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An interrupted time series analysis of the cardiovascular health benefits of a coal coking operation closure

Wuyue Yu* and George D Thurston

New York University Grossman School of Medicine, New York, NY, United States of America
* Author to whom any correspondence should be addressed.

E-mail: wy726@nyu.edu

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Supplementary material for this article is available online

Abstract

With the widespread implementation of air pollution mitigation strategies for health and climate policy, there is an emerging interest in accountability studies to validate whether a reduction of air pollution exposure, in fact, produces the human health benefits estimated from past air pollution epidemiology. The closure of a coal coking plant provides an ideal 'natural' experiment opportunity to rigorously evaluate the health benefits of air pollution emissions reductions. In this study, we applied an interrupted time series model to test the hypothesis that the substantial reduction in air pollution induced by the closure of the Shenango, Inc. coke plant in Pittsburgh, PA during January, 2016 was followed by immediate and/or longer-term cumulative local cardiovascular health benefits. We observed a 90% decrease in nearby SO_2 levels, as well as significant reductions in coal-related fine particulate matter constituents (sulfate and arsenic), after the closure. Statistically significant cardiovascular health benefits were documented in the local population, including a 42% immediate drop (95% CI: 33%, 51%) in cardiovascular emergency department (ED) visits from the pre-closure mean. A longer-term downward trend was also observed for overall emergency visits at −0.14 (95% CI: −0.17, −0.11) visits per week rate of decrease after the closure, vs. a rise of 0.17 (95% CI: 0.14, 0.20) visits per week before. Similarly, inpatient cardiovascular hospitalizations per year showed a decrease after closure (−27.97 [95% CI: −46.90, −9.04], as compared with a 5.09 [95% CI: −13.84, 24.02] average increase in cases/year over the prior three years). Our study provides clear evidence that this intervention lowering fossil fuel-associated air pollution benefited public health in both the short and longer term, while also providing validation of the past use of observational air pollution epidemiology effect estimates in policy analyses.

1. Introduction

A growing body of research has documented associations between air pollution exposures and increased adverse health outcomes, providing a scientific basis for the setting of air pollution standards and air quality improvement policies (Rich 2017, Schraufnagel *et al* 2019b). The potential health benefits of these regulations are usually estimated based on concentration-response models from existing observational epidemiological studies at ambient levels, but the resulting health benefits of air quality improvements have not yet been as extensively validated with documented after-the-fact outcome evidence (Boogaard *et al* 2017). This quandary is largely due to the usually long time taken to implement such control programs, which can then be confounded by factors such as population composition and/or health care coverage changes. Therefore, to inform and support further regulatory actions, demonstration of human health benefits resulting from implementations of real-world control policies is of emerging interest and necessity (Bell *et al* 2011). Accountability studies, which quantify the air quality improvement and health benefits of abrupt air pollution interventions and regulatory actions, have therefore become increasingly important (Henneman *et al* 2017, Rich 2017). These studies, which leverage air and health outcome records during abrupt pollution interventions, or 'natural' experiments, provide opportunities to rigorously test the causal link between air pollution and health (Boogaard *et al* 2017, Henneman *et al* 2017). Our research provides such a novel real-world test of the hypothesis that reductions of fossil-fuel related industrial air pollution result in associated reductions in adverse cardiovascular health effects.

The closure of the Shenango, Inc. coke plant, located in Pittsburgh, PA on Neville Island in the Ohio River in Allegheny County, provides such an opportunity to conduct accountability research to investigate the pollution profile and health outcome changes associated with a major coking plant shutdown. The metallurgical coke used in iron and steel industry is produced by destructive heated distillation of coal in oxygen-free coke ovens (Weitkamp *et al* 2005, Mu *et al* 2013). Coke plant operations are known to generate high emissions of hazardous air pollutions including particulate matter, sulfur dioxide, volatile compounds, and trace elements related to coal combustion (Ghose *et al* 1999, Weitkamp *et al* 2005, Khare and Baruah 2011, Mu *et al* 2013, Saikia *et al* 2015). Past epidemiological studies of such sources have found that occupational exposures to coke oven emissions are associated with various adverse health outcomes, including chronic obstructive pulmonary diseases (Hu *et al* 2006), lung function decline (Wang *et al* 2016), hypertension (Yang *et al* 2017), cancers (U.S. Department of Health and Human Services 2016) and neurobehavioral function impairments (Qiu *et al* 2013). High levels of heavy metals and metalloids detected in the environment around coking plants could also potentially induce health risks in nearby local communities via multiple biological pathways (Cao *et al* 2014).

The general association between air pollution exposure and negative health effects is well-established, and studies have found that the fossil-fuel-combustion-related emission sources contribute to large health burden (Yang *et al* 2019, Vohra *et al* 2021). However, despite the known hazardous air pollutants released into the atmosphere by such coal-processing facilities, and past statistical associations between those industrial point source air pollutants and adverse health effects (Bhopal *et al* 1994, Aylin *et al* 2001, Parodi *et al* 2003, 2005), there is currently only limited documented epidemiological evidence for an association between elevated pollution exposures specifically from an operational coke works and negative health outcomes. This paucity of research can primarily be attributed to the difficulty in statistically differentiating the effects of the plant emissions from other air pollution sources, as well as health-impactful factors in the vicinity of the plants (such as the commonly low income status of nearby residents), as well as unavailability of spatially detailed health and/or source-specific air pollution exposure data (e.g. via source apportionment of particulate matter concentrations) (Thurston *et al* 2011). This abrupt coking plant closure analysis avoids these potentially confounding issues, allowing a clear discernment of the health effects of such a coking facility's air pollution.

Before its closure, the Shenango, Inc. coke plant was a significant point emission source of air pollution in Pittsburgh, PA (Kelly and Fischman). Based on the 2011 point source emission inventory (Allegheny County Health Department Air Quality Program 2019), this shutdown in January 2016 caused reductions of 97.3 tons yr^{-1} of primary $PM_{2.5}$ and 901.6 tons yr^{-1} of $PM_{2.5}$ precursors (e.g. SO_2), accounting for 3.5% of Allegheny County's annual point source emissions. With this precipitous alteration of the local air pollution profile, the plant's vicinity has therefore become an ideal case-study to discern whether the air pollution improvement benefited the health of the surrounding community. Already, one preliminary analysis found that, after the shutdown of the Shenango, Inc. coke plant, the annual rates of overall hospitalization and emergency department visits for both cardiovascular and respiratory diseases significantly decreased (Brink *et al* 2019). However, that simplistic analysis has been critiqued as insufficient evidence to conclude that the drop substantially resulted from the air pollution reduction at the coke plant, nor to identify the pollutant constituent that may have caused such a change, without a more detailed analysis of the health and air pollution data, including versus an unaffected control case during the same period (Marusic 2018). A more comprehensive analysis is needed to facilitate a fuller assessment of the potential health benefits of a coke plant air pollution cleanup.

In this study, we seek to address the plant closure evaluation challenges by applying a more rigorous interrupted time series (ITS) analysis of health data collected after, versus before, the closure. As one of the strongest quasi-experimental designs to allow the discernment of health impacts in such situations like dramatic air pollution emission changes, the ITS analysis has become increasingly frequently used for health outcome evaluations of exposures and public health interventions (Bernal *et al* 2017, 2018, Yinon and Thurston 2017, Burns *et al* 2019, Turner *et al* 2020). This study therefore applies statistically rigorous ITS models to test our hypothesis that the substantial reduction in local air pollution induced by the closure of the Shenango, Inc. coke plant was accompanied by immediate and/or longer-term declines in cardiovascular disease hospitalizations and emergency department visits.

2. Method

2.1. Study period and sites

The Shenango, Inc. coke plant, located on an island in the middle of the Ohio River in Allegheny County, at 200 Neville Rd, Pittsburgh, PA 15 225, was closed on 7 January 2016. The study period for our evaluation of the air quality and cardiovascular health effects covered the three years before, and three years after, the shutdown, from 2013 to 2018. Data from the exposure site (i.e. adjacent to the Shenango, Inc. coke plant address), a positive control site (i.e. adjacent to a still-operating coke plant, the Clairton Coke Works address), and a negative control site (i.e. an area in the same state with comparable population density as the exposed site, but without any coking operations nearby) were compared to identify and intercompare site-specific changes in air pollution, and their contemporaneous incidence of cardiovascular clinical health outcomes occurring at each study area before and after the plant shutdown.

2.2. Air monitoring data

We acquired air pollution data for selected government-run monitoring sites, as available from the Allegheny County Health Department (ACHD) Air Monitoring Network and the EPA Chemical Speciation Network (CSN) at the exposure and control sites (see supplement). Two ACHD monitors, located 600 m from the Shenango coke plant (at the exposure site) and 2.5 km from the Clairton coke plant (at the positive control site) respectively, were employed to capture the immediately local $PM_{2.5}$ and SO_2 trends.

Three comparable CSN monitors, located near the three study sites were also employed in the analyses: (a) the Shenango exposure site (the Lawrenceville station): Located at 301 39th St, Pittsburgh, PA 15 201, the Lawrenceville CSN monitor site, which is the closest CSN site to the plant (10.6 km); (b) the positive control (Liberty) site: Located at 2743 Washington Blvd, McKeesport, PA 15 133, which is 25.9 km from the Shenango plant, but near to (3 km from) the still-operating Clairton coke plant; and, (c) the negative control site (the MILLER AUTO SHOP 1 MESSENGER ST site): Located at 1 Messenger St, Johnstown, PA 15 902, this CSN monitor site is in Johnstown urban area without coking operations nearby. The $PM_{2.5}$ and SO_2 data at the study sites from 2013 to 2018 were extracted for comparison before and after the coke plant closure date. Elemental constituent concentration data at the Shenango exposure site (the Lawrenceville station) were also assessed to identify PM component differences upon coke plant shutdown.

2.3. Inpatient hospitalizations and emergency department visits data

For each study area, multiple neighboring zip codes were selected to be combined and analyzed for health outcomes (see supplement). We acquired quarterly hospital inpatient data from the Pennsylvania Health Care Cost Containment Council (PHC4). The organization would not provide zip code level counts at shorter time intervals. Total number of inpatient hospitalization cases for total cardiovascular diseases (ICD-9 codes 390-459, ICD-10 codes I00-I99), ischemic heart diseases (ICD-9 codes 410-414, ICD-10 codes I20-I25) and cerebrovascular diseases (ICD-9 codes 430-438, ICD-10 codes I60-I69), based on Principal Diagnosis Code, were aggregated by time interval and residential zip code (Alexeeff *et al* 2021).

In addition, emergency department (ED) visit counts data were procured from the EpiCenter syndromic surveillance database maintained by the Pennsylvania Department of Health. Daily cardiovascular and traumatic injury ED visit counts (i.e. a control outcome, not expected to be affected by air pollution) for populations near the exposure site, and weekly counts from near both control sites were aggregated by their respective adjacent residential zip codes. Due to the Pennsylvania Department of Health data release restrictions, small count values ($1 \leq N < 5$) needed to be redacted; we substituted the missing data with $N = 2.5$ in the main analysis (representing 42.4% of daily observations and 3.4% of weekly observations at the exposure zip codes, and 0.9% and 3.5% of weekly observations at the positive and negative control zip code groupings, respectively). For continuity of comparison, only those healthcare facilities that were enrolled in the EpiCenter reporting system beginning before 2013 were included in the main model. Weekly aggregated counts at the exposure site by sex and age group (0–17 years old, >65 years old) were also procured for stratified analysis. The count data were deidentified and the study was approved by the Pennsylvania Department of Health Institutional Review Board.

2.4. Study design and statistical approach

The ACHD local daily mean air quality data and health data were assessed for potential changes in trends before and after the closure of the coking plant using the ITS method. The size of the intervention effect is estimated using a segmented regression analysis of ITS (Bernal *et al* 2017):

$$\mathrm{Y}_t = \beta_0 + \beta_1 T + \beta_2 X_t + \beta_3 P X_t + f(t)$$

where Y_t is the health outcome at time t; T is the time elapsed since the start of the study; β_0 represents the baseline level at $T = 0$; β_1 is the trend before plant closure; β_2 indicates the step-level change in health outcome at the time of plant closure, as X_t is an indicator variable for plant closure (0 for pre-closure, 1 for post-closure); P indicates the time passed after the closure occurred, β_3 is the health outcome trend slope change during the time following the closure, and $f(t)$ is a term controlling for seasonality using splines (Bhaskaran *et al* 2013). Ambient air quality data from the ACHD and EPA CSN monitors were grouped based on sample date (before and after the coke plant closure) and compared using two-tailed t-tests for pre- vs. post-closure differences. Statistical analyses were performed using R Statistical Software version 4.2.2 (R Core Team 2022).

Residual autocorrelations were evaluated with the Breusch-Godfrey test. The 95% confidence intervals of the fitted interrupted time series regression model parameters were derived by assuming normality and using the R confint command. Models were tested in sensitivity analysis using both the imputed and non-imputed ED visit data and cyclic cubic splines with different degrees of freedom (DF) and stratification by month to adjust for seasonality. Further stratified analysis was performed to investigate the health outcome changes by sex and age subgroups; trends between cardiovascular outcome and traumatic injury control outcome were also compared in stratified subgroup analysis.

3. Results

The study area populations remained stable over the study period at the case and the positive control sites, and the sociodemographic properties were comparable to county and state statistics (table 1). The annual mean daily ambient air $PM_{2.5}$ level monitored at the case site and negative control site were similar in 2015, the year before the Shenango coal coking plant closure, while the levels at the exposed control site, with an operating plant, was slightly higher (table 1).

A significant overall (3 year average, pre vs. post) reduction of ambient SO_2 is observed after the plant closure, both at the ACHD monitoring site (just across the river from the Shenango coal coking plant), and at the nearby Lawrenceville CSN monitoring site (table 2). In contrast, no significant SO_2 change was observed at the monitoring sites located near the still operating Clairton coke plant. The mean ambient SO_2 levels at the site next to the plant decreased by 90% after the closure, while at the nearest CSN monitor (at Lawrenceville, 10.6 km away) the SO_2 levels decreased by 50%.

As a test whether the noted SO_2 reductions were coal-related, measurements of trace elements with known characteristic sources at the nearest (Lawrenceville) CSN site were also assessed for potential changes in PM constituents after the closure (Thurston *et al* 2011). We found reductions in key coal-related $PM_{2.5}$ constituents: sulfate dropped from 2.22 (95% CI: 2.05, 2.38) μg m^{-3} to 1.32 (95% CI: 1.24, 1.39) μg m^{-3}, while arsenic (As) dropped from 1.29 (95% CI: 1.07, 1.50) ng m^{-3} to 0.44 (95% CI: 0.29, 0.60) ng m^{-3}) ($p < 0.001$), consistent with $PM_{2.5}$ composition changes expected from such a coking plant closure.

Also consistent with a beneficial effect by the plant closure, a statistically significant downward trend in the quarterly counts of cardiovascular inpatient hospitalization cases was seen post-closure in study zip codes near the Shenango plant ($p < 0.05$) (see table 3, figure 1). The difference from the pre-closure trend was −33.06 (95% CI: −59.08, −7.05) cases/year for cardiovascular inpatient hospitalization (from a 5.09 [95% CI: −13.84, 24.02] cases/year rate of increase before closure, to a −27.97 [95% CI: −46.90, −9.04] cases/year rate of decrease after the closure). Similar beneficial changes in hospitalization trends were also observed for ischemic heart diseases and cerebrovascular diseases after closure: We saw a change of −13.89 (95% CI: −26.42, −1.35) ischemic heart diseases hospitalizations/year (from a 6.26 [95% CI: −2.86, 15.38] cases/ year rate of increase before the closure to a −7.63 [95% CI: −16.75, 1.49] cases/year rate of decrease after the closure), and a change of −12.21 (95% CI: −20.25, −4.17) cerebrovascular diseases hospitalizations/year rate (from a 1.61 [95% CI: −4.24, 7.45] cases/year increase in rate before closure to a −10.60 [95% CI: −16.45, −4.76] cases/year rate of decrease after the closure). In sharp contrast to the near-plant study area, no significant health outcome changes were observed from the projected trend in either of the control populations over time after the plant closure.

Similarly, while a statistically significant upward time trend was observed in cardiovascular emergency department visits at all three study locales before the intervention, there was an immediate drop, and then a longer-term downward trend, in the incidence of daily and weekly cardiovascular emergency department visits only in the coking plant neighboring community after the shutdown of the Shenango coke plant. Compared with the pre-closure emergency department visit trend, an immediate decrease of 18.61 visits (95% CI: 14.71, 22.52), 42% relative to the pre-closure weekly mean visits ($N = 44.2$ [95% CI: 42.2, 46.1]), was observed at the week after the shutdown. The difference in post-closure long-term trend from pre-closure trend was −0.31 (95% CI: −0.35, −0.27) cases/week, from a 0.17 [95% CI: 0.14, 0.20] cases/week increase in rate before closure to a −0.14 [95% CI: −0.17, −0.11] cases/week rate of decrease after the

Table 1. Sociodemographic and ambient air pollution exposure characteristics of study populations, Allegheny County and Pennsylvania State.

	Population 2010	Population 2020	% Population change in 10 years	% Poverty	% Nonwhite	2015 annual daily mean $PM_{2.5}$, $\mu g\ m^{-3}$ (Mean ± SE)
Exposure (Coke Plant Shutdown)						
Avalon	74 964	75 389	0.6%	13.5%	26.0%	11.4 ± 0.320
Positive Control (Coke Plant Operating)						
Clairton	58 419	58 237	−0.3%	10.7%	12.2%	13.0 ± 0.467
Negative Control (No Coking Operation Nearby)						
Johnstown	37 929	34 652	−8.6%	19.3%	11.8%	11.8 ± 0.295
Allegheny County	1223 348	1250 578	2.2%	10.5%	20.0%	
Pennsylvania	12 702 379	13 002 700	2.4%	12.1%	19.0%	

Table 2. $PM_{2.5}$ and SO_2 Concentrations at the ACHD and CSN monitors (exposure and positive control site).

		$PM_{2.5}$			SO_2		
	Period	Mean($mg\ m^{-3}$)	SE	*P*-value	Mean (ppm)	SE	*P*-value
Exposure (Coke Plant Shutdown)							
Avalon (ACHD Monitor)	1 January 2013–6 January 2016	12.1	0.172	<0.001	1.55	0.051	<0.001
	7 January 2016–31 December 2018	9.7	0.142		0.18	0.010	
Lawrenceville (CSN Monitor)	1 January 2013–6 January 2016	9.2	0.390	0.747	1.30	0.038	<0.001
	7 January 2016–31 December 2018	9.4	0.324		0.64	0.017	
Positive Control (Coke Plant Operating)							
Liberty (ACHD Monitor)	1 January 2013–6 January 2016	12.6	0.234	<0.001	4.35	0.159	0.200
	7 January 2016–31 December 2018	10.8	0.221		4.07	0.154	
Clairton (CSN Monitor)	1 January 2013–6 January 2016	12.2	0.615	0.264	4.35	0.148	0.200
	7 January 2016–31 December 2018	13.3	0.765		4.08	0.152	

closure. In contrast, no change from the long-term upward trend was observed in study control populations, away from the Shenango plant (table 4, figure 2). Sensitivity analysis using the original unimputed data and all healthcare providers in the database yielded similar conclusions (see supplement).

Significant immediate and longer-term cardiovascular outcome health improvements were especially found to be associated with the closure among sensitive subpopulations living near the facility. Notably, we found a statistically significant immediate reduction and downward trend of cardiovascular ED visits in those over 65 years of age in areas near the plant after the closure: Before Shenango coke plant closure, the weekly mean ED visit rate in population over 65 years of age at the case site was 16.4 visits per week (95% CI: 15.4, 17.3); the coke plant closure was associated with an immediate change of −5.04 [95% CI: −7.18, −2.90] visits followed by a long-term change of −0.13 [95% CI: −0.16, −0.11] visits/week, from a 0.06 [95% CI: 0.04, 0.07] cases/week rate of increase before closure to a −0.08 [95% CI: −0.09, −0.06] cases/week rate of decrease after the closure) (see table 5, figure 3). Moreover, such a reduction in medical visits after the closure was not seen in counts of visits for physical injuries, a control health outcome not thought to be affected by air pollution, confirming the specificity of the closure health benefits to biologically plausible outcomes.

4. Discussion

This study used the ITS method to evaluate the immediate and longer-term (cumulative) air pollution exposure change impacts on the incidence of cardiovascular outcomes after the closure of the Shenango, Inc.

Table 3. Main results from interrupted time-series analysis for cardiovascular inpatient hospitalizations.

	Exposure (coke plant shutdown)		Positive control (coke plant operating)		Negative control (no coking operation nearby)	
	Effect size estimate (95% CI)	*p*-value	Effect size estimate (95% CI)	*p*-value	Effect size estimate (95% CI)	*p*-value
Cardiovascular Hospitalizations, yearly						
Pre-intervention slope, β1	5.09 (−13.83, 24.02)	0.578	−19.82 (−40.91, 1.27)	0.064	−13.32 (−30.16, 3.53)	0.114
Immediate effect, β2	−12.15 (−59.23, 34.92)	0.593	37.34 (−15.12, 89.79)	0.151	−22.55 (−64.44, 19.35)	0.272
Post-intervention slope change, β3	**−33.06** (−59.08, −7.05)	**0.016**	24.52 (−4.47, 53.50)	0.092	13.64 (−9.52, 36.79)	0.231
Ischemic Heart Diseases Hospitalizations, yearly						
Pre-intervention slope, β1	6.26 (−2.86, 15.38)	0.166	0.53 (−8.57, 9.63)	0.900	−3.14 (−9.54, 3.27)	0.320
Immediate effect, β2	1.41 (−21.27, 24.09)	0.897	13.77 (−8.87, 36.41)	0.220	−12.95 (−28.88, 2.97)	0.100
Post-intervention slope change, β3	**−13.89** (−26.42, −1.35)	**0.032**	−4.68 (−17.20, 7.83)	0.440	4.03 (−4.78, 12.83)	0.350
Cerebrovascular Diseases Hospitalizations, yearly						
Pre-intervention slope, β1	1.60 (−4.24, 7.45)	0.570	−3.79 (−9.21, 1.63)	0.158	−4.93 (−9.95, 0.08)	0.053
Immediate effect, β2	8.89 (−5.65, 23.43)	0.214	9.88 (−3.60, 23.36)	0.140	6.62 (−5.85, 19.09)	0.278
Post-intervention slope change, β3	**−12.21** (−20.25, −4.17)	**0.005**	5.20 (−2.25, 12.65)	0.159	4.62 (−2.28, 11.51)	0.176

[a] Adjusted for quarter of year. Statistically significant association at $\alpha = 0.05$.

coal coking plant in January 2016. We confirmed simultaneous immediate and long-term declines in air pollution and cardiovascular disease rate in the neighboring resident community following the shutdown, when compared to expected trends from before the closure. The total cardiovascular ED visits in the coking plant neighboring community were 61% fewer than the predicted trend during the three years after the closure, while there were 13% fewer total cardiovascular hospitalizations. Residents over 65 years of age comprised 60% of the cardiovascular ED visit reduction. These results are clearly consistent with the conclusion that the plant closure was responsible for the reductions seen in the near-plant zip codes.

Our findings of the local air pollution trends are consistent with previous reports on this coal coking plant's point source emissions and local air quality impact (Huet-Vaughn *et al* 2018, Kelly and Fischman). The shutdown of the industrial emission source had the greatest estimated effect on ambient SO_2 levels directly related to coal processing at the monitors closest to the coke plant; the SO_2 change was smaller at monitoring site 10.6 km away, and no longer significant at the positive control site 25.9 km away with other emission sources. The measured $PM_{2.5}$ levels measured closest to the coke plant (from the ACHD monitoring network) decreased after the plant closure, becoming similar with the measurements 10.6 km away (from the EPA monitoring network). We also observed significant changes in coal-related trace element levels (As and S) at the CSN monitor nearest the coking plant. Similar air pollution findings have been reported in studies in Europe and Asia, identifying elevated levels of SO_2 and particulate matter arsenic, sulfate in the proximity of coking plants (Khare and Baruah 2011, Díaz-Somoano *et al* 2012, Mu *et al* 2012, Zajusz-Zubek *et al* 2017).

To the best of our knowledge, this is the first study using a statistically rigorous ITS analysis to investigate the health benefits in the local community after a coal coking plant closure. While past studies have suggested that living in the vicinity of coke plants can potentially increase health risks in resident populations (Parodi *et al* 2005, Porter *et al* 2014), our statistical findings of both short- and longer-term cardiovascular health improvements in local residents more definitively add to the growing body of evidence that policies implemented to regulate and reduce industrial emissions have real public health benefits (Henneman *et al* 2019, Martenies *et al* 2019, Rauner *et al* 2020). We found that both hospitalization and emergency department visit counts significantly decreased 40% immediately after the shutdown of the coke plant in the near-plant exposure population, and then statistically significantly continued downward in the months that followed. However, the near-plant community reduction in cardiovascular medical visits after the closure was not found in the positive or negative control populations during the same post-closure period, consistent with the interpretation of the near-plant reductions as due to the plant closure.

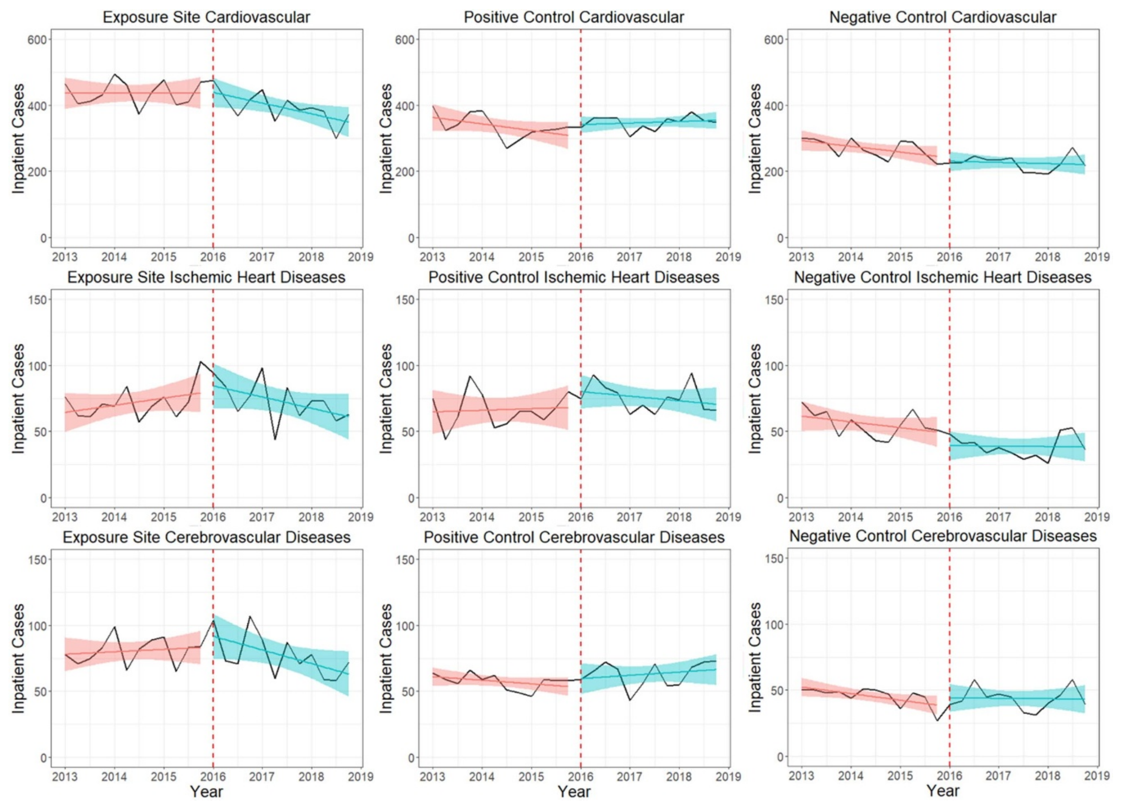

Figure 1. Segmented regression results for (a) quarterly inpatient cardiovascular diseases hospitalization cases, (b) quarterly inpatient ischemic heart diseases cases, and c) cerebrovascular diseases cases at the exposure site (Avalon), positive control site (Clairton) and negative control site (Johnstown), 2013–2018.
Red solid line: Inpatient regression line before Shenango shutdown.
Blue solid line: Inpatient regression line after Shenango shutdown.
The vertical line represents the day of the coke plant closure.

Table 4. Main results from interrupted time-series analysis for cardiovascular ED visits.

	Exposure (coke plant shutdown)		Positive control (coke plant operating)		Negative control (no coking operation nearby)	
	Effect Size Estimate (95% CI)	*P*-Value	Effect Size Estimate (95% CI)	*P*-Value	Effect Size Estimate (95% CI)	*P*-Value
Cardiovascular emergency department visits, daily						
Pre-intervention slope, β1	**0.0033** (0.0029, 0.0038)	**<0.001**				
Immediate effect, β2	**−2.5356** (−2.9829, −2.0882)	**<0.001**				
Post-intervention slope change, β3	**−0.0063** (−0.0069, −0.0056)	**<0.001**				
Cardiovascular emergency department visits, weekly						
Pre-intervention slope, β1	**0.1685** (0.1387, 0.1982)	**<0.001**	**0.0246** (0.0093, 0.0400)	**0.002**	**0.0166** (0.0043, 0.0289)	**0.008**
Immediate effect, β2	**−18.6111** (−22.5155, −14.7067)	**<0.001**	−0.3551 (−2.3706, 1.6605)	0.729	**−1.6572** (−3.2708, −0.0436)	**0.044**
Post-intervention slope change, β3	**−0.3102** (−0.3517, −0.2686)	**<0.001**	0.0160 (−0.0055, 0.0374)	0.144	−0.0124 (−0.0296, 0.0048)	0.157

[a] Adjusted for seasonality. Statistically significant association at $\alpha = 0.05$.

There are known air pollution health effect mechanisms that are consistent with the cardiovascular benefits we noted after the plant closure. Coal-related air pollution can cause oxidative stress, inflammation, and systemic health effects, and thus increase cardiovascular health risk (Schraufnagel *et al* 2019a, Maciejczyk *et al* 2021), so It is biologically plausible that the shutdown of the coal coking plant reduced both

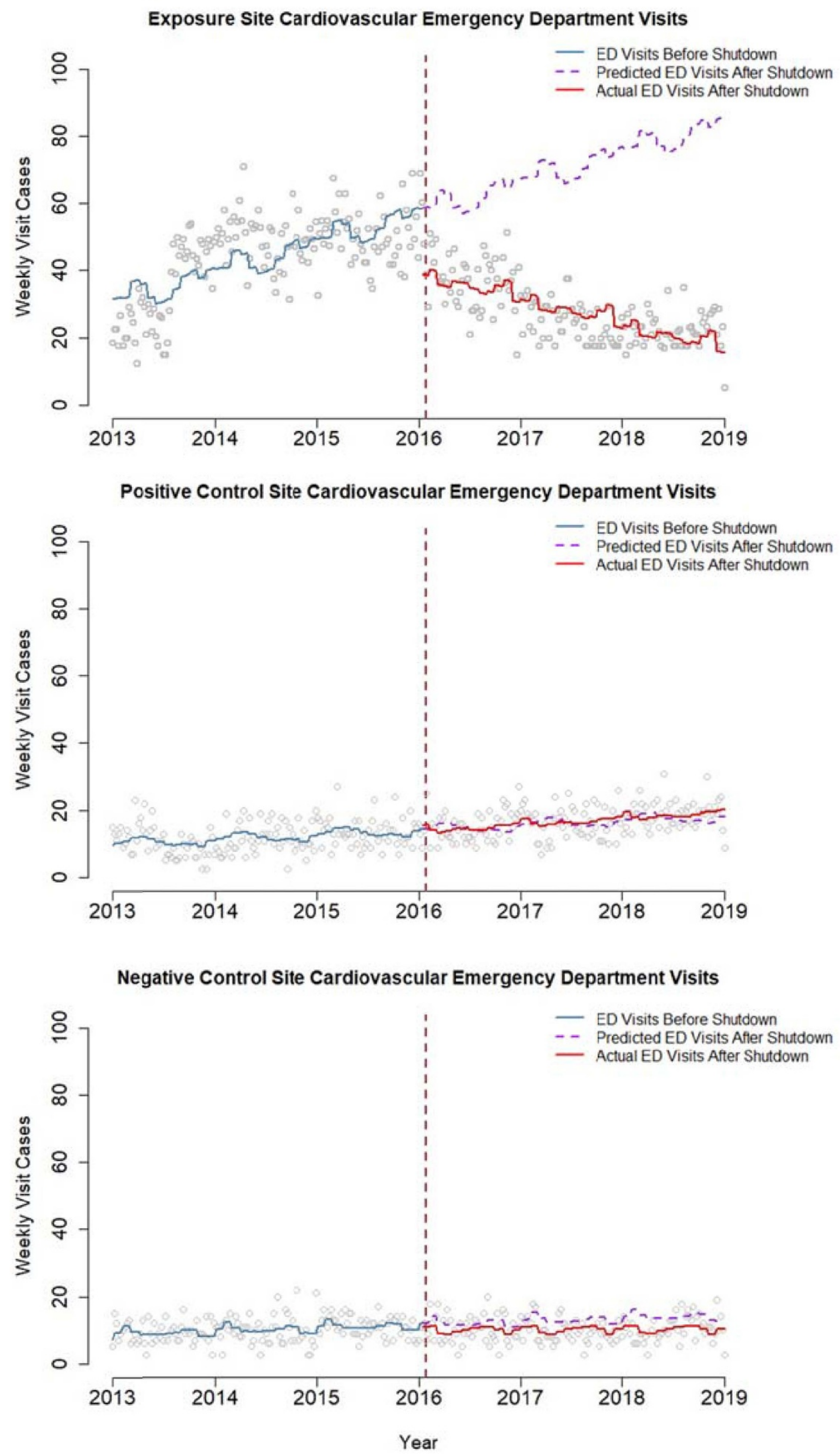

Figure 2. Segmented regression results for weekly cardiovascular ED visits at the exposure site, exposed control site and unexposed control site, 2013–2018.
Blue solid line: Inpatient before Shenango shutdown.
Purple dashed line: Predicted trend of inpatient without Shenango shutdown.
Red solid line: Actual inpatient after intervention. The vertical line represents the day of the coke plant closure.

acute and chronic systemic inflammation among nearby residents. The immediate and longer-term benefits from a quantum drop in air pollution exposure are also consistent with steady reductions in ill-effects that have similarly been found over time following smoking cessation (Gratziou 2009, Polosa *et al* 2018). In

Table 5. Main results from interrupted time-series analysis for cardiovascular ED visits.

	Cardiovascular diseases, Age >65 years old, weekly		Traumatic injury, Age >65 years old, weekly	
	Effect size estimate (95% CI)	p-value	Effect size estimate (95% CI)	p-value
Pre-intervention slope, β1	**0.0581** (0.0418, 0.0744)	**<0.001**	**0.0263** (0.0038, 0.0488)	**0.022**
Immediate effect, β2	**−5.0397** (−7.1783, −2.9011)	**<0.001**	−2.0791 (−5.0348, 0.8765)	0.167
Post-intervention slope change, β3	**−0.1347** (−0.1574, −0.1119)	**<0.001**	0.0142 (−0.0172, 0.0457)	0.375

[a] Adjusted for seasonality. Statistically significant association at $\alpha = 0.05$.

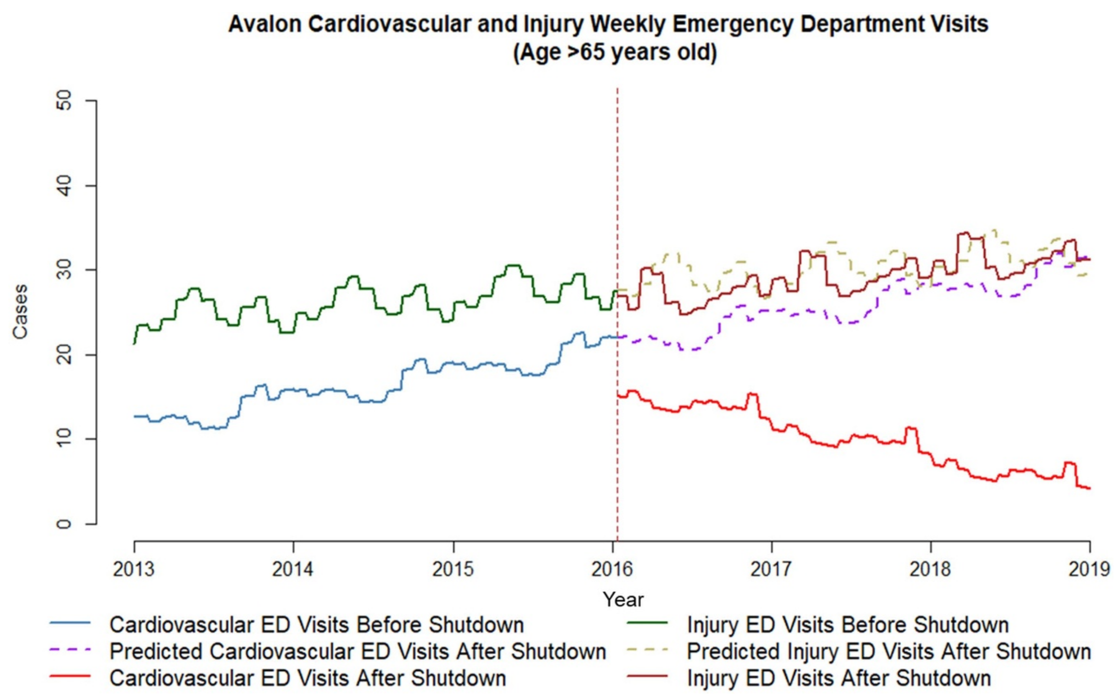

Figure 3. Segmented regression results weekly cardiovascular and injury ED visits of people >65 years of age at exposure site (Avalon).
The vertical line represents the day of the coke plant closure.

contrast to the cardiovascular benefits of closure, control outcome traumatic injury ED visits, not biologically relevant to coke plant air pollution exposures, were unaffected: these control outcome counts followed the pre-closure cardiovascular visits trend in the same near-plant study population. Thus, the cardiovascular health benefits that coincided with the coking plant closure were only among residents in the exposure area, and also specific to disease categories that were plausibly affected by air pollution. The specificity of effects to both the exposed population and to plausible health outcomes is supportive of the conclusion of a causal inference of cardiovascular health benefits from the pre- vs. post-closure air pollution reductions (Hill 1965, Fedak *et al* 2015). Thus, our results also provide confirmation of the usefulness of epidemiological time series and cohort study results for the estimation of the potential health benefits from clean air policies.

Previous studies have ranked Pittsburgh as one of the cities with highest levels of air pollution and most air-pollution related deaths in the United States (American Lung Association 2022, Mckeon *et al* 2022). Historically, stationary source air pollution emissions in the Pittsburgh region have largely come from industrial sources, such as coking operations like Shenango and Clairton, so understanding the health outcomes of industrial air pollution is uniquely critical for improving public environmental health of communities near such emission sources (Lange *et al* 2022). Other studies have also found that low-socioeconomic-status communities experience higher levels of criteria air pollutants, partially from industrial sources (Hajat *et al* 2015, Boing *et al* 2022, Jbaily *et al* 2022). These communities, exposed to higher level of pollution, may also experience greater response to such pollution, and face higher overall risk for negative health outcomes (Gwynn and Thurston 2001). By demonstrating the public health benefits from the ending of these coal coking plant exposures, our study provides scientific inputs for the policy-making process at other industrial sites with high levels of air pollution emissions, thus further justifying action to control emissions, as well as the addressing of environmental injustices to communities living near such plants.

Despite its well-balanced design, there were certain limitations to this study. First, we were limited by the data release rules of the local health data agencies, and were therefore unable to acquire health data at a higher spatial-temporal resolution for inpatient hospitalization or with detailed diagnosis information for the emergency department visits. Consequently, we had more limited power to detect the health effects for specific disease categories such as ischemic heart diseases and cerebrovascular diseases in smaller subpopulations that may be at higher risk. Also, unlike the control sites, we were unable to completely eliminate statistical autocorrelation from the imputed daily ED visits data analysis at the Shenango exposure site, but we did find similar health effect results with the unimputed data, for which there was no significant autocorrelation.

Second, despite our extensive efforts to evaluate potential confounding via rigorous inclusion of both positive and negative control populations, as well as consideration of a control outcome of traumatic injury cases within the same population, the possibility of unaddressed confounding cannot be excluded. However, given our measures, and the geographic and administrative proximity between the exposure site and positive control site, we are not aware of any other particular policy changes that took place at the study sites during our study period that could have alternatively led to the robust observed trends we found.

Another potential study limitation is that, because our analysis employed aggregated count data, we were unable to adjust for health conditions and lifestyle factors at the individual participant level. There also were modest demographic differences between the study sites and the county and state population: our exposure population had a slightly higher poverty rate and percentage of non-white population and a smaller population growth rate. Caution should be given in the generalization of our findings to a population with very different population characteristics.

5. Conclusion

Overall, our research provides compelling scientific evidence that this intervention eliminating fossil-fuel related coal-coking air pollution emissions significantly improved both the air quality and cardiovascular health of the nearby community. In addition, this work provides rigorous validation of past policy applications of statistical associations found between acute air pollution exposures and adverse health to estimate clean air health benefits.

Data availability statement

The data cannot be made publicly available upon publication because the cost of preparing, depositing and hosting the data would be prohibitive within the terms of this research project. The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iDs

Wuyue Yu https://orcid.org/0000-0003-4802-6536
George D Thurston https://orcid.org/0000-0001-9429-2267

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