t$  is within posttreatment period;  $D_{it}$  equals 1, otherwise it equals 0);  $f_i$  represents the vector of unobserved latent factor (time-varying district-level parameter);  $\lambda_i$  represents the factor loading of  $f_i$ ; and  $\epsilon_{it}$  represents the idiosyncratic error. The treatment effect (fire plume exposure) for district  $i$  at date  $t$ , can be simplified as the difference between  $Y_{it}^1$  (when  $D_{it}=1$ ) and  $Y_{it}^0$  (when  $D_{it}=0$ ), which is represented by  $\delta_{it}$ . Although,  $Y_{it}^0$  cannot be observed for exposed district  $i$  for the posttreatment period, it can be estimated using a synthetic control.

By using time-series data of disease incidence cases for 79 control districts, the interactive fixed effect model estimates  $f_i$  with the assumption that  $f_i$  will be identical across fire plume-exposed and control districts.  $\lambda_i$  is estimated to minimize the difference between the mean squared prediction error for the pretreatment period for fire plume-exposed district  $i$ . Based on the estimated parameters, a synthetic control,  $\hat{Y}_{it}^0$ , is estimated.<sup>25,34</sup> If disease incidence counts for fire plume-exposed district  $i$  and synthetic control are comparable for the pretreatment period, synthetic control could be a good approximation of  $Y_{it}^0$  for the posttreatment period.

We obtained the  $\delta_{it}$  for each of the three fire plume-exposed districts ( $Y_{it}^1 - Y_{it}^0$ ) and estimated the average cumulative treatment effect  $\left( \left( \sum_{i=1}^3 \left( \sum_{t=t_1}^{t_2} \delta_{it} \right) \right) / 3 \right)$  from the initial fire to extinction ( $t_1$ : 13 March 2023,  $t_2$ : 15 March 2023) and from the initial fire to 1 wk after extinction ( $t_1$ : 13 March 2023,  $t_2$ : 22 March 2023). Parametric bootstrapping ( $n=1,000$ ) was used to estimate 95% confidence intervals (CIs). The GSC analyses were implemented by using the R software package “gsynth”, and the “Cumeff” function was used to estimate the cumulative treatment effect.<sup>35</sup> We also computed the average percentage changes in disease incidence counts for treated districts during the 10 d following the fire. This was calculated by dividing the average cumulative treatment effect observed in exposed districts after the factory fire by the observed average cumulative disease incidence counts in those treated districts during the 10 d preceding the fire.

To estimate excess air pollution, the monitored level at Station 1 (Munpyeong Station) was used as the surrogate exposure level to represent the level of air pollution experienced by the residents in the fire plume-exposed districts (Figure 1). The remaining 10 fixed stations in Daejeon were used as controls and the GSC method was applied. We calculated the percentage changes in air pollution levels by comparing the cumulative treatment effect monitored at Station 1 during the 10 d following the

factory fire with the observed cumulative daily air pollution levels recorded in the 10 d preceding the fire.

The following sensitivity analyses were conducted. First, we conducted stratification analysis for different age groups (0–14, 15–64, and  $\geq 65$  y). Second, we applied different definitions of exposed districts by including 12 districts in Dae-deok municipality (Figure S1). Third, we applied different definitions of the pretreatment period by considering a period of 40 d before the fire event (from 1 February to 12 March 2023). Fourth, instead of using disease incidence counts, we used counts of the total number of hospital visits for each disease category. Fifth, to evaluate the chronic effect of smoke exposure, we conducted long-term analyses using different definitions of posttreatment periods (30, 60, 90, and 120 d from 13 March 2023). Finally, we selected the time point of 1 y before the fire event and ran an identical analysis as a negative control, with the expectation of null results. SAS (version 9.4; SAS Institute, Inc.) was used to analyze the NHID data, and R software (version 4.2.1; R Development Core Team) was used to apply the GSC method. Map figures were drawn using QGIS software (version 3.28; QGIS Development Team).

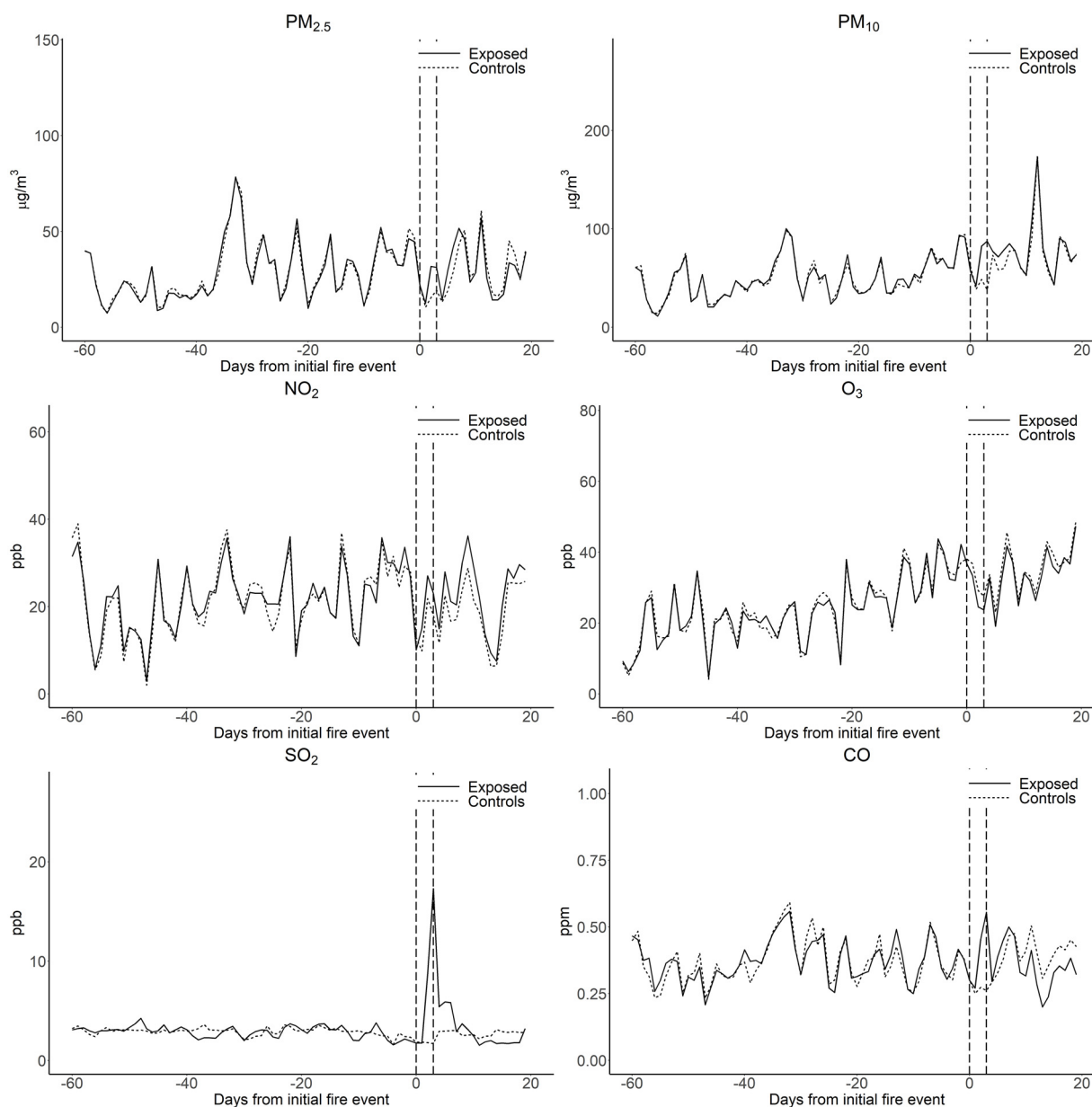
## Results

Table S3 shows the observed changes in average daily air pollution levels at Station 1 and control stations (other stations in daejeon) 10 d before and after the factory fire. Compared with the period before the fire, Station 1 showed smaller decreases in PM<sub>2.5</sub> (–5.9  $\mu\text{g}/\text{m}^3$ ) and NO<sub>2</sub> (–2.0 ppb) after the fire accident when compared with other stations (controls: –11.3  $\mu\text{g}/\text{m}^3$  changes for PM<sub>2.5</sub>; –5.0 ppb changes for NO<sub>2</sub>). There were increases in PM<sub>10</sub> (2.4  $\mu\text{g}/\text{m}^3$ ), SO<sub>2</sub> (3.4 ppb), and CO (0.02 ppm) at Station 1 after the fire, whereas other stations showed decreases in these pollutant levels (controls: –12.5  $\mu\text{g}/\text{m}^3$  for PM<sub>10</sub>, 0.1 ppb for SO<sub>2</sub>, and –0.05 ppm for CO).

Figure 2 shows the daily air pollution monitoring trends at Station 1 and the synthetic control generated based on the other 10 monitoring stations within Daejeon. Comparable patterns in monitored air pollutant levels between Station 1 and the synthetic control were observed before the fire, whereas there was an increase in air pollution at Station 1 during and a week after the fire. Table 1 presents the estimated excess air pollution exposure at Station 1. During and a week after the fire, additional exposure to 125.2 (95% CI: 44.9, 156.7)  $\mu\text{g}/\text{m}^3$  of PM<sub>10</sub>, 50.4 (95% CI: 12.7, 99.8) ppb of NO<sub>2</sub>, 32.0 (95% CI: 21.0, 35.9) ppb of SO<sub>2</sub>, and 0.5 (95% CI: 0.1, 1.2) ppm of CO was estimated at Station 1, representing 18.1%, 19.1%, 135.6%, and 13.2% increases in PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, and CO exposure, respectively, compared with that in the 10 d before the fire. During the 3 d while the fire was burning, additional exposure to 29.8 (95% CI: 21.0, 37.4)  $\mu\text{g}/\text{m}^3$  of PM<sub>2.5</sub> was estimated for the Station 1.

Table S4 shows the disease incidence counts in exposed and control districts during the 10 d before and after the start of the fire. The change in disease incidence counts between the two 10-d periods was similar for both exposed and control districts for all disease categories except for lung diseases due to external agents (a 0.2-person increase was observed in exposed districts compared with no change in control districts).

Table 2 and Figure 3 and Figure S5 show the estimated excess disease incidence counts among residents living in the exposed districts when compared with synthetic controls. During the fire period, an average increase of incidence counts for other diseases of the upper respiratory tract (codes J30–J39) [11.7 persons (95% CI: 4.5, 21.0)], lung disease due to external agents (codes J60–J70) [1.9 persons (95% CI: 1.6, 2.4)], and other diseases of the respiratory system (codes J95–J99) [1.8 persons (95% CI: 0.8, 2.7)] was observed in each exposed district. From the initial fire to 1



**Figure 2.** Daily air pollution levels [particulate matter with aerodynamic diameters of  $\leq 10$  ( $PM_{10}$ ) and  $2.5 \mu m$  ( $PM_{2.5}$ ), nitrogen dioxide ( $NO_2$ ), ozone ( $O_3$ ), sulfur dioxide ( $SO_2$ ), and carbon monoxide ( $CO$ )] monitored at Station 1 and estimated as synthetic control values before and after the tire factory fire ( $-60$  to  $20$  d from the fire). The solid line represents the monitored values at Station 1, and the dotted line represents the estimated synthetic control values. The dotted vertical lines represent the duration of the tire factory fire ( $0-2$  d from the fire). Summary data can be found in [Tables 1](#) and [S3](#).

**Table 1.** Monitored (A:  $-10$  to  $-1$  d from the factory fire) and estimated excess changes (B:  $0-2$  d of active fire, and C:  $0-2$  d of active fire plus 1 wk after the fire extinction) in air pollution levels [particulate matter with aerodynamic diameters of  $\leq 10$  ( $PM_{10}$ ) and  $2.5 \mu m$  ( $PM_{2.5}$ ), nitrogen dioxide ( $NO_2$ ), ozone ( $O_3$ ), sulfur dioxide ( $SO_2$ ), and carbon monoxide ( $CO$ )] at Station 1.

Pollutants	A: Monitored cumulative pollutant levels at Station 1 before factory fire ( $-10$ to $-1$ d)	B: Estimated cumulative changes in air pollutant levels at Station 1 ( $0-2$ d)	C: Estimated cumulative changes in air pollutant levels at Station 1 ( $0-9$ d)	Percentage changes in air pollutant levels ( $C/A \times 100$ )
$PM_{2.5}$ ( $\mu g/m^3$ )	370.0	29.8 (21.0, 37.4)	54.9 ( $-27.5$ , 99.5)	14.8 ( $-7.4$ , 26.9)
$PM_{10}$ ( $\mu g/m^3$ )	691.7	81.5 (62.9, 94.9)	125.2 (44.9, 156.7)	18.1 (6.5, 22.7)
$NO_2$ (ppb)	264.3	12.6 (5.1, 34.6)	50.4 (12.7, 99.8)	19.1 (4.8, 37.8)
$O_3$ (ppb)	348.7	$-13.2$ ( $-26.6$ , 0.8)	$-27.4$ ( $-56.8$ , $-2.6$ )	$-7.9$ ( $-16.3$ , $-0.7$ )
$SO_2$ (ppb)	23.6	22.3 (17.1, 24.2)	32.0 (21.0, 35.9)	135.6 (89.0, 152.1)
$CO$ (ppm)	3.8	0.5 (0.3, 0.7)	0.5 (0.1, 1.2)	13.2 (2.6, 31.6)

Note: The estimated excess changes describe the difference between the daily air pollution levels monitored at Station 1 and the synthetic control values. Cumulative values (95% CIs) are shown here for each period. The daily temporal air pollution patterns measured at Station 1 and synthetic control are presented in [Figure 2](#). CI, confidence interval.



**Table 2.** Observed (A: -10 to -1 d from the factory fire) and estimated excess changes (95% CIs) (B: 0-2 d of active fire, and C: 0-2 d of active fire plus 1 wk after the fire extinction) in disease incidence counts (*n*) for residents of the three exposed districts [persons (*n*): Moksang district 6,682; Deogam district: 13,596; Seokbong district: 16,414].

Disease categories	ICD-codes	A: Average disease incidence counts ( <i>n</i> ) in exposed districts (-10 to -1 d)	B: Average excess change in incidence counts ( <i>n</i> ) in exposed districts (0-2 d)	C: Average excess change in incidence counts ( <i>n</i> ) in exposed districts (0-9 d)	Average percentage changes in disease incidence counts in exposed districts (C/A × 100)
<b>Respiratory disease</b>					
Acute upper respiratory infections	J00-J06	71.0	0.1 (-10.9, 11.5)	21.2 (-2.5, 42.9)	29.9 (-3.5, 60.4)
Influenza and pneumonia	J09-J18	4.7	-2.3 (-7.6, 9.5)	-3.7 (-16.3, 99.9)	-78.7 (-346.8, 423.4)
Other acute lower respiratory infections	J20-J22	76.0	4.6 (-3.9, 15.0)	-3.3 (-16.7, 21.7)	-4.3 (-22.0, 28.6)
Other diseases of upper respiratory tract	J30-J39	58.0	11.7 (4.5, 21.0)	20.6 (6.2, 37.4)	35.5 (10.7, 64.5)
Chronic lower respiratory diseases	J40-J47	8.3	-1.5 (-4.8, 1.9)	-4.1 (-11.5, 3.9)	-49.4 (-138.6, 47.0)
Lung diseases due to external agents	J60-J70	0.3	1.9 (1.6, 2.4)	2.5 (2.1, 3.3)	833.3 (700.0, 1,100.0)
Other respiratory diseases principally affecting the interstitium	J80-J84	0.0	-0.2 (-0.6, 0.5)	-0.2 (-0.9, 0.6)	—
Other diseases of pleura	J90-J94	0.0	-0.1 (-0.4, 0.4)	-0.2 (-0.8, 0.6)	—
Other diseases of the respiratory system	J95-J99	1.7	1.8 (0.8, 2.7)	2.3 (0.2, 4.2)	135.3 (11.8, 247.1)
<b>Psychological disease</b>					
Mood disorders	F30-F39	3.0	1.3 (-0.7, 3.2)	-0.4 (-4.0, 3.0)	-13.3 (-133.3, 100.0)
Neurotic, stress-related, and somatoform disorders	F40-F48	5.3	-0.7 (-2.9, 1.9)	-1.1 (-5.0, 2.9)	-20.8 (-94.3, 54.7)
Behavioral syndromes associated with physiological disturbances	F50-F59	2.0	-1.0 (-2.2, 0.7)	0.2 (-2.0, 3.0)	10.0 (-100.0, 150.0)
<b>Dermatological disease</b>					
Infections of the skin and subcutaneous tissue	L00-L08	14.0	0.8 (-3.3, 5.2)	2.3 (-4.0, 8.8)	16.4 (-28.6, 62.9)
Dermatitis and eczema	L20-L30	33.3	1.4 (-2.5, 6.0)	-1.3 (-10.3, 6.8)	-3.9 (-30.9, 20.4)
Papulosquamous disorders	L40-L45	0.3	-0.2 (-1.0, 0.9)	1.0 (-0.5, 2.7)	333.3 (-166.7, 900.0)
Urticaria and erythema	L50-L54	14.0	-1.1 (-4.7, 1.5)	5.9 (-0.6, 11.2)	42.1 (-4.3, 80.0)
<b>Disease of eye, ear, and vertiginous syndrome</b>					
Disorders of eyelid, lacrimal system and orbit	H00-H06	18.7	-0.3 (-5.2, 4.3)	-1.2 (-11.2, 7.2)	-6.4 (-59.9, 38.5)
Diseases of middle ear and mastoid	H65-H75	9.7	-1.9 (-5.6, 1.7)	-3.4 (-11.1, 3.9)	-35.1 (-114.4, 40.2)
Diseases of inner ear	H80-H83	8.3	-1.7 (-3.7, 0.9)	-0.9 (-5.0, 3.6)	-10.8 (-60.2, 43.4)
Episodic and paroxysmal disorders	G40-G47	12.7	3.1 (0.5, 5.7)	8.5 (3.7, 13.4)	66.9 (29.1, 105.5)
<b>Disease for negative control analysis</b>					
Intestinal infectious diseases	A00-A09	27.3	1.7 (-2.8, 7.0)	1.9 (-7.2, 13.5)	7.0 (-26.4, 49.5)
Diseases of external ear	H60-H62	9.3	-1.0 (-4.5, 2.7)	-0.3 (-5.3, 5.4)	-3.2 (-57, 58.1)
Diseases of esophagus, stomach, and duodenum	K20-K31	10.7	-0.2 (-2.4, 2.5)	1.0 (-3.2, 5.2)	9.3 (-29.9, 48.6)
Injuries to the wrist and hand	S60-S69	12.3	-1.3 (-5.0, 2.8)	-0.6 (-9.2, 7.5)	-4.9 (-74.8, 61.0)

Note: The estimated excess change was derived by first calculating the difference in the incidence counts of each exposed district and the corresponding synthetic control, then taking the average of the three values. All values are cumulative values (95% CIs) for each period. The average disease-specific incidence counts of exposed districts are visualized in Figure 3 and Figure S5. —, Not applicable; CI, confidence interval; ICD-10, *International Classification of Diseases, 10th Revision*.

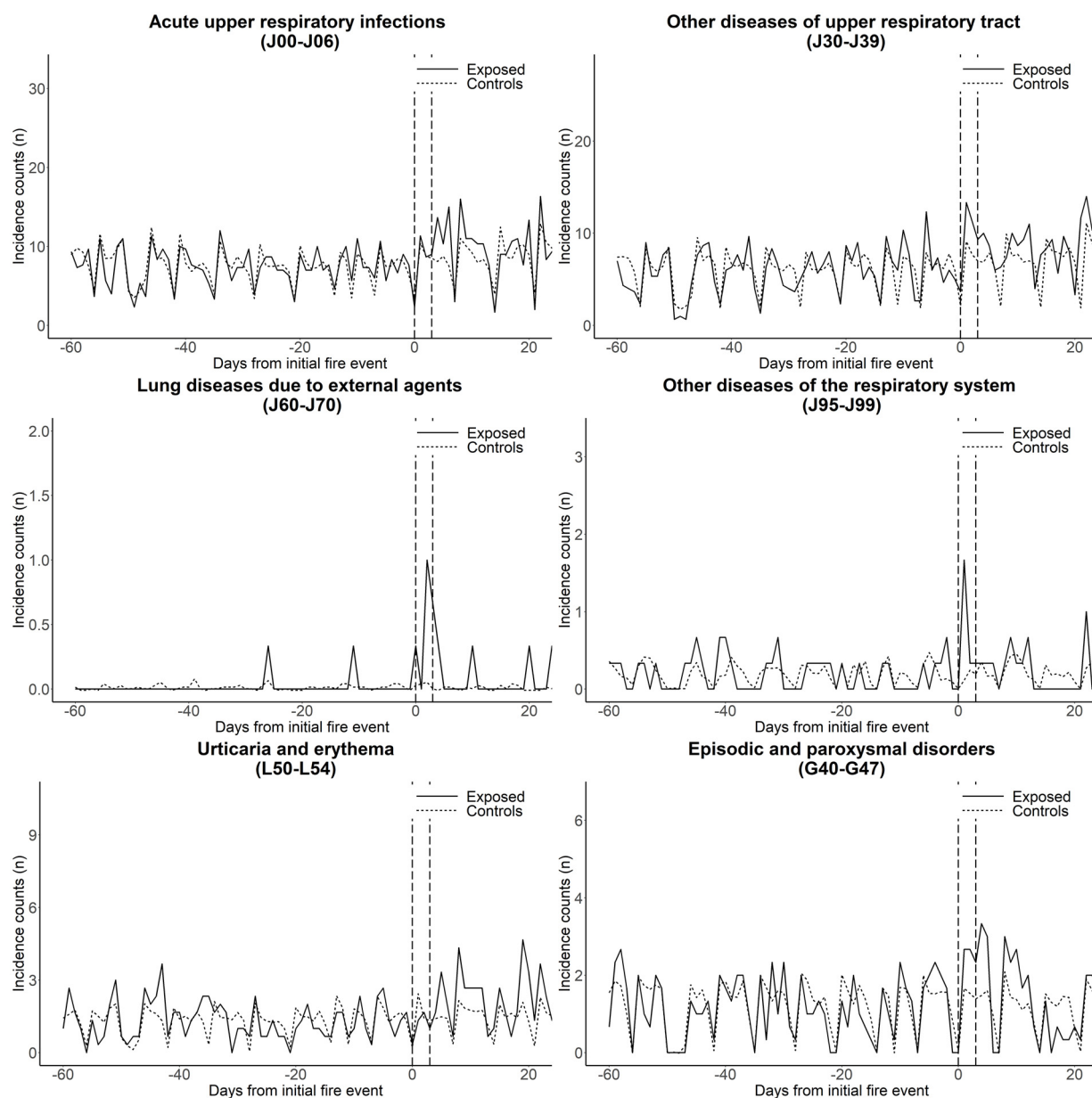
wk after extinguishment, there was an average increase of 20.6 persons (95% CI: 6.2, 37.4) diagnosed with other diseases of the upper respiratory tract, 2.5 persons (95% CI: 2.1, 3.3) diagnosed with lung disease due to external agents, and 2.3 persons (95% CI: 0.2, 4.2) diagnosed with other diseases of the respiratory system in each exposed district. Incidence counts for these three categories, increased by 35.5%, 833.3%, 135.3%, respectively, when compared with the average incidence counts during the 10 d before the fire.

We did not detect changes in the incidence of psychological disorders, diseases of the eye and ear, and negative control outcomes. However, incidence counts of urticaria and erythema (codes L50-L54) [5.9 persons (95% CI: -0.6, 11.2)] and episodic and paroxysmal disorders (codes G40-G47) [8.5 persons (95% CI: 3.7, 13.4)] increased during and 1 wk after the fire in each exposed district (Table 2). Sensitivity analyses with different pretreatment period definitions (40 d) produced results similar to those of the main analysis (Table S5).

Age group-stratified analysis (Table S6) showed increases in disease incidence cases for lung disease due to external agents [1.9 persons (95% CI: 1.7, 2.3)], other diseases of the respiratory

system [1.6 persons (95% CI: 0.3, 3.1)], urticaria and erythema [4.8 persons (95% CI: 0.0, 9.5)], and episodic and paroxysmal disorder [7.6 persons (95% CI: 3.5, 11.4)] in residents 15-64 years of age living in each exposed district during the 10-d period after the onset of the fire event. Meanwhile, the younger age group (0-15 years of age) showed an increase in other diseases of upper respiratory tract [5.3 persons (95% CI: 2.3, 10.9)].

The analysis in which 12 districts of Dae-deok municipality were defined as exposed (Table S7) showed an increase in incidence cases of lung disease due to external agents [0.6 persons (95% CI: 0.3, 1.0)] and episodic and paroxysmal disorders [4.1 persons (95% CI: 1.3, 6.7)]. The analysis using counts of the total number of hospital visits (as opposed to disease incidence counts) showed an increase of 54.5 (95% CI: 19.4, 87.0) visits for other diseases of the upper respiratory tract, 3.2 (95% CI: 2.1, 4.2) visits for lung disease due to external agents, 3.0 (95% CI: 0.3, 6.1) visits for other disease of the respiratory system, and 13.5 (95% CI: 2.5, 25.3) visits for urticaria and erythema in each exposed district 10 d after the factory fire (Table S8). The sensitivity analysis in which a hypothetical fire event was set 1 y before the actual fire showed a null association, as expected (Table S9).



**Figure 3.** Average daily disease incidence counts in exposed districts [persons (*n*): Moksang district 6,682; Deogam district: 13,596; Seokbong district: 16,414] and synthetic controls before and after the tire factory fire (–60 to 20 d from the fire). The solid line represents exposed districts, and the dotted line represents the synthetic control. The dotted vertical lines represent the duration of the tire factory fire (0–2 d from the fire). The parentheses below the disease categories indicate the corresponding disease code. Summary data can be found in Table 2.

When the analysis was extended for 90 d after the initial factory fire, a prolonged increase in incidence cases was observed in residents of each exposed district for chronic lower respiratory disease [69.4 persons (95% CI: 11.5, 118.7)], lung disease due to external agents [3.0 persons (95% CI: 0.6, 5.6)], and urticaria and erythema [42.4 persons (95% CI: 12.5, 72.6)] (Table S10 and Figure S6).

## Discussion

In this study, we found that residents of the three districts located close to the tire factory experienced excess air pollution exposure and disease incidence during and 1 wk after the factory fire. Compared with the other 10 monitoring stations in Daejeon, the air pollution monitoring station located 500 m from the factory measured an excess of 125.2  $\mu\text{g}/\text{m}^3$  of  $\text{PM}_{10}$ , 50.4 ppb of  $\text{NO}_2$ ,

and 32.0 ppb of  $\text{SO}_2$  during and 1 wk after the tire factory fire. On average, in the three districts near the factory, there was a 20.6-person increase in the incidence of other diseases of the respiratory system, a 2.5-person increase in the incidence of lung disease due to external agents, a 2.3-person increase in the incidence of other diseases of the respiratory system, and an 8.5-person increase in the incidence of episodic and paroxysmal disorders during and 1 wk after the tire factory fire when compared with the incidences in the other districts of Daejeon.

Plumes generated from tire fires contain hazardous gaseous substances. The outdoor concentrations of  $\text{PM}_{2.5}$ , carbon oxides, sulfur oxides, EC, VOCs, and PAHs were significantly increased in air samples collected near an Iowa landfill tire fire in 2012.<sup>6,7</sup> The concentrations of PAHs increased immediately after a major landfill tire fire in Spain in 2016 and were six times higher than those in the surrounding control regions.<sup>11</sup> Laboratory



experiments suggest that tire combustion produces 165 subtypes of PAHs and other aromatic compounds, such as benzene, toluene, ethylbenzene, styrene, and other heterocyclic compounds.<sup>1</sup> In addition, incomplete combustion and the collapse of construction materials may release other toxicants, such as asbestos, lead, and glass fibers.<sup>36</sup> Therefore, in addition to the increase in air pollutants observed in this study, there might have been an increase in release of other hazardous airborne chemicals related to tire fires during and after the Daejeon tire factory fire.

Epidemiological evidence regarding the impacts of tire fire smoke remains limited. The fire at a tire pile site in Westley, California, in 1999 lasted for 36 d and burned 5 million tires. On analyzing 86 calls from county nurses during the fire period, researchers found that the majority of complaints were regarding symptoms of headache; coughing; difficulty breathing; eye, nose, and throat irritation; wheezing; and nausea; and ~20% of calls were from patients with a history of asthma.<sup>8</sup> In a residential address-based comparison, children exposed to the smoke from a tire cellar fire that occurred in Bogotá, Columbia, in 2014 showed symptoms of red eyes and stuffy nose.<sup>9</sup> Fire plumes from 160,000 burning tires in Amberley, New Zealand, lasted for 7 d and caused a transient increase in exposure to airborne irritants, such as PM<sub>2.5</sub> and SO<sub>2</sub>, in individuals residing 1 km from the fire site.<sup>10</sup> During the first 3 d after the fire, there were reports of difficulty breathing and throat irritation in residents.

It is well known that air pollution is associated with several respiratory diseases, including acute infections, asthma, chronic obstructive pulmonary disease, and lung cancer.<sup>37</sup> Short-term exposure to air pollution deteriorates respiratory defense mechanisms, including mechanical (tight junction of epithelial cells and fluid and mucous barrier) and immunological processes (innate immune response and antioxidant mechanisms).<sup>38,39</sup> Similarly, the skin can be damaged by exposure to air pollution and organic compounds, such as PAHs. In addition to the direct damage from the chemicals, the increased secretion of sebum, oxidative stress, and release of pro-inflammatory cytokines after pollutant exposure can cause atopic dermatitis, inflammatory diseases, psoriasis, acne, and exacerbation of preexisting dermatological problems.<sup>40</sup>

A series of epidemiological studies have reported that short-term exposure to various air pollutants is positively associated with hospital visits and symptom onset related to episodic and paroxysmal disorders, including epilepsy and migraine.<sup>41–43</sup> This association may be explained by neurogenic inflammation and oxidative stress induced by air pollution exposure.<sup>44</sup> Therefore, the observed increase in the incidence of respiratory, skin, and neurological diseases during and after the tire factory fire in our study appears biologically plausible.

Several retrospective studies on urban fire disasters have analyzed hospital data. Medical records from two acute care hospitals located near the site of an 8-d long warehouse fire in California showed an increase in the incidence of lower respiratory diseases (asthma, bronchitis, and pneumonia) during the fire.<sup>15</sup> Based on medical records from a single pediatric emergency department, there was an increase in asthma hospital visits and admissions after a 10 h scrapyard fire in Philadelphia.<sup>14</sup> However, previous studies relied on temporal comparisons, and proper controls were not used. In addition, only a subset of medical hospitals in the fire plume-exposed regions was involved.

Our study used district-level hospital-use information coupled with state-of-the-art synthetic control methods to assess the effects of the factory fire on disease development. This was made possible by Korea's universal health insurance system, which records individual medical usage data and detailed residential information.<sup>23</sup> The random nature of a disaster provides a unique opportunity to study a fire as a natural experiment. The use of

synthetic control methods makes both temporal and location-based comparison available.<sup>33</sup> Additional evaluation of the dose-response relationship and replication of the association with independent events might increase the possibility of a causal interpretation of our study findings.<sup>21</sup>

There have been several environmental shocks, such as industrial accidents (as in this manuscript) or natural hazards (e.g., wildfires, extreme heat), that can be analyzed as natural experiments. Considering such events as natural experiments is possible if we can demonstrate that the timing of the event is independent from the trends in the health outcomes of interest, which is a reasonable assumption for such unexpected or sudden accidents. We can then capitalize on the timing of such natural experiments and use dedicated quasi-experimental methods to assess the effects of such events on health outcomes of interest and deal with several unmeasured confounders by design.<sup>45</sup>

Different quasi-experimental methods that can be employed to capitalize on the timing of such natural experiments have been proposed and can be seen as extensions of difference-in-differences methods when control groups are available.<sup>26</sup> In a recent paper with Nianogo et al.,<sup>25</sup> we showed that data-adaptive methods such as the generalized synthetic control method outperform canonical difference-in-differences and synthetic control methods in considering complex time trends and minimizing the difference between the treated units (i.e., affected by the natural experiment, the factory fire accident) and estimated synthetic control group that approximates the counterfactual trend (i.e., in the absence of the event of interest). Briefly, the generalized synthetic control method uses time-series data (for the outcome, lagged outcomes and potential time-varying confounders) for the treated unit (or multiple units if multiple units are considered) and control units separately to understand the time-varying relationship between latent factors and outcomes of interest.<sup>33</sup> Then, a weighting procedure is applied to build a synthetic control time series that mimics the trends of the outcome before the occurrence of the event/natural experiment of interest to represent the best approximation of the counterfactual trend.<sup>33</sup> This approach can also be seen as an extension of a two-way fixed effects model where time-invariant unobserved confounders are also considered.<sup>26</sup> In a recent paper by Sheridan et al.,<sup>26</sup> we showed how such an approach can be particularly suitable for environmental epidemiological applications and provided a detailed explanation of the implementation of this method and reproducible syntax.

Following the tire factory incident in Daejeon, 10 dust absorption vehicles owned by the city and 4 road-cleaning vehicles from the Dae-deok municipality were deployed to remove airborne dust. The city's Department of Education assisted 17 schools near the incident site by performing hazard assessments of school fields, evaluating indoor air quality, supplying funds for the replacement of air purifier filters, and cleaning the affected schools. However, to the best of our knowledge, structured response protocols for massive urban fire disasters and research guides for residents of affected communities are not available in Korea.

Disasters may affect physiological and psychological well-being and cause property damage and displacement of inhabitants.<sup>46–49</sup> Under expected climate change scenarios, an increased number of industrial fire disasters are expected.<sup>13,50</sup> Therefore, a proper management plan for public response to a fire should be proactively developed. If possible, the plan should be tailored to manage specific types of disasters (wildfires, urban fires, and natural disasters) and should take into consideration the emergency response capability of the region.

This study has several limitations that we would like to acknowledge. First, exposure misclassification may have occurred

when defining fire plume “affected” and “control” districts. The distribution of fire smoke is affected by firefighting activities and meteorological conditions, including temperature, wind direction, and dilution and emission rates.<sup>7</sup> Although we considered satellite images and wind directions around the factory during the fire period, detailed environmental exposure and meteorological assessments were not available, similar to previous disaster studies.<sup>13</sup> However, performing a sensitivity analysis using different definitions of “exposed” districts did not change the study results.

Second, only a limited number of air pollutants were evaluated, given that we were restricted to pollutants that are routinely monitored. Previous industrial fire disasters and tire fires not only increased the levels of conventional air pollutants but also those of organic and inorganic pollutants, including PAHs, VOCs, and heavy metals, which were not measured in this study.<sup>51–53</sup> In addition, tire factory plumes may affect not only air pollution levels but also the surrounding water and soil quality.<sup>53</sup> Therefore, in line with the first limitation, a prompt high-quality environmental assessment of the surrounding environment during and after a fire disaster is required to estimate the overall environmental burden and to explicitly define exposed individuals.<sup>13</sup> As in previous disaster studies,<sup>13</sup> accurate estimation of personal environmental exposure was not available in this study. The air pollution levels in the exposed district were estimated solely from the monitoring results of a fixed station (Station 1) located 500 m from the factory. In addition, an increased number of hourly observations for particulate matter at Station 1 were missing in the hours following the fire incident (Table S1 and Figure S4). Although it is reasonable to assume that the missing values in the monitoring results may be due to the extremely high concentration of pollutants after the fire event, detailed reasons for the missing observations were not provided by the Ministry of Environment. Furthermore, residents living near the factory presumably changed their daily routines (e.g., spending more time indoors and increasing the use of masks or air purifiers with high-efficiency particulate air filters) to minimize their exposure to the fire plumes. However, such changes cannot be confirmed without detailed assessment of personal activity patterns.

Third, because this study was based on hospital visit data, minor symptoms and complaints occurring outside of the hospital setting were neglected.<sup>15</sup> Therefore, this study may underestimate the true health-related impact of the tire fire incident.

Fourth, this study did not evaluate the population susceptible to tire fire smoke. This study aimed to outline the overall disease burden resulting from the tire factory event. Owing to the small populations and disease incidence counts available for district-level comparisons, it was not possible to perform further stratified analyses.

## Conclusion

Despite the frequency of landfill tire fire accidents and abundance of exposure assessment studies, few studies have reported on the public health impact of tire fire smoke. We studied a major fire event that occurred in a tire manufacturing factory in Daejeon, Korea, on 12 March 2023 and lasted for 3 d, used state-of-art quasi-experimental methods capitalizing on the timing of the fire, and considered multiple disease categories. Tire fire plumes may contain toxic pollutants that affect the health of individuals residing near factories. The residents in tire factory fire plume-exposed districts show increased development of respiratory, skin, and neurological disorders. Proper management plans for public response to urban fire disasters and for epidemiological assessment of affected residents after such disasters are needed.

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