ENVIRONMENTAL FACTORS AND HOSPITAL UTILIZATION FOR PEDIATRIC ASTHMA IN SOUTH TEXAS: AIR POLLUTION, HOSPITAL LENGTH OF STAY, AND READMISSIONS

A Dissertation

by

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ABSTRACT

Hospital length of stay (LOS) has been identified as a proxy measure of healthcare expenditures and cost of care in the United States. Hospital readmission is one of the most important asthma-related health outcomes to consider since repeated hospitalizations could lead to a large burden on patients/caregivers, hospitals, and the government with regard to healthcare resources, cost and quality. However, there are limited studies investigating the potentially important associations between ambient air pollution and hospital utilization outcomes, including LOS and hospital readmissions, for pediatric asthma. In addition, few studies have examined factors affecting the high frequency of hospitalization for pediatric asthma.

The first study investigated the association between ambient air pollution and LOS among children with asthma in South Texas. The findings of this study showed that the increased ozone level was significantly associated with prolonged LOS (>2 nights) in the single- and two-pollutant models. The second study examined effects of ambient air pollutants on preventable hospital readmission for pediatric asthma in South Texas. This study found adverse effects of $PM_{2.5}$ and ozone concentrations on avoidable hospital readmissions among children with asthma. In addition, this study showed that younger age and exposure during the warmer season were associated with the effect of ambient air pollutants.

The final study identified individual and environmental characteristics of children with asthma who had a higher frequency of hospitalizations in a low-income community of South Texas. The results revealed that a modest number of patients with the highest number of hospitalizations accounted for substantial hospital resource utilization. This study also showed that the age of 5-11 years, longer LOS at index admission, initial admission during warm season, and high level of outdoor air pollution in residential neighborhoods present as significant characteristics of pediatric asthma patients with a higher number of hospitalizations in South Texas.

In conclusion, these findings may help health professionals, public health experts, school leaders, and policymakers consider the importance of ambient air pollution on hospital LOS and repeated admissions, among pediatric patients with asthma during education sessions, medical care practice, and policy formulation, emphasizing preventive measures.

DEDICATION

I dedicate this dissertation to my beloved wife and my family.

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This work was supervised by a dissertation committee consisting of Professor Genny Carrillo [committee chair] of the Department of Environmental and Occupational Health, Professor Bita A. Kash [co-chair] of the Department of Health Policy and Management, Professor Mark Benden of the Department of Environmental and Occupational Health, and Professor Xiaohui Xu of the Department of Epidemiology and Biostatistics. The data analyzed for the dissertation papers was provided by Professor Genny Carrillo. All work conducted for the dissertation was completed by the student independently.

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NOMENCLATURE

LOS	Length of Stay
PM	Particulate Matter
ICD	International Classification of Diseases
CDC	Center for Disease Control and Prevention
EPA	Environmental Protection Agency
TCEQ	Texas Commission on Environmental Quality
TRAP	Traffic-related Air Pollution
ED	Emergency Department
SVI	Social Vulnerability Index

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1. INTRODUCTION

1.1. Background and Significance

Asthma is one of the most prevalent chronic diseases in the United States (U.S.). According to the Centers for Disease Control and Prevention (CDC), about 7.9% of the U.S. population (about 25 million) had asthma in 2017 and the asthma prevalence of children younger than 18 years old (8.4%) was higher than the adult asthma prevalence (7.7%). The CDC report showed that asthma prevalence of children aged 5-11 years and 12-17 years were 8.7% (about 2.5 million) and 11.1% (about 2.7 million), respectively; and the asthma prevalence of those under the federal poverty threshold (below 100% of poverty level) was 11.7% [1].

Notably, asthma is a common chronic respiratory disease among children, leading to asthma attacks, school absences, and hospitalizations [2]. A recent study found that about half of the children with asthma experienced more than one school absence and about 5% of them were hospitalized in 2016 [3]. According to the CDC statistics, more than half of the children with asthma (51.6%) experienced one or more asthma attacks in 2017 [1]. Moreover, children with asthma had higher healthcare utilization compared to adults with asthma in 2016. For example, the hospital inpatient discharge for children per 10,000 population (10.7) had over two times higher rate than adults (4.4). The rates per 10,000 population in physician office visits (332.9) and emergency department visits (74.3) for children were also higher than those for adults (300.3 and 50.3), respectively [1].

The rate of pediatric asthma hospitalization is different across race/ethnicity and income. A study revealed that the asthma-related admission rate of African American children (363.9 per 100,000) and Hispanic children (128.8) were higher than those of White children (83.8) and Asian/Pacific Islander children (78.2) in 2010. In addition, the same study showed that the rate of asthma-related hospital stays were higher among children in the lowest income communities (182.8 per 100,000) than those in the highest income communities (95.2) [4].

Previous studies have shown that asthma results in a substantial financial burden on the national level [5,6]. Especially, exacerbations of asthma leads to increasing use of healthcare resources, such as hospital length of stays and emergency department visits, and asthma-related healthcare costs [7,8]. A review paper about the economic burden of pediatric asthma in the U.S. showed that children with asthma ($3,075-13,612) had about two times higher average total annual costs than those without asthma ($1,628-6,695) [9]. Another study using the Medical Expenditure Panel Survey (MEPS) data showed that the estimated total cost of asthma in the U.S. based on the pooled sample of about 214,000 individuals was about $82 billion between 2008 and 2013. It is important to note that the medical costs were the largest component among all expenses ($50.3 billion) [10].

Hospital-related health outcomes have been used as essential measurements in asthma management and treatment since they are the largest components of asthma-related healthcare resources and costs. A research that reviewed 68 studies about the economic burden of asthma revealed that hospitalization and medication were the biggest components of direct costs, while work or school absences were those of indirect costs [11]. A review paper also presented that hospitalization accounted for most of the costs for asthma care. In fact, the estimated national annual cost of asthma hospitalization in 2009 was about $1.6 billion [9].

Another study that used MEPS data of 2007-2013 demonstrated that school-aged children with asthma (6-17 years) had a higher rate of all-cause annual hospital care, including emergency department visits, hospitalizations, outpatient visits, and prescription drugs, and higher annual healthcare expenditures than those without asthma. As a result, the total annual healthcare expenditure for school-aged children with asthma in the nation was $5.92 billion in 2013 [6]. Additionally, a study focusing on children with Medicaid found that the hospital admission rate for children were four times higher for those with asthma than those without the condition (11.65% vs. 2.84%, $p<0.0001$) [12].

As such, identifying factors that are related to hospital utilization is an important topic to address in order to not only prevent avoidable hospitalizations, but also improve use of resources and reduce overall healthcare costs [13]. Although a number of studies has identified the individual-level risk factors associated with various health outcomes in pediatric asthma hospitalization [14–16], few studies have investigated the relationship between environmental factors and hospital utilization including length of stay and readmissions. Also, none of studies examines factors associated with pediatric asthma hospitalizations in low-income communities in the U.S.

1.2. Overall Objective

The overall objective of my dissertation is to examine the associations between environmental factors, including ambient air pollution, and hospital-related health outcomes, such as length of stay and readmissions, among children with asthma in South Texas. Three studies are presented in my dissertation. The first paper investigates the association between short-term ambient air pollution and hospital length of stay in pediatric hospitalization for pediatric asthma. The second paper explores the effect of ambient air pollution on hospital readmissions among children with asthma by using a case-crossover study design. Lastly, the final paper seeks to identify the high utilizers in pediatric asthma hospitalizations and examine their individual-level and environmental characteristics.

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2. ASSOCIATION BETWEEN AMBIENT AIR POLLUTION AND HOSPITAL LENGTH OF STAY AMONG CHILDREN WITH ASHTMA IN SOUTH TEXAS*

2.1. Background

Hospital length of stay (LOS) is a significant determinant of overall healthcare expenses, and often viewed as a proxy for cost of care. As such, increased LOS causes a substantial economic burden on patients/families and health insurance, including the government [1]. Despite improvements in medical care and medication, the median hospital LOS for pediatric asthma has not changed significantly for the past decades [2]. Additionally, hospital LOS is frequently regarded as an important measurement of healthcare efficiency and resource utilization and greatly affects healthcare planning, hospital capacity, and policy [3,4].

Identifying factors that affect hospital LOS is crucial in order to improve health outcomes and effective use of healthcare resources as well as reduce healthcare costs [4]. Several studies have examined the determinants of hospital LOS among patients with asthma. Two studies that investigated all age groups revealed that age, gender, race/ethnicity, admission day, and season were significant factors that influence hospital LOS [5,6]. The other studies on children with asthma found that gender, obesity status,

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complex chronic conditions, and season were significantly associated with prolonged hospital LOS [7–9].

In recent years, there is a growing body of literature that examines the relationship between air pollution and asthma hospitalizations. A systematic review found 87 time-series or case-crossover studies that evaluated the association between exposures to outdoor air pollutants and asthma exacerbation outcomes, including hospital admissions and emergency room visits. The study's meta-analysis found that six major air pollutants, namely ozone, NO_2, SO_2, $PM_{2.5}$, PM_{10}, and CO, were significantly associated with an increased risk of asthma-related hospitalization [10].

Although air pollution affects the health of all age groups, children are more vulnerable to respiratory effects of air pollutants than adults since children are still in developmental and physiologic stages [11–15]. In addition, children are highly exposed to air pollutants because they tend to spend more time outside playing and engaging in physical activity [16,17]. Accordingly, several international studies have explored the effect of air pollution on pediatric asthma hospitalization. A study focusing on children in Vietnam found that short-term exposure to air pollutants including NO_2 were statistically significant with increased daily counts of hospitalizations due to asthma and bronchitis [18]. A recent study conducted in Taiwan also reported that air pollutants, including PM_{10}, $PM_{2.5}$, and SO_2, were positively associated with hospitalizations among children with asthma [19].

Despite the general utility of LOS as a healthcare outcome, only a few studies have explored the relationship between ambient air pollution and hospital LOS among patients with asthma or other respiratory diseases. A study using the 1999–2007 United States (U.S.) National Inpatient Sample data found that $PM_{2.5}$ exposure was significantly associated with the total costs and charges in pediatric asthma hospitalization, but the study did not find any significant relationships between outdoor air pollutants and hospital LOS [20]. On the other hand, significant results were observed in two studies conducted in Asian countries. One study for adults with asthma in China found that ambient air pollutants, including $PM_{2.5}$ and NO_2, were significantly associated with increased LOS in a stratifying subgroup analysis for sex, age, and season [4]. The other study, conducted in Hanoi, Vietnam, showed a significantly positive association between exposure to ozone and hospital LOS among children with acute lower-respiratory infection (ALRI) [21].

Despite the serious public health burden of pediatric asthma hospitalization in the U.S., there are limited studies that investigated the relationship between outdoor air pollution and hospital LOS among children with asthma in the U.S. setting, especially in low-income communities. Therefore, the purpose of this study is to examine the effects of ambient air pollution prior to hospitalization on hospital LOS among pediatric patients with asthma in South Texas, a region with pronounced low-income communities, health disparities, and known environmental health issues [22].

2.2. Methods

2.2.1. Study Setting and Data Source

Hospitalization records were obtained from the Driscoll Children's Hospital electronic database to analyze cases of children aged 18 years old or younger with a primary diagnosis of asthma admitted between 1 January 2010 and 31 December 2014. This hospital, located in Corpus Christi, Texas, is a tertiary medical center with 189 beds for pediatric patients and more than 30 medical and surgical specialties that provide healthcare to children living in South Texas [23]. All diagnoses were coded using the International Classification of Diseases, 9th Revision (ICD 9) at discharge (codes 493.0–493.92). Records included information such as age, gender, ethnicity, type of insurance, admission date, discharge date, family history of asthma or respiratory disease, experience of asthma education, use of medication, and census tract information of each child's residence (i.e., a geographical unit of analysis larger than city block but smaller than city which constitutes the U.S. Census Bureau's construct for neighborhood level) [24,25].

The average daily air pollution concentration data, including particulate matter ($PM_{2.5}$) and ozone, between 1 January 2010 and 31 December 2014, were collected from the U.S. Centers for Disease Control and Prevention (CDC) National Environmental Public Health Tracking Network [26]. These data include the estimates of the mean modeled predictions of $PM_{2.5}$ and ozone concentrations in the census tract level developed by the Downscaler model of the U.S. Environmental Protection Agency (EPA) [27]. These air pollution data are valuable since they estimate the predictions of the two air pollutants in all census tracts in the nation, excluding Hawaii and Alaska. The data also include the areas that do not have air monitoring sites, as well as the daily average modeled concentration levels between 2001 and 2014. This is important given that most monitoring sites do not take samples for $PM_{2.5}$ and ozone on a daily basis [27].

The meteorological data (daily mean temperatures) were obtained from the Texas Commission on Environmental Quality (TCEQ) to control for the impact of weather on the LOS for patients with asthma. The temperature data were collected based on the information measured in the nearest air monitoring station from each patient's residence by using the geographic information system (GIS) program (ArcMap 10.4, ESRI, Redlands, CA. USA). This study protocol was reviewed and approved by the Institutional Review Boards of the Texas A&M University and Driscoll Children's Hospital.

2.2.2. Measurement

Hospital length of stay (LOS), the outcome variable of this study, was defined as the total number of nights spent in the hospital from the admission date to the discharge date. In the analysis, this variable was dichotomized as (1) two nights or fewer and (2) more than two nights based on the median LOS for the study population. Ambient air pollution data for $PM_{2.5}$ and ozone concentration levels were the primary independent variables. The daily mean $PM_{2.5}$ and ozone levels from admission day to seven days before admission for each patient were collected individually based on their admission dates and residential census tract information. The data for $PM_{2.5}$ refers to the mean estimated 24 h average concentration in µg/m3 and the data for ozone indicates the mean estimated 8 h average concentration in parts per billion (ppb) within three meters of the surface of the earth [27].

The effects of air pollutants were measured with different lag days from Lag0 (admission day) to Lag0–7. For example, Lag0–7 represents the eight-day moving average of air pollutant concentrations between admission day and the seventh day before admission. The moving averages were used to evaluate the cumulative effects of air pollutants on hospital LOS [4]. The temperature variable was also measured as the moving averages of daily mean temperatures for the same periods as for the air pollution metric for each patient.

Furthermore, age, gender, ethnicity, type of insurance, season, and admission day have been identified as significant factors that affect LOS for patients with asthma in previous literature [5–7,28]. Other factors associated with asthma control or exacerbation, including family history of asthma, use of medication, asthma education, and outdoor temperature, also may affect the relationship between outdoor air pollution and LOS [29–32]. Accordingly, potential confounders were included in the regression models as follows: age when admitted to the hospital (5–11 years old or 12–18 years old), gender (male or female), ethnicity (Hispanic or non-Hispanic), type of insurance (public via U.S. Medicaid, private, or self-pay), family history of asthma or other respiratory disease (yes or no), use of medication (yes or no), experience of asthma education (yes or no), season (warm defined as May to October or cold defined as November to April), admission day (weekday as Monday to Thursday or weekend as

Friday to Sunday), and outdoor temperature (moving averages as noted above, in Celsius).

2.2.3. Statistical Analysis

Descriptive statistics of the study population were calculated to estimate the mean, standard deviation (SD), and the minimum and maximum for continuous variables or percentages for categorical variables. Pearson correlation was used to assess whether $PM_{2.5}$ and ozone pollutants are highly correlated. In addition, multivariate binomial logistic regression analyses were performed to determine the association between exposure to each air pollutant and hospital LOS on the day of admission (Lag0) and individual cumulative days prior to the admission day (Lag0–1~Lag0–7). The regression models controlled for the other covariates noted above.

In addition to the single-pollutant regression models, the two-pollutant models including both $PM_{2.5}$ and ozone levels were used to adjust for the mutual effect of air pollutants. The odds ratios (ORs) and 95% confidence intervals (CIs) were estimated for associations between short-term exposure to air pollution on the days prior to admission and hospital LOS. Stratified analyses by age, gender, and season were performed in order to evaluate the effect of confounding factors on the association between air pollutants and LOS for pediatric asthma. All statistical analyses were conducted by using the Stata 14 version (StataCorp LLC, College Station, TX, USA). A p-value less than 0.05 was considered statistically significant.

2.3. Results

Table 2.1 shows descriptive statistics of the study population (N=711). The average age of the total participants was nine years old, ranging from five to 18 years old, and three quarters (75.4%) were between five to 11 years old. The low LOS group (≤two nights) had a slightly greater proportion of five to 11 year-old children, compared to the high LOS group (>two nights). The study population consisted of more males (59.1%) than females (40.9%), and the proportion was similar in both LOS groups. About 74% of the children were Hispanic, having a higher rate in the high LOS group (77.4% vs. 73.3%).

Over two-thirds of the study population had public insurance (68.7%), and most of the participants (92%) used some form of medication for their asthma care. About half had a family history of asthma or respiratory diseases (49.5%), and this showed to be particularly higher among the high LOS group (56.2%) than the low LOS group (47.6%). Almost all of the study population had received asthma education (95.2%) in the past, and over 60% of them were admitted to the hospital on a weekday (60.6%) and in the cold season (61.6%). None of the characteristics between the two groups were significantly different.

Table 2.1 Descriptive Statistics of Study Population (N=711)

Variables	Total†	High (LOS>2)†	Low (LOS≤2)†	p-value
Total	711 (100.0)	160 (100.0)	551 (100.0)	
Age (continuous)	9.2±3.5 (5, 18)	9.5±3.6 (5, 18)	9.1±3.5 (5, 18)	0.152
Age				0.451
5-11 years old	536 (75.4)	117 (73.1)	419 (76.0)	
12-18 years old	175 (24.6)	43 (26.9)	132 (24.0)	
Gender				0.925
Female	291 (40.9)	66 (41.3)	225 (40.8	
Male	420 (59.1)	94 (58.7)	326 (59.2)	
Ethnicity				0.305
Hispanic	527 (74.2)	123 (77.4)	404 (73.3)	
Non-Hispanic	183 (25.8)	36 (22.6)	147 (26.7)	
Insurance				0.733
Public (Medicaid)	488 (68.7)	108 (67.5)	380 (69.0)	
Private	205 (28.8)	49 (30.6)	156 (28.3)	
Self-pay	18 (2.5)	3 (1.9)	15 (2.7)	
Use of medication				0.206
Yes	654 (92.0)	151 (94.4)	503 (91.3)	
No	57 (8.0)	9 (5.6)	48 (8.7)	
Family history of asthma or respiratory diseases				0.053
Yes	352 (49.5)	90 (56.2)	262 (47.6)	
No	359 (50.5)	70 (43.8)	289 (52.4)	
Recipient of asthma education				0.265
Yes	677 (95.2)	155 (96.9)	522 (94.7)	
No	34 (4.8)	5 (3.1)	29 (5.3)	
Admission day				0.199
Weekday (Mon.-Thu.)	431 (60.6)	90 (56.2)	341 (61.9)	
Weekend (Fri.-Sun.)	280 (39.4)	70 (43.8)	210 (38.1)	
Admission season				0.526
Warm (May-October)	273 (38.4)	58 (36.3)	215 (39.0)	
Cold (November-April)	438 (61.6)	102 (63.7)	336 (61.0)	
Year				0.081
2010	166 (23.3)	48 (30.0)	118 (21.4)	
2011	133 (18.7)	34 (21.1)	99 (18.0)	
2012	154 (21.7)	26 (16.3)	128 (23.2)	
2013	125 (17.6)	26 (16.3)	99 (18.0)	
2014	133 (18.7)	26 (16.3)	107 (19.4)	

Note: †Mean± standard deviation (minimum, maximum) or N (%)

Summary statistics of daily average air pollutant concentration levels ($PM_{2.5}$ and ozone) and temperatures for the study population from Lag0 to Lag0–7 are shown in Table 2.2. The average values for $PM_{2.5}$, ozone, and temperatures were similar among the cumulative lag days. However, the minimum and maximum values for each one were different, indicating that the closer the cumulative days are to admission day (such as Lag0, Lag0–1, and Lag0–2), the larger the variations are for the values. For example, the variation for average $PM_{2.5}$ values in Lag0 was about 25 (2.48–27.28), which was higher than the variation (about 12) on Lag0–7 (4.38–16.01). The same patterns were evident among the average values for ozone and temperatures. The Pearson correlation tests between $PM_{2.5}$ and ozone from Lag0 to Lag0–7 revealed small correlations ranging from 0.092 to 0.123 (See Appendix A).

Table 2.2 Summary Statistics of Daily Average Air Pollutant Concentrations and Temperatures from Lag0 to Lag0-7

Lag days	$PM_{2.5}$ (μg/m^3)				Ozone (ppb)				Temperature (°C)			
pre-admission	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Lag0	8.43	3.41	2.48	27.28	37.43	11.92	10.09	75.23	20.71	6.78	1.06	33.33
Lag0-1	8.45	2.89	2.96	23.01	37.66	11.14	13.74	75.29	20.65	6.64	2.11	32.92
Lag0-2	8.47	2.50	3.57	19.96	37.80	10.42	15.69	73.35	20.65	6.52	1.78	32.41
Lag0-3	8.48	2.24	3.80	17.85	37.84	9.74	16.84	73.58	20.66	6.45	1.02	32.08
Lag0-4	8.47	2.10	3.75	16.46	37.87	9.24	17.39	72.57	20.65	6.37	2.99	32.1
Lag0-5	8.46	1.96	3.88	16.71	37.81	8.85	17.48	71.85	20.63	6.34	5.82	32.15
Lag0-6	8.45	1.85	4.08	16.46	37.72	8.39	17.73	69.02	20.62	6.33	6.33	32.24
Lag0-7	8.47	1.78	4.38	16.01	37.61	8.05	17.93	67.21	20.61	6.33	6.63	32.37

Note: SD: Standard Deviation; ppb: parts per billion

Table 2.3 and Figure 2.1 illustrate the results of multivariate binomial logistic regression analysis to examine the associations between ambient air pollution and hospital LOS on the admission day (Lag0) and cumulative several days before the admission day (Lag0–1 to Lag0–7) in the single- and two-pollutant models, adjusting for several confounders. In the single-pollutant models, the increased ozone concentration level was significantly associated with prolonged hospital LOS from Lag0–1 to Lag0–3 ($p<0.05$). Positive relationships were also consistently found in Lag0–4, Lag0–5, and Lag0–6, but they were not statistically significant. Moreover, in the two-pollutant model, the ozone concentration level showed a significant positive association with LOS on Lag0–2 ($p=0.048$). However, the $PM_{2.5}$ concentration level did not have any significant association with LOS, although all of the adjusted ORs showed positive relationships between $PM_{2.5}$ concentration level and hospital LOS.

Table 2.3 Results of Multivariate Binomial Logistic Regression Analysis in Single- and Two-Pollutant Models

Lag days pre-admission	Single-pollutant models				Two-pollutant models			
	$PM_{2.5}$		Ozone		$PM_{2.5}$		Ozone	
	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value
Lag0	1.021 (0.970, 1.074)	0.427	1.014 (0.999, 1.029)	0.059	1.017 (0.965, 1.071)	0.528	1.014 (0.999, 1.029)	0.068
Lag0-1	1.050 (0.989, 1.114)	0.112	1.016 (1.000, 1.032)	0.049*	1.044 (0.983, 1.109)	0.162	1.015 (0.999, 1.031)	0.069
Lag0-2	1.051 (0.980, 1.126)	0.162	1.018 (1.001, 1.036)	0.033*	1.043 (0.972, 1.119)	0.247	1.017 (1.000, 1.035)	0.048*
Lag0-3	1.049 (0.970, 1.134)	0.231	1.019 (1.000, 1.037)	0.048*	1.041 (0.962, 1.127)	0.317	1.017 (0.999, 1.036)	0.063
Lag0-4	1.047 (0.963, 1.138)	0.279	1.018 (0.999, 1.038)	0.063	1.040 (0.955, 1.131)	0.366	1.018 (0.998, 1.037)	0.079
Lag0-5	1.054 (0.964, 1.152)	0.246	1.019 (0.998, 1.039)	0.076	1.047 (0.956, 1.146)	0.321	1.017 (0.997, 1.038)	0.095
Lag0-6	1.053 (0.957, 1.158)	0.288	1.019 (0.997, 1.041)	0.086	1.045 (0.948, 1.140)	0.376	1.018 (0.996, 1.040)	0.107
Lag0-7	1.055 (0.956, 1.165)	0.287	1.018 (0.996, 1.041)	0.113	1.047 (0.946, 1.158)	0.372	1.017 (0.994, 1.040)	0.141

Note: Adjusted for age, gender, ethnicity, family history of asthma or respiratory diseases, type of insurance, use of medication, experience of asthma education, season, admission day, and temperature. * $p<0.05$

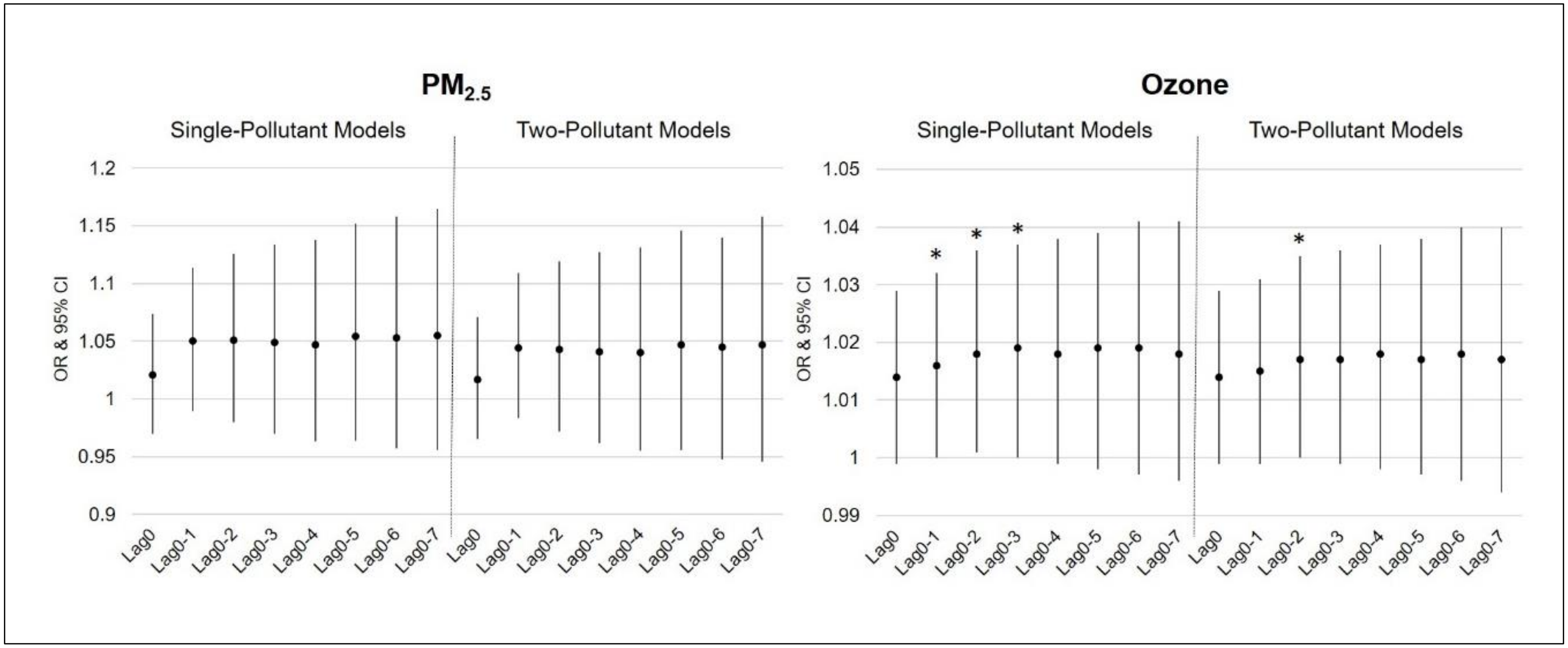

Figure 2.1 Lag Structures of the Odds Ratio (OR) and 95% Confidence Interval (CI) of $PM_{2.5}$ and Ozone with Hospital Length of Stay in Single- and Two-Pollutant Models. Note: OR—odds ratio; 95% CI—95% confidence interval; * p<0.05.

Table 2.4 presents the results of multivariate binomial logistic regression analysis to examine the associations between air pollution and hospital LOS stratified by age. In the group of children aged 5–11 years old, the elevated $PM_{2.5}$ concentration level was significantly associated with longer LOS on Lag0–1 in the single-pollutant (p=0.022) and two-pollutant (p=0.035) models. However, the ozone concentration level did not show significant associations with hospital LOS. Additionally, in the group of children aged 12–18 years old, none of the associations were found to be statistically significant in either the single- or two-pollutant models.

Table 2.4 Results of Multivariate Binomial Logistic Regression Analysis Stratified by Age in Single- and Two-Pollutant Models

Single-pollutant models								
Lag days	5-11 years old				12-18 years old			
	$PM_{2.5}$		Ozone		$PM_{2.5}$		Ozone	
	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value
Lag0	1.052 (0.992, 1.116)	0.092	1.015 (0.998, 1.033)	0.091	0.926 (0.821, 1.046)	0.262	1.012 (0.983, 1.042)	0.422
Lag0-1	1.086 (1.012, 1.165)	0.022*	1.017 (0.998, 1.036)	0.081	0.941 (0.822, 1.076)	0.373	1.014 (0.982, 1.047)	0.403
Lag0-2	1.077 (0.993, 1.167)	0.074	1.019 (0.999, 1.040)	0.063	0.958 (0.821, 1.118)	0.590	1.013 (0.979, 1.048)	0.467
Lag0-3	1.077 (0.984, 1.179)	0.107	1.020 (0.998, 1.043)	0.072	0.930 (0.780, 1.109)	0.422	1.008 (0.972, 1.045)	0.672
Lag0-4	1.079 (0.979, 1.189)	0.124	1.019 (0.996, 1.044)	0.096	0.922 (0.769, 1.104)	0.375	1.008 (0.970, 1.048)	0.670
Lag0-5	1.089 (0.982, 1.209)	0.107	1.018 (0.994, 1.044)	0.148	0.929 (0.771, 1.121)	0.443	1.015 (0.975, 1.056)	0.474
Lag0-6	1.109 (0.975, 1.219)	0.129	1.019 (0.993, 1.046)	0.159	0.922 (0.756, 1.126)	0.426	1.015 (0.973, 1.058)	0.485
Lag0-7	1.095 (0.974, 1.231)	0.127	1.018 (0.991, 1.047)	0.193	0.928 (0.757, 1.138)	0.475	1.014 (0.971, 1.059)	0.525
Two-pollutant models								
Lag days	5-11 years old				12-18 years old			
	$PM_{2.5}$		Ozone		$PM_{2.5}$		Ozone	
	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value
Lag0	1.047 (0.986, 1.112)	0.134	1.014 (0.996, 1.032)	0.131	0.922 (0.816, 1.042)	0.194	1.014 (0.984, 1.045)	0.363
Lag0-1	1.080 (1.005, 1.160)	0.035*	1.015 (0.996, 1.034)	0.134	0.935 (0.816, 1.071)	0.332	1.016 (0.983, 1.050)	0.354
Lag0-2	1.069 (0.984, 1.160)	0.114	1.017 (0.997, 1.038)	0.096	0.951 (0.814, 1.112)	0.530	1.014 (0.979, 1.050)	0.425
Lag0-3	1.069 (0.975, 1.172)	0.154	1.018 (0.996, 1.041)	0.103	0.928 (0.778, 1.107)	0.408	1.009 (0.972, 1.047)	0.636
Lag0-4	1.071 (0.971, 1.182)	0.171	1.018 (0.995, 1.042)	0.132	0.919 (0.768, 1.102)	0.364	1.010 (0.970, 1.050)	0.637
Lag0-5	1.083 (0.974, 1.204)	0.140	1.016 (0.992, 1.042)	0.197	0.924 (0.765, 1.116)	0.410	1.016 (0.976, 1.059)	0.435
Lag0-6	1.083 (0.967, 1.214)	0.165	1.017 (0.991, 1.044)	0.165	0.912 (0.745, 1.117)	0.374	1.018 (0.975, 1.063)	0.418
Lag0-7	1.090 (0.968, 1.227)	0.153	1.017 (0.989, 1.045)	0.237	0.914 (0.741, 1.127)	0.400	1.018 (0.973, 1.065)	0.433

Note: Adjusted for gender, ethnicity, family history of asthma or respiratory diseases, type of insurance, use of medication, experience of asthma education, season, admission day, and temperature. * $p<0.05$

Table 2.5 demonstrates the results of regression analysis stratified by gender in single- and two-pollutant models, while controlling for several confounders. For females, we did not find significant relationships, although we observed all of the adjusted ORs were positive. Additionally, no significant associations in single- and two-pollutant models were found among males.

Table 2.6 describes the results of season-stratified regression models adjusting for several covariates. During the warm season, ozone concentration level was observed to be significantly associated with prolonged LOS, especially from Lag0–2 to Lag0–7 in the single-pollutant models ($p<0.05$ or $p<0.01$). Additionally, the positive relationships between ozone and LOS were consistently significant from Lag0–2 to Lag0–5 in the two-pollutant model ($p<0.05$). Yet, the $PM_{2.5}$ concentration level did not show a significant effect on hospital LOS. Ozone concentration had a significant effect on increased hospital LOS only on Lag0 during the cold season in both single- and two-pollutants models ($p<0.05$). However, there were no significant associations for $PM_{2.5}$ concentration in the cold season.

Table 2.5 Results of Multivariate Binomial Logistic Regression Analysis Stratified by Gender in Single- and Two-Pollutant Models

Lag days	Female				Male			
	Single-pollutant models							
	$PM_{2.5}$		Ozone		$PM_{2.5}$		Ozone	
	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value
Lag0	1.023 (0.944, 1.108)	0.579	1.015 (0.991, 1.038)	0.221	1.021 (0.953, 1.093)	0.557	1.011 (0.992, 1.032)	0.231
Lag0-1	1.076 (0.979, 1.183)	0.130	1.016 (0.991, 1.042)	0.218	1.044 (0.963, 1.132)	0.298	1.015 (0.994, 1.036)	0.168
Lag0-2	1.096 (0.984, 1.221)	0.096	1.020 (0.993, 1.047)	0.141	1.031 (0.937, 1.135)	0.534	1.017 (0.994, 1.041)	0.142
Lag0-3	1.085 (0.961, 1.223)	0.187	1.023 (0.994, 1.052)	0.118	1.034 (0.928, 1.151)	0.546	1.015 (0.990, 1.041)	0.241
Lag0-4	1.093 (0.958, 1.247)	0.184	1.027 (0.996, 1.058)	0.085	1.022 (0.914, 1.143)	0.701	1.012 (0.986, 1.039)	0.367
Lag0-5	1.131 (0.985, 1.299)	0.080	1.030 (0.998, 1.064)	0.067	1.006 (0.890, 1.136)	0.928	1.010 (0.983, 1.038)	0.474
Lag0-6	1.135 (0.983, 1.309)	0.083	1.033 (0.999, 1.069)	0.060	0.995 (0.872, 1.135)	0.940	1.009 (0.981, 1.038)	0.533
Lag0-7	1.106 (0.955, 1.282)	0.180	1.030 (0.994, 1.067)	0.097	1.017 (0.886, 1.167)	0.813	1.010 (0.980, 1.041)	0.517
	Two-pollutants models							
Lag days	Female				Male			
	$PM_{2.5}$		Ozone		$PM_{2.5}$		Ozone	
	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value
Lag0	1.017 (0.938, 1.103)	0.680	1.039 (0.991, 1.038)	0.224	1.018 (0.949, 1.091)	0.616	1.011 (0.992, 1.032)	0.247
Lag0-1	1.066 (0.968, 1.175)	0.193	1.013 (0.987, 1.039)	0.335	1.042 (0.960, 1.131)	0.326	1.014 (0.993, 1.036)	0.182
Lag0-2	1.083 (0.969, 1.210)	0.160	1.016 (0.989, 1.044)	0.240	1.026 (0.932, 1.131)	0.596	1.017 (0.994, 1.040)	0.153
Lag0-3	1.067 (0.942, 1.208)	0.308	1.019 (0.991, 1.049)	0.187	1.032 (0.926, 1.149)	0.572	1.015 (0.989, 1.040)	0.249
Lag0-4	1.071 (0.933, 1.228)	0.331	1.023 (0.992, 1.055)	0.143	1.021 (0.912, 1.143)	0.716	1.012 (0.986, 1.039)	0.372
Lag0-5	1.107 (0.958, 1.278)	0.168	1.025 (0.992, 1.058)	0.140	1.005 (0.889, 1.136)	0.937	1.010 (0.983, 1.038)	0.475
Lag0-6	1.109 (0.955, 1.287)	0.176	1.027 (0.993, 1.064)	0.124	0.994 (0.870, 1.135)	0.928	1.009 (0.981, 1.039)	0.532
Lag0-7	1.082 (0.927, 1.262)	0.317	1.026 (0.989, 1.063)	0.164	1.016 (0.884, 1.166)	0.828	1.010 (0.980, 1.040)	0.521

Note: Adjusted for age, ethnicity, family history of asthma or respiratory diseases, type of insurance, use of medication, experience of asthma education, season, admission day, and temperature.

Table 2.6 Results of Multivariate Binomial Logistic Regression Analysis Stratified by Season in Single- and Two-Pollutant Models

Single-pollutant models								
Lag days	**Warm season**				**Cold season**			
	$PM_{2.5}$		**Ozone**		**$PM_{2.5}$**		**Ozone**	
	OR (95% CI)	**p-value**	**OR (95% CI)**	**p-value**	**OR (95% CI)**	**p-value**	**OR (95% CI)**	**p-value**
Lag0	1.025 (0.947, 1.109)	0.544	1.014 (0.993, 1.036)	0.198	1.022 (0.954, 1.095)	0.538	1.027 (1.003, 1.053)	0.028*
Lag0-1	1.046 (0.961, 1.139)	0.298	1.021 (0.999, 1.044)	0.058	1.063 (0.973, 1.161)	0.178	1.022 (0.995, 1.051)	0.115
Lag0-2	1.070 (0.972, 1.178)	0.167	1.027 (1.004, 1.051)	0.020*	1.035 (0.932, 1.150)	0.520	1.021 (0.990, 1.053)	0.180
Lag0-3	1.094 (0.984, 1.216)	0.097*	1.032 (1.007, 1.057)	0.012*	1.001 (0.887, 1.130)	0.983	1.018 (0.984, 1.053)	0.309
Lag0-4	1.105 (0.987, 1.237)	0.083*	1.036 (1.009, 1.063)	0.009**	0.983 (0.863, 1.120)	0.798	1.015 (0.979, 1.053)	0.421
Lag0-5	1.122 (0.996, 1.265)	0.058*	1.036 (1.008, 1.066)	0.012*	0.977 (0.847, 1.127)	0.750	1.017 (0.978, 1.058)	0.397
Lag0-6	1.121 (0.989, 1.269)	0.073*	1.037 (1.006, 1.069)	0.018*	0.977 (0.835, 1.142)	0.770	1.021 (0.979, 1.064)	0.337
Lag0-7	1.131 (0.995, 1.286)	0.059*	1.035 (1.003, 1.068)	0.030*	0.959 (0.812, 1.132)	0.621	1.025 (0.980, 1.072)	0.283
Two-pollutants models								
Lag days	**Warm season**				**Cold season**			
	$PM_{2.5}$		**Ozone**		**$PM_{2.5}$**		**Ozone**	
	OR (95% CI)	**p-value**	**OR (95% CI)**	**p-value**	**OR (95% CI)**	**p-value**	**OR (95% CI)**	**p-value**
Lag0	1.009 (0.927, 1.099)	0.830	1.013 (0.991, 1.036)	0.251	1.034 (0.964, 1.109)	0.344	1.029 (1.004, 1.055)	0.021*
Lag0-1	1.023 (0.933, 1.121)	0.633	1.019 (0.996, 1.043)	0.100	1.076 (0.983, 1.178)	0.111	1.026 (0.997, 1.055)	0.075
Lag0-2	1.038 (0.935, 1.152)	0.484	1.024 (1.000, 1.049)	0.047*	1.043 (0.938, 1.160)	0.432	1.022 (0.991, 1.055)	0.158
Lag0-3	1.058 (0.942, 1.187)	0.343	1.028 (1.002, 1.054)	0.036*	1.009 (0.893, 1.141)	0.877	1.018 (0.984, 1.054)	0.304
Lag0-4	1.066 (0.942, 1.205)	0.310	1.031 (1.003, 1.059)	0.028*	0.989 (0.868, 1.129)	0.878	1.015 (0.978, 1.053)	0.436
Lag0-5	1.083 (0.951, 1.232)	0.229	1.030 (1.001, 1.061)	0.043*	0.985 (0.853, 1.139)	0.843	1.016 (0.977, 1.057)	0.419
Lag0-6	1.081 (0.945, 1.238)	0.253	1.031 (0.999, 1.063)	0.057	0.987 (0.843, 1.157)	0.876	1.020 (0.978, 1.064)	0.354
Lag0-7	1.096 (0.954, 1.257)	0.194	1.028 (0.995, 1.062)	0.096	0.973 (0.822, 1.152)	0.751	1.023 (0.978, 1.071)	0.316

Note: Adjusted for age, gender, ethnicity, family history of asthma or respiratory diseases, type of insurance, use of medication, experience of asthma education, admission day, and temperature. * $p<0.05$, ** $p<0.01$

2.4. Discussion

In this study, we examined the association between short-term exposure to outdoor air pollution and hospital LOS among children with asthma in South Texas. We found that increased ozone concentration prior to hospital admission was significantly associated with prolonged hospital LOS for pediatric patients with asthma in both single- and two-pollutant models. This result may be explained by the fact that exposure to ozone can adversely affect the respiratory system, including coughing, chest tightness or pain, throat irritation, and airway inflammation, especially exacerbating asthma conditions [33]. The result also supports previous research for pediatric patients with other respiratory diseases, such as pneumonia or ALRI, in different settings. For example, a study showed that high levels of ozone concentration before hospitalization were related to increased LOS among children aged 0–5 years old with ALRI in Hanoi, Vietnam [21]. The other study revealed that ozone had significantly positive effects on LOS in pneumonia hospitalizations among U.S. children less than 18 years of age [34].

Further, age-stratified analysis showed that association between ambient air pollution and LOS may differ with age. The current study found that elevated $PM_{2.5}$ concentration was significantly related with prolonged LOS among younger children aged 5–11 years old. However, the same associations were not significant, among older children aged 12–18 years old, although they were positive. The finding of this study is consistent with research reporting that $PM_{2.5}$ was positively associated with LOS among U.S. children with pneumonia [34]. Other studies have also reported on the positive effects of PM_{10} on LOS among Chinese adults with asthma [4] and Vietnamese children aged 2–5 years with ALRI [21], although $PM_{2.5}$ was not significantly associated with LOS. This study confirms that outdoor air pollutants are significantly associated with hospital LOS for at least some pediatric asthma patients in South Texas.

Conversely, the models stratified by gender demonstrated that ambient air pollutants ($PM_{2.5}$ and ozone) did not show a significant effect on hospital LOS among girls and boys in the single- and two-pollutant models. This study therefore did not observe gender as a modifying factor in the effect of outdoor air pollution on LOS among children with asthma. This finding is contrary to a study that found the positive effect of ambient air pollutants, especially $PM_{2.5}$ concentration, on LOS among females aged 15 years or older in China [4]. Since very few studies examined the impact of gender on the association between outdoor air pollution and hospital LOS, more evidence is still needed to assess the gender differences in the relationship for pediatric patients with respiratory diseases like asthma.

Season-stratified models revealed a positive correlation of $PM_{2.5}$ and ozone concentration levels on hospital LOS during the warm season and cold season generally, but significant associations were observed only for ozone. Our findings are consistent with a previous study indicating significantly positive associations of particulate matters, including $PM_{2.5}$ and PM_{10}, among adults with asthma on LOS during the cold season and warm season [4]. The current study's results are also in line with those of previous studies that reported on the effects of season on the relationship between outdoor air pollution and hospitalization outcomes for pediatric asthma. For example, most studies found that ozone concentrations had significantly positive effects on asthma hospitalizations or ED visits in the warm season [35–38]. Additionally, some studies presented that asthma hospital visits peak in the fall season, especially for school-aged children, despite ozone level peaking in the summer season. The explanation has been speculated to be that students transmit respiratory viruses and bacteria to their peers during the school year, causing an asthma attack [39–41].

However, in contrast to our findings of no significant relationship for $PM_{2.5}$, some evidence reported significant association between $PM_{2.5}$ and asthma hospital admission (or ED visits) in the warm season [42,43]. Although our results indicate that season might be a modifying factor for the relationship between outdoor air pollution and LOS among people with asthma, additional studies need to be undertaken to confirm the modifying effect of season.

2.4.1. Limitations

There are some limitations to this study. First, we used the estimates of the modeled predictions of ambient air pollution data by the Downscaler approach. Although this approach covered all areas in the census tract level, including regions with no air monitors, it may not accurately reflect the exact air conditions of participants' residence and personal exposure, particularly in regions with limited monitoring data [44]. Additionally, temperature data collected from a few monitoring sites may not reflect actual temperature due to variations in distances to the nearest monitoring site. As a result, this may lead to measurement error. Second, we included only two air pollutants (PM2.5 and ozone) in this study due to limited availability of data. Future study should include other air pollutants, such as PM10, NO2, and SO2, in order to have a better understanding of their relationships with hospital LOS.

Third, some patient-level factors, such as severity and type of comorbidities (e.g., obesity) [6,9,45], could affect individuals' hospital LOS, but these factors were unavailable in the hospital database. Future study should consider these factors to control for their effects on the relationship between ambient air pollution and LOS. Fourth, hospital LOS may not always be an accurate outcome measure due to patients' situations. Particularly in this low-income population, the point at which a patient is ready for discharge sometimes differs from the actual length of stay. Additionally, there are various definitions to operationalize the concept of increased LOS; a gold standard does not exist [46,47]. Yet, previous studies have used hospital LOS that is greater than the mean or median values as prolonged LOS [7,21,48,49]. Lastly, this study was conducted in a single hospital located in South Texas so that generalizability of results to other settings in different regions may be limited.

2.4.2. Public Health and Policy Implications

The findings of this study have important public health and policy implications. First of all, this study suggests that the importance of outdoor air pollution on asthma control and management should be emphasized in asthma education, particularly for parents and guardians of pediatric patients. Given that asthma education is an effective way to improve knowledge for asthma management and health outcomes of children with asthma [28,50,51], it would be important to supplement and highlight educational contents on outdoor air pollution in the curriculum, such as the different types of ambient air pollutants, their impacts on health outcomes, and practical ways to minimize exposure to harmful outdoor air pollutants. Particularly, the current asthma education contents at Driscoll Children’s Hospital focus on indoor air pollutants and have limited information about outdoor air pollution. Thus, the contents about ambient air pollution need to be included in the asthma education at the hospital. This study also suggests that healthcare professionals, who are in charge of asthma education, actively communicate with children with asthma and their family how to check daily outdoor air pollution levels and explain the importance of limiting outdoor activities on days when air pollutant levels are high.

In addition, this study will help hospital leaders and pediatricians who serve children with asthma gain a better understanding on how ambient air pollution could be an important indicator for identifying pediatric patients with asthma who have a risk for longer LOS. This may also help inform more effective healthcare resource allocation and utilization, focusing on care for children from regions with high levels of air pollution, in order to decrease hospital LOS. Furthermore, our results may help school leaders understand the effects of outdoor air pollutants on health outcomes of children, especially those with asthma, and consider the outdoor air quality when planning for outdoor activities or school events. Finally, the findings of this study offer important evidence to policymakers who support policies related to ambient air pollution control.

2.5. Conclusions

This study found the adverse effects of outdoor air pollutants, including $PM_{2.5}$ and ozone concentrations, on hospital LOS for pediatric asthma in South Texas, especially in low-income communities. Our results showed that age and season might be modifying factors on the relationship between ambient air pollution and LOS. These findings may help health professionals and policymakers consider the importance of ambient air pollution on health outcomes and hospital LOS among pediatric patients with asthma during education sessions, medical care practice, and policy formulation, emphasizing preventive measures that need to be included in educational programs targeted for children.

2.6. References

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3. EFFECT OF AMBIENT AIR POLLUTION ON HOSPITAL READMISSIONS AMONG PEDIATRIC ASTHMA PATIENT POPULATION IN SOUTH TEXAS: A CASE-CROSSOVER STUDY

3.1. Introduction

Hospital readmission is an important asthma-related health outcomes to consider since repeated hospitalizations could lead to a large burden on patients/caregivers, hospitals, and the government with regard to healthcare resources, cost and quality [1,2]. In addition, a study found that children who are rehospitalized for asthma might differ in disease severity, access to care, or environmental exposures when compared with those who were hospitalized only once [3]. However, asthma readmissions can be potentially prevented with appropriate and timely primary care given that asthma is regarded as one of the ambulatory care-sensitive conditions [4–6]. As such, reducing preventable hospital readmissions is a key priority in order to decrease healthcare costs and improve quality of care and patient experience [7].

Exposure to air pollution has been regarded as a significant trigger for asthma exacerbation that may lead to repeated hospitalizations. Studies have classified air pollution into two types: indoor and outdoor. With regard to indoor air pollution, common air pollutants include moisture, smoking, dust, and chemicals; these can all serve as asthma triggers in children. Several studies found that exposure to indoor environmental conditions, such as dust mites and indoor mold, was a significant factor for pediatric asthma exacerbations in the school setting [8,9].

Further, two studies specifically examined the relationship between indoor air quality and hospital readmissions for children with asthma. One study showed that exposure to tobacco in the indoor setting, such as detectable serum or salivary cotinine collected by biomarkers, was revealed to be significantly associated with increased risk of hospital readmission [10]. The second study found that detection of poor air quality, such as higher levels of fungi and yeast, in a child's bedroom increased the risk of hospital readmission [11]. The study also reported that having a carpeted floor in the bedroom as well as a high frequency of vacuuming at home were both significantly related with increased chance of rehospitalization for children with asthma [11].

In the case of outdoor air pollution, this subject has been studied and considered as a significant factor leading to hospital readmission among children with asthma. Previous studies have shown that exposure to traffic-related air pollution (TRAP) was associated with adverse respiratory health effects in children, including exacerbation of asthma symptoms [12,13]. Other studies have also examined the relationship between TRAP exposure and hospital readmission for children with asthma or bronchodilator-responsive wheezing. For instance, one study found that higher TRAP exposure was significantly associated with greater risk of readmission in the unadjusted model, but this relationship was not significant in the adjusted model [14]. Another study reported that the local traffic-generated air pollution, including traffic-related nitrogen oxide (NO_x) and carbon monoxide (CO), were significantly related to repeated hospitalizations for asthma among children, indicating that TRAP in close proximity to the children's homes could increase the severity of asthma symptoms [15].

In addition, two studies investigated the relationship between residential proximity to major roads and hospitalizations among children with asthma. One study found that children with asthma living in closer proximity to a major roadway was associated with a greater number of wheezing with medication requirements and more hospitalizations even after controlling for several confounders. That is, the closer a child's home is to a major roadway, the poorer the asthma control of the child [16]. The other study stated that children living within 300 meters from major roads were more likely to be repeatedly hospitalized for asthma [17]. In particular, the relationships between readmissions and residence close to heavy traffic roads were stronger among girls than boys, as well as among children with no insurance or with government insurance than those with private insurance [17].

However, there is a paucity of studies that evaluate the impacts of short-term exposure to specific ambient air pollutants other than TRAP on preventable hospital readmissions among pediatric asthma patients. This lack of understanding is especially true for relatively low-income communities. To address this gap in literature, this study examined the effects of ambient air pollutants, including $PM_{2.5}$ and ozone concentrations, on the risk of preventable hospital readmission for pediatric asthma patients in South Texas.

3.2. Materials and Methods

3.2.1. Data Sources and Study Setting

Hospitalization data for pediatric asthma between January 1, 2010 and December 31, 2014 were collected from Driscoll Children's Hospital database. The hospital, which focuses on pediatric care, is located in the city of Corpus Christi, and has 189 beds serving the children of South Texas. The information recorded on the data included basic demographics (gender, age, ethnicity), type of insurance, dates of admission and discharge, the International Classification of Diseases 9th Revision (ICD-9) diagnosis code, and census tract information of each patient's residence. The inclusion criteria of the study participants were children aged 5 to 18 years old and those who were readmitted to the hospital due to asthma as a primary diagnosis (ICD-9, 493) during the study period. The subsequent admissions after index hospitalization for each patient were included as readmission cases in this study. This study protocol was reviewed and approved by the Institutional Review Boards of the Texas A&M University and Driscoll Children's Hospital.

Data on ambient air pollutants during the study period was gathered from the Centers for Disease Control and Prevention (CDC) environmental public health tracking network [18]. The daily average predicted atmospheric particulate matter 2.5 (or $PM_{2.5}$) and ozone concentrations in the census tract level were estimated from the Downscaler model of the U.S. Environmental Protection Agency (EPA) [19]. The data used in this study was the average daily air pollution concentration, including $PM_{2.5}$ and ozone, given the data availability. The data for $PM_{2.5}$ and ozone indicate the mean estimated 24-hour average concentration ($\mu g/m^3$) and the mean estimated 8-hour average concentration within three meters of the surface of the earth (parts per billion [ppb]), respectively [20]. The meteorological data of daily mean temperatures was collected from the Texas Commission on Environmental Quality (TCEQ) in order to adjust for the impact of temperature on the association between ambient air pollution and pediatric asthma rehospitalization. The geographic information system (GIS) program (ArcMap 10.4, ESRI, Redlands, CA) was used to obtain the temperature data measured in the nearest air monitoring station from each patient's residence.

3.2.2. Study Design and Measurement

A time-stratified case-crossover study design was applied to evaluate the short-term effects of ambient air pollution on hospital readmission for children with asthma. In this study, air pollution data for each patient was collected for the case period, which indicates the week of the readmission date, and three control periods, which refer to the week before, the week after, and two weeks after the readmission date. Namely, each of two air pollutant concentrations ($PM_{2.5}$ and ozone) was collected from readmission day (Lag0) to three days before readmission (Lag1 - Lag3) in the week of hospital readmission for the case period and the corresponding days (4 days: Lag0 - Lag3) in each of the three weeks for control periods.

To assess the relationships between ambient air pollutants and hospital readmission, we fit the models with different lag structures between the readmission day (Lag0) and three single-lag days (Lag1 - Lag3). We also evaluated the associations with cumulative-day lags, indicating 2-day (Lag0-1), 3-day (Lag0-2), and 4-day (Lag0-3) moving averages of $PM_{2.5}$ and ozone concentrations since single-day lag models might underestimate the relationships [21]. For example, Lag0-2 would refer to the averaged values of each air pollutant in a total of 3 days from Lag0 to Lag2 for the case period and control periods. The air pollution exposure during the case period was compared with that of the control periods for each participant.

In addition to single-pollutant models, two-pollutant models were conducted to investigate the effect of each air pollutant on hospital readmission, controlling for the other air pollutant. Potential confounders such as individual-level characteristics were controlled by the study design since case and control periods are compared for the same patient [22]. However, temperature information was included as a time-varying factor in the analysis.

3.2.3. Statistical Analysis

Demographic characteristics of the study population were calculated to estimate the mean and standard deviation (SD) for continuous variables and percentages for categorical variables. Pearson correlation tests were performed to assess if ambient air pollutants ($PM_{2.5}$ and ozone) and temperature are highly correlated. Conditional logistic regression analysis was conducted to examine associations between ambient air pollution and the odds of a hospital readmission for pediatric asthma. We controlled temperature for the same periods as air pollution in all of the models. The results are presented as adjusted odds ratios (ORs) and 95% confidence intervals (CIs). Stratified analyses by age (5-11 years old or 12-18 years old), gender (girls or boys) and season (warm: May-October or cold: November-April) were used to assess effects as a modifier. All analyses were conducted by using the Stata 14 version (StataCorp LLC, College Station, TX). All statistical tests were two-sided, and a p-value < 0.05 was considered to be statistically significant.

3.3. Results

A total of 111 patients were readmitted to the children's hospital due to asthma during 2010-2014 (Table 3.1). The average age was about 9 years old and the number of males was higher than females (57.6 vs. 42.3%). Most of patients readmitted to the hospital were Hispanic (79.3%) and about 70% had public insurance (Medicaid). The average time to readmission was about 386 days, and only 8.1% of patients had 30-day readmission and about 37% were readmitted to the hospital in 1 year or longer. The readmissions in the cold season were a little higher than those in the warm season (52.3% vs. 47.7%).

Table 3.1 Descriptive Characteristics of Asthma Pediatric Patients Readmitted to the Hospital during 2010-2014 (N=111)

Variable	Mean ± SD [Min, Max] or N (%)
Age (years)	9.54 ± 3.34 [5, 18]
Age	
5-11 years old	88 (79.3)
12-18 years old	23 (20.7)
Gender	
Female	47 (42.3)
Male	64 (57.6)
Ethnicity	
Hispanic	88 (79.3)
Non-Hispanic	23 (20.7)
Type of insurance	
Public (Medicaid)	78 (70.3)
Private	29 (26.1)
Self-pay	4 (3.6)
Days to readmission (days)	386.5 ± 364.24 [1, 1651]
1 – 30 days	9 (8.1)
31 – 90 days	12 (10.8)
91 – 180 days	19 (17.1)
181 - 365 days	30 (27.1)
366 days or longer	41 (36.9)
Season	
Warm (May – October)	53 (47.7)
Cold (November – April)	58 (52.3)
Year	
2010	13 (11.7)
2011	22 (19.8)
2012	18 (16.2)
2013	26 (23.4)
2014	32 (28.8)

Note: SD – standard deviation

Table 3.2 displays summary statistics of daily ambient air pollutant concentrations and daily temperature in South Texas during 2010-2014. The overall mean of $PM_{2.5}$ and ozone concentrations were 8.3 ($\mu g/m^3$) and 37.37 (ppb) respectively.

The overall average temperature in the study region was 20.2℃ and its range was between 8.83 and 29.73℃. The results of the Pearson correlation tests showed that ambient air pollutant and temperature were not highly correlated with each other (correlation coefficient r= -0.214 to 0.077, p<0.05) (APPENDIX B).

Table 3.2 Summary Statistics of Daily Ambient Air Pollutant Concentrations and Daily Temperature in South Texas during 2010-2014

	Mean	SD	Min	Percentile			Max	IQR
				25	50	75		
$PM_{2.5}$ (μg/m^3)	8.30	1.49	4.66	7.19	8.25	9.19	12.37	2.0
Ozone (ppb)	37.37	6.81	20.53	31.47	37.24	42.11	52.84	10.64
Temperature (℃)	20.20	5.85	8.83	16.31	21.01	26.91	29.73	10.6

Note: SD: Standard Deviation; IQR: Interquartile ranges

Table 3.3 describes the results of conditional logistic regression models to examine the association between ambient air pollution and preventable hospital readmission. We found that the elevated $PM_{2.5}$ concentration was significantly associated with an increased risk of preventable hospital readmission on Lag1 in both single-pollutant (OR=1.082, 95% CI=1.008-1.162, p=0.030) and two-pollutant models (OR=1.080, 95% CI=1.005-1.161, p=0.036), controlling for temperature. Also, we observed a significant positive association of preventable hospital readmission with ozone concentration on Lag0 in the two-pollutant model (OR=1.023, 95% CI=1.001-1.045, p=0.042). However, none of the ambient air pollutants were significant on cumulative-day lags (Lag0-1 ~ Lag0-3) in single- and two-pollutant models. Figure 3.1 illustrates the lag structures of ORs and 95% CIs of $PM_{2.5}$ and ozone concentrations with hospital readmissions for children with asthma in single- and two-pollutant models on single- and multiple-day lags.

Table 3.3 Results of Conditional Logistic Regression Models between Ambient Air Pollution and Hospital Readmissions

Single- and cumulative-day lags	Single-Pollutant model				Two-Pollutant model			
	$PM_{2.5}$		Ozone		$PM_{2.5}$		Ozone	
	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value
Lag0	0.972 (0.897-1.052)	0.479	1.020 (0.999-1.041)	0.064	0.954 (0.878-1.037)	0.272	1.023 (1.001-1.045)	0.042*
Lag1	1.082 (1.008-1.162)	0.030*	1.008 (0.987-1.028)	0.469	1.080 (1.005-1.161)	0.036*	1.005 (0.984-1.025)	0.665
Lag2	0.984 (0.914-1.059)	0.664	1.001 (0.979-1.022)	0.955	0.983 (0.912-1.059)	0.655	1.001 (0.980-1.023)	0.904
Lag3	0.985 (0.914-1.063)	0.700	1.007 (0.988-1.027)	0.472	0.980 (0.907-1.059)	0.613	1.008 (0.988-1.028)	0.429
Lag0-1	1.046 (0.954-1.147)	0.334	1.016 (0.993-1.039)	0.168	1.036 (0.942-1.138)	0.468	1.014 (0.992-1.037)	0.222
Lag0-2	1.032 (0.929-1.145)	0.558	1.013 (0.989-1.038)	0.292	1.023 (0.921-1.138)	0.667	1.012 (0.988-1.037)	0.667
Lag0-3	1.017 (0.907-1.140)	0.779	1.015 (0.988-1.042)	0.275	1.006 (0.896-1.131)	0.915	1.015 (0.988-1.042)	0.290

Note: Models adjusted for temperature; * $p<0.05$

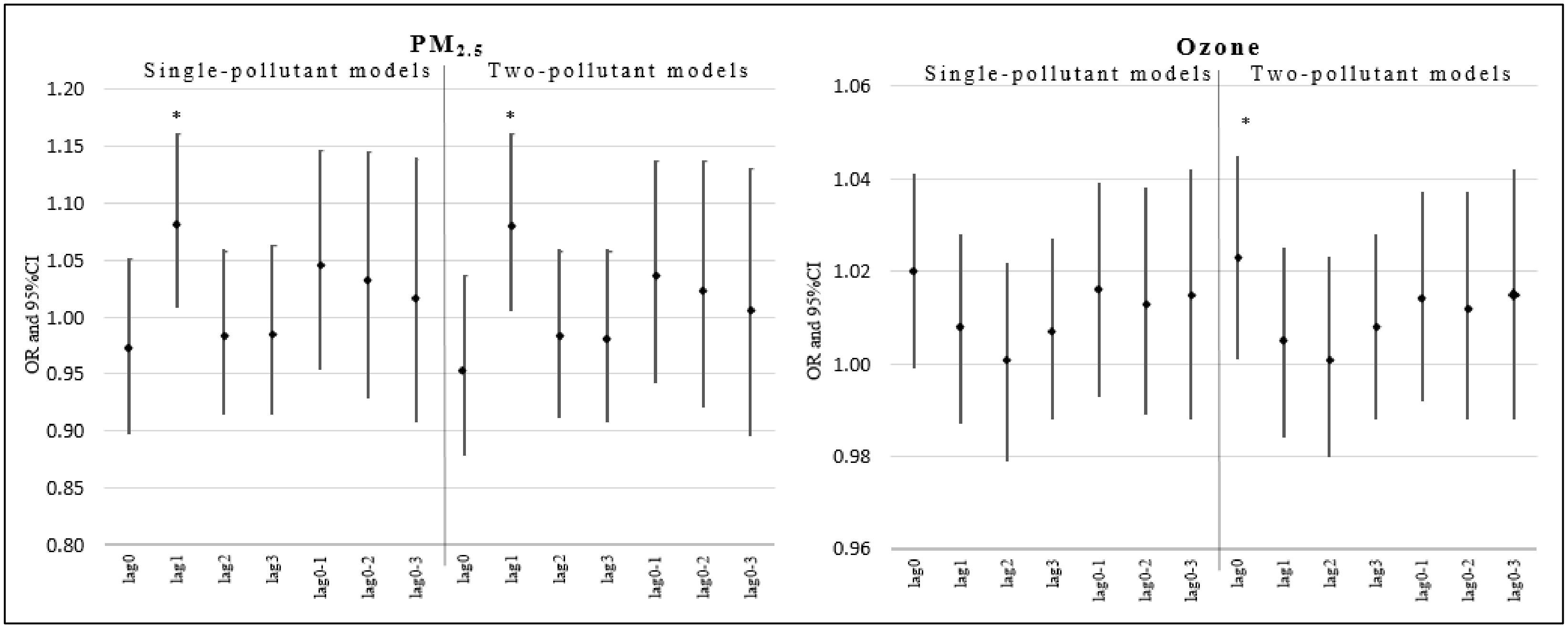

Figure 3.1 Odds Ratio (OR) and 95% Confidence Interval (CI) of $PM_{2.5}$ and Ozone with Hospital Readmissions for Children with Asthma in Single- and Two-Pollutant Models (*$p<0.05$)

Table 3.4 demonstrates the results of conditional logistic regression models stratified by age. We found that the association between ozone concentration and risk of preventable readmission was significantly positive on Lag0 in the two-pollutant model among children aged 5-11 years, adjusting for temperature (OR=1.029, 95% CI=1.004-1.055, p=0.022). Yet, none of the associations for $PM_{2.5}$ concentration were significant. On the other hand, there was no significant relationship of ambient air pollutants with preventable hospital readmission among those aged 12-18 years old. The results of conditional logistic regression models stratified by gender shown in Table 3.5 indicates that associations between ambient air pollutants and pediatric asthma rehospitalization were not significant among males and females.

Table 3.4 Results of Conditional Logistic Regression Models Stratified by Age

Single- and cumulative-day lags	5-11 years old				12-18 years old			
	Single-Pollutant		Two-Pollutant		Single-Pollutant		Two-Pollutant	
	$PM_{2.5}$	Ozone	$PM_{2.5}$	Ozone	$PM_{2.5}$	Ozone	$PM_{2.5}$	Ozone
Lag0	0.934 (0.850-1.026)	1.022 (0.999-1.047)	0.908 (0.821-1.004)	1.029* (1.004-1.055)	1.123 (0.942-1.337)	1.009 (0.964-1.057)	1.122 (0.942-1.336)	1.008 (0.965-1.054)
Lag1	1.075 (0.994-1.162)	1.009 (0.986-1.033)	1.071 (0.990-1.159)	1.006 (0.982-1.030)	1.112 (0.924-1.338)	1.001 (0.959-1.046)	1.113 (0.924-1.339)	1.002 (0.960-1.045)
Lag2	0.962 (0.881-1.050)	1.003 (0.980-1.027)	0.959 (0.878-1.048)	1.005 (0.981-1.029)	1.045 (0.908-1.204)	0.983 (0.933-1.034)	1.062 (0.917-1.230)	0.978 (0.927-1.031)
Lag3	0.983 (0.905-1.067)	1.004 (0.982-1.026)	0.980 (0.902-1.066)	1.005 (0.983-1.027)	0.969 (0.795-1.182)	1.016 (0.968-1.067)	0.953 (0.779-1.166)	1.019 (0.969-1.071)
Lag0-1	1.017 (0.917-1.127)	1.018 (0.993-1.044)	1.000 (0.899-1.112)	1.018 (0.992-1.045)	1.174 (0.945-1.459)	1.006 (0.958-1.056)	1.176 (0.946-1.462)	1.007 (0.960-1.055)
Lag0-2	0.994 (0.880-1.122)	1.016 (0.989-1.044)	0.982 (0.868-1.111)	1.017 (0.989-1.045)	1.152 (0.923-1.437)	1.000 (0.948-1.056)	1.153 (0.923-1.440)	0.997 (0.946-1.051)
Lag0-3	0.983 (0.861-1.121)	1.016 (0.987-1.047)	0.970 (0.848-1.110)	1.017 (0.987-1.048)	1.123 (0.879-1.435)	1.006 (0.948-1.067)	1.122 (0.877-1.435)	1.003 (0.946-1.063)

Note: Models adjusted for temperature; * $p<0.05$

Table 3.5 Results of Conditional Logistic Regression Models Stratified by Gender

Single- and cumulative-day lags	Girls				Boys			
	Single-Pollutant		Two-Pollutant		Single-Pollutant		Two-Pollutant	
	$PM_{2.5}$	Ozone	$PM_{2.5}$	Ozone	$PM_{2.5}$	Ozone	$PM_{2.5}$	Ozone
Lag0	0.936 (0.819-1.070)	1.021 (0.989-1.054)	0.902 (0.776-1.048)	1.029 (0.993-1.066)	0.994 (0.900-1.099)	1.019 (0.991-1.047)	0.983 (0.888-1.089)	1.019 (0.991-1.048)
Lag1	1.113 (0.997-1.244)	1.012 (0.984-1.042)	1.108 (0.989-1.240)	1.007 (0.977-1.037)	1.061 (0.965-1.166)	1.002 (0.973-1.032)	1.061 (0.965-1.166)	1.001 (0.972-1.031)
Lag2	0.972 (0.858-1.102)	1.003 (0.973-1.035)	0.967 (0.849-1.101)	1.006 (0.974-1.038)	0.986 (0.900-1.079)	0.996 (0.967-1.027)	0.986 (0.900-1.080)	0.996 (0.967-1.027)
Lag3	0.984 (0.875-1.107)	1.007 (0.979-1.037)	0.972 (0.858-1.100)	1.010 (0.980-1.041)	0.985 (0.892-1.087)	1.005 (0.979-1.033)	0.984 (0.891-1.087)	1.006 (0.979-1.033)
Lag0-1	1.053 (0.911-1.218)	1.018 (0.986-1.052)	1.032 (0.885-1.203)	1.016 (0.983-1.051)	1.044 (0.926-1.175)	1.012 (0.982-1.044)	1.038 (0.921-1.171)	1.011 (0.980-1.043)
Lag0-2	1.038 (0.882-1.222)	1.016 (0.981-1.052)	1.019 (0.859-1.208)	1.015 (0.979-1.052)	1.026 (0.897-1.175)	1.009 (0.974-1.044)	1.025 (0.895-1.173)	1.008 (0.974-1.044)
Lag0-3	1.015 (0.852-1.209)	1.016 (0.979-1.054)	0.989 (0.821-1.193)	1.017 (0.978-1.057)	1.013 (0.872-1.176)	1.011 (0.973-1.050)	1.012 (0.871-1.176)	1.011 (0.973-1.050)

Note: Models adjusted for temperature

Table 3.6 displays the results of conditional logistic regression models stratified by season. We observed that both $PM_{2.5}$ and ozone had more of an effect on the risk of preventable rehospitalization during the warm season (May-October) compared with the cold season (November-April). Specifically, the association between $PM_{2.5}$ and preventable readmission was found to be positively significant on Lag1 in single-pollutant (OR=1.134, 95% CI=1.019-1.155, p=0.021) and two-pollutant models (OR=1.125, 95% CI=1.009-1.254, p=0.034) as well as on Lag0-1 in single-pollutant model (OR=1.146, 95% CI=1.003-1.309, p=0.046) in the warm season. For ozone, positive relationships with hospital readmission were observed on Lag0 in both single-pollutant (OR=1.043, 95% CI=1.012-1.075, p=0.007) and two-pollutant models (OR=1.043, 95% CI=1.010-1.078, p=0.01), and on Lag0-1 in single-pollutant model (OR=1.033, 95% CI=1.002-1.065, p=0.037) in the warm season. No significant associations were found in the cold season.

Table 3.6 Results of Conditional Logistic Regression Models Stratified by Season

Single- and cumulative-day lags	Warm season (May-October)				Cold season (November-April)			
	Single-Pollutant		Two-Pollutant		Single-Pollutant		Two-Pollutant	
	$PM_{2.5}$	Ozone	$PM_{2.5}$	Ozone	$PM_{2.5}$	Ozone	$PM_{2.5}$	Ozone
Lag0	1.056 (0.941-1.184)	1.043** (1.012-1.075)	0.993 (0.874-1.127)	1.043* (1.010-1.078)	0.920 (0.818-1.034)	1.023 (0.986-1.062)	0.922 (0.818-1.038)	1.022 (0.985-1.061)
Lag1	1.134* (1.019-1.262)	1.016 (0.989-1.043)	1.125* (1.009-1.254)	1.009 (0.982-1.037)	1.032 (0.933-1.141)	1.013 (0.975-1.053)	1.030 (0.931-1.138)	1.013 (0.975-1.052)
Lag2	1.038 (0.933-1.155)	1.003 (0.976-1.031)	1.037 (0.930-1.158)	1.001 (0.973-1.030)	0.934 (0.837-1.042)	1.008 (0.970-1.047)	0.932 (0.835-1.041)	1.009 (0.970-1.050)
Lag3	1.011 (0.915-1.116)	1.013 (0.989-1.039)	0.995 (0.895-1.106)	1.014 (0.988-1.041)	0.956 (0.853-1.071)	1.011 (0.973-1.051)	0.956 (0.853-1.071)	1.011 (0.972-1.052)
Lag0-1	1.146* (1.003-1.309)	1.033* (1.002-1.065)	1.105 (0.961-1.271)	1.025 (0.993-1.059)	0.965 (0.844-1.104)	1.023 (0.982-1.066)	0.968 (0.846-1.108)	1.022 (0.981-1.066)
Lag0-2	1.151 (0.989-1.340)	1.026 (0.994-1.060)	1.123 (0.960-1.314)	1.020 (0.987-1.054)	0.926 (0.793-1.081)	1.023 (0.977-1.071)	0.927 (0.795-1.082)	1.023 (0.977-1.072)
Lag0-3	1.132 (0.965-1.329)	1.031 (0.997-1.066)	1.098 (0.929-1.296)	1.025 (0.990-1.062)	0.892 (0.744-1.070)	1.029 (0.976-1.085)	0.894 (0.747-1.070)	1.029 (0.975-1.087)

Note: Models adjusted for temperature; * $p<0.05$ ** $p<0.01$

3.4. Discussion

This study examined the effects of ambient air pollution on preventable hospital readmission among children with asthma in South Texas. We found that short-term exposure to $PM_{2.5}$ concentration was positively associated with an increased risk of preventable rehospitalization for pediatric asthma in both single- and two-pollutant models. Ozone pollutant also had a significantly positive effect on asthma hospital readmission in the two-pollutant model. Specifically, significant associations between ambient air pollutants and hospital readmissions were found in the readmission day (Lag0) and the day before readmission day (Lag1).

The findings of this study provide support for the adverse effects of ambient air pollutants on the risk of preventable hospital readmission for pediatric asthma. This is important new knowledge, given that previous studies only included traffic-related air pollutants (TRAPs). For example, a study reported that residential exposure to specific TRAPs including NO_x and CO were significantly associated with an elevated risk of rehospitalizations for pediatric asthma [15]. Another study targeting children with asthma or bronchodilator-responsive wheezing showed that exposure to TRAPs affected hospital readmission, especially among white children [14]. In addition, one other study showed that the residential proximity to major roads or freeways (within 300 meters) increased the risk of hospital readmission for pediatric asthma [17]. As a result, the current study extends the findings of earlier evidence about a relationship between outdoor air pollutants and hospital readmissions for asthma.

The results of this study were consistent with those of previous studies that explored the effect of ambient air pollutants on pediatric asthma exacerbations, including hospital admission and emergency department (ED) visits. A review of 22 studies reported that exposures to $PM_{2.5}$, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) were significantly associated with asthma exacerbation among children less than 18 years of age [23]. Multiple studies have also found positive relationships between $PM_{2.5}$ and asthma hospitalization or ED visits for pediatric patients [24–27]. Moreover, previous research revealed the adverse effects of ozone concentration on asthma exacerbations for children in different settings, such as Texas [28], New York [29], California [30], China [24], HongKong [31] and Korea [32].

Based on this study, the effects of ambient air pollutants on preventable hospital readmission varied by age and season. We found that ozone concentration may contribute to increasing the odds of preventable hospital readmission for younger children aged 5-11 years but not for those aged 12-18 years. There is no evidence that substantiates the effects of $PM_{2.5}$ or ozone on pediatric asthma rehospitalization by age; however, one study presented that traffic-related NO_x and CO had significant age-effect on readmission for infants but not for children aged 1 to 18 years [15]. Age-stratified models of studies reporting the impact of $PM_{2.5}$ and ozone on asthma pediatric exacerbations had mixed results in different age groups. Studies found a significant association between air pollutants ($PM_{2.5}$ and/or ozone) and asthma exacerbations among preschool children (5 years or less) [25,26,33], those aged 5-14 years [25,34], and those aged 6-18 years [24,33].

The models stratified by season showed significant positive effects of $PM_{2.5}$ and ozone on preventable hospital readmission during the warm season, while such effects were not observed during the cold season. Our results were consistent with those of previous studies that examined the association between ambient air pollutants and asthma exacerbations for pediatric asthma. Most studies that were previously conducted found a significant effect of $PM_{2.5}$ on asthma hospitalization or ED visits during the warm season (May-October or April-September), and none in the cold season [25,26,35,36]. Another study also found a stronger association in the warm season than in the cold season [34]. Additionally, other studies have also revealed a significant relationship between ozone and asthma exacerbations in the warm season [35,37,38]. This finding is most likely due to the fact that children tend to play outside or have more outdoor activities at home and at school during the warm season compared to the cold season. Their houses are also more likely to be ventilated during the warm season, which may increase their personal exposure to ambient air pollutants [25,39,40].

The models stratified by gender did not show any significant associations in the current study. This finding is contrary to previous research, which suggested that gender could be a modifying factor of the relationship between TRAPs and hospital readmission. One study found that TRAPs including NO_x and CO were associated with pediatric asthma rehospitalizations among females only [15]. Another study revealed that the adverse impact of residence near heavy traffic on repeated asthma hospitalization was stronger among females than males (in the 6-18 years of age group) [17]. The gender difference was also observed in previous studies that investigated the relationship between ambient air pollutants ($PM_{2.5}$ and ozone) and asthma exacerbations for pediatric asthma [24–26,33].

3.4.1. Limitations

This study has several limitations. First, we used daily average air pollutant concentrations predicted by the statistical model at the census tract level as a proxy for personal exposure to outdoor air pollution, which may cause an exposure measurement error and thus underestimate the impacts of ambient air pollutants [41]. Second, the temperature data may not be accurate since the distance from the residence to the closest monitoring sites varied for each patient. This may also lead to measurement error. Third, only one children's hospital in South Texas, where ambient air pollutant concentrations were relatively low, was included in this study. As such, the findings may not be generalizable to other settings in different regions. Further study should be conducted in other regions with higher ambient air pollution to confirm the association. Fourth, some important factors that may potentially be associated with personal exposure to air pollution, such as the amount of time spent for outdoor activities and the level of indoor air pollution, were not included in this study due to unavailability of data. Finally, air pollution data were linked to the patients' residential census tract; however, we cannot guarantee that the patients were actually living or staying in that address during the study period.

3.4.2. Health Policy and Practice Implications

The findings of this study have several important implications for public health and healthcare services to reduce preventable hospital readmission. First, it would be important for children with asthma, who have experienced hospitalization earlier, to limit outdoor activities and/or habitually wear a facemask when going outside on days with high levels of $PM_{2.5}$ and ozone concentrations. This will help minimize personal exposure to air pollutants. The parents or families with younger children with asthma should also be more cautious about their children's outdoor activities on days with high levels of ambient air pollutants and particularly during the warm season. Second, the results of this study can help healthcare professionals, who serve pediatric patients with asthma, to understand that ambient air pollutants, including $PM_{2.5}$ and ozone, could increase the risk of preventable hospital readmission among children with asthma.

Third, previous evidence showed pre-discharge patient/family education is a successful intervention to reduce preventable readmission [42,43]. Therefore, it would be important for hospital leaders or healthcare workers in children's hospitals to consider emphasizing the contents related to ambient air pollution when delivering education to the children with asthma and their family before discharge as one of the readmission reduction initiatives. The educational contents may include effects of ambient air pollution, federal standards for each air pollutant, and how to check daily outdoor air quality and prevent air pollutant exposure. Finally, children's hospitals will be able to collaborate with asthma education/prevention programs in the community to follow-up with pediatric patients with asthma more effectively, given a study's argument that optimal inpatient asthma care includes an effective transition to the community with constant follow-up care to prevent repeated hospitalization [42]. Home visit asthma education has especially been proven to be effective in improving asthma-related health outcomes for the population living in disadvantaged communities with limited access to healthcare and education [44–46]. The community-hospital partnership for education and follow-up for pediatric patients with asthma may play a significant role in reducing preventable hospital readmission [47].

3.5. Conclusions

This is the first study, to the best of our knowledge, which investigates the association between short-term exposures to ambient air pollution and preventable hospital readmissions for pediatric asthma patients in South Texas. Our study confirms adverse effects of $PM_{2.5}$ and ozone concentrations on preventable hospital readmission among children with asthma in low-income communities. We discovered that younger age and exposure during the warmer season were associated with the effects of ambient air pollutants. Our findings contribute to the limited scientific evidence regarding the effect of ambient air pollutants on hospital readmission for pediatric asthma. However, further research is still warranted to confirm our findings.

3.6. References

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4. PEDIATRIC ASTHMA HOSPITALIZATION: INDIVIDUAL AND ENVIRONMENTAL CHARACTERISTICS OF HIGH UTILIZER

4.1. Introduction

Preventable hospital readmissions are an important indicator of healthcare quality as high readmission rates can indicate sub-optimal care during a hospital stay and post discharge (1–3). Asthma-related readmissions are also one of the most widely used and accepted outcome measurements of asthma exacerbations, asthma control, and care quality (4–6). These rehospitalizations are prioritized in the United States (U.S.) given that hospital readmissions increase healthcare costs and negatively affects quality of life for both children and their parents/caregivers (7,8).

In addition, repeated hospitalizations accounted for up to 40% of all pediatric asthma hospitalization and about one-third of the total cost in national pediatric asthma in the U.S. (9). Given that many readmissions are considered preventable with effective coordination of services and transitional care (10,11), reducing preventable hospital readmissions is essential to enhance quality of care and decrease financial healthcare burdens (12). By one estimate, preventing hospital readmissions could reduce U.S. healthcare costs by over $25 billion annually (13).

In addition to demographic and clinical risk factors, studies support that air pollution is a significant contributing factor for pediatric asthma readmissions (14,15). Specifically, exposure to indoor air pollutants is regarded as a risk factor for asthma hospital readmissions, including tobacco exposure (16,17), house dust mites and indoor mold (18,19), and fungi and yeast levels in children's bedrooms (20). Other studies have found that outdoor air pollution was significantly associated with hospital readmissions among children with asthma, specifically traffic-related air pollution (14,21) and residential proximity to major roads (22,23).

A growing body of literature also recognizes the significance of area-based socioeconomic deprivation on hospital-related health outcomes for asthma. These health outcomes involve hospitalization and emergency department (ED) visits (24), in-hospital mortality (25), length of stay (LOS) and costs (26), and readmission rates (26–28). Higher levels of area-based deprivation in neighborhoods where children live was also specifically associated with increased risk of hospital readmissions for pediatric asthma (26,28,29); air pollution also presented as a modifying effect for asthma-related pediatric ED visits in Atlanta (30).

These studies only focused on a single readmission after the index hospitalization. Other investigations defined multiple admissions as *at least one* readmission (31,32,33). However, few studies have identified the characteristics of patients with a high frequency or series of hospitalizations. For example, a retrospective cohort study based on thirty-seven U.S. children's hospitals during 2003-2008 revealed that age, race/ethnicity, and use of public insurance were important characteristics associated with the highest number of readmissions (34).

To date, no studies have examined the characteristics of high utilizers for pediatric asthma. Considering the potential differences that may exist in asthma severity, preventive care access, or air pollutant exposure among children who have been hospitalized once or multiple times (35), it would be important to differentiate patients with single versus multiple readmissions and assess whether there is any distinct characteristic found among the highly repeated hospital utilizers. Identifying those children at an early stage would allow hospitals to use their resources more effectively and reduce acute health service utilization of children without increased costs (36).

Therefore, this study examines individual-level and environmental characteristics of pediatric asthma patients with the highest frequency of hospitalizations in South Texas. This study will provide hospital leaders with a summary of evidence-based profiles of high utilizers of hospitalization among children with asthma and inform innovative, efficient strategies to reduce repeated hospitalizations.

4.2. Materials and Methods

4.2.1. Study Population and Data Source

This hospital-based retrospective study pooled data over 7 years to identify high utilizers of hospital services among pediatric asthma patients and examine their individual-level and environmental characteristics. The study included children aged 5-18 years old, living in South Texas, who were admitted at least once to our children's hospital in South Texas with a primary diagnosis of asthma between 2010-2016. This study was approved by the [censored for blind review] Institutional Review Board.

Data was gathered from multiple sources. First, hospitalization data for children admitted to the hospital due to asthma (International Classification of Diseases, 9th Revision, 493-493.92 or ICD, 10th Revision, J45.21-J45.909) were collected through the hospital's electronic database. All records included age, gender, ethnicity, type of insurance, use of medication, admission date, discharge date, and patients' residential census tract information. The research team collected outdoor air pollution data from the Environmental Public Health Tracking Network of the Centers for Disease Control and Prevention (CDC) (37). The daily average predictions modeled for two types of air pollutants, such as Particulate Matter 2.5 (PM2.5) and ozone concentrations, were estimated by using the Downscaler model of the U.S. Environmental Protection Agency at the census tract level (38). The data available were limited to those between 2001 and 2014, so we calculated the average values during 2010-2014 in order to obtain the overall air pollution levels in each census tract.

We gathered social deprivation data from the social vulnerability index (SVI) created by the Agency for Toxic Substances and Disease Registry of the CDC (39). This percentile rank index was developed to determine social vulnerability of each community in the census tract level by using fifteen social factors based on the U.S. census data, including poverty, education transportation, minority status, and household composition (40). The fifteen social factors are presented in Appendix C. Given data availability, the social vulnerability variable was created as an average of SVI values for 2010, 2014, and 2016 in census tract level to cover the study period. We linked the data of outdoor air pollution and social vulnerability index to the hospitalization data by using census tract information.

4.2.2. Measurement

In this study, hospitalization was defined as a hospital admission with at least one night stay in the hospital. Patients admitted and discharged on the same day were excluded from the analysis. A unique medical record number was used to track each patient's hospitalizations during the study period. The dependent variable representing hospital utilization groups was determined based on the total number of hospitalizations between 2010 and 2016 for pediatric patients with asthma who were admitted to the hospital. This ordinal variable was divided into three groups given its distribution: (i) low utilization group (hospitalized once with no readmissions), (ii) medium utilization group (hospitalized 2 or 3 times), and (iii) high utilization group (hospitalized 4 times or more). Patients in the high utilization group represented the 97.5th percentile in the distribution of hospitalizations among the study population. Hospital resource utilization, including the number of admissions, the number of nights spent in the hospital, and time between hospitalizations (days), was accumulated for each patient during the entire study period and calculated to compare among the three hospital utilization groups. We divided the time between hospitalizations for patients who had at least one readmission into four categories: i) 1-30 days, ii) 31-90 days, iii) 91-365 days, or iv) 366 days or longer.

The independent variables contained various individual-level and environmental factors, all of which may affect hospital readmission for pediatric asthma patients to a certain degree. First, individual-level characteristics included age (5-11 years old or 12-18 years old), gender (male or female), ethnicity (Hispanic or non-Hispanic), type of insurance (public: Medicaid or private/self-pay), use of medication (yes or no), LOS (1 night, 2 nights or ≥3 nights), season (warm: May-October or cold: November-April) and year. The information gathered at the initial admission was used in this study.

Environmental characteristics for this study included two types of air pollutants ($PM_{2.5}$ and ozone levels) and social deprivation in neighborhoods where children live. We measured these variables based on each patient's census tract information. $PM_{2.5}$ and ozone concentrations were divided into four categories as quartiles: quartile 1 (the lowest) to quartile 4 (the highest) (41). Social deprivation factor was estimated by calculating the average of social vulnerability index (SVI) data of years 2010, 2014, and 2016 to cover the years of 2010 to 2016 in each census tract. The range of this index is between 0 (least vulnerable) to 1 (most vulnerable). We also categorized this variable into four categories by quartile from quartile 1 (the lowest) to quartile 4 (the highest) for outdoor air pollution.

4.2.3. Statistical Analysis

Hospital resource utilization of asthma patients during 2010-2016 was compared among the hospital utilization groups by calculating median and interquartile range (IQR) since the data was not normally distributed. We calculated the baseline characteristics of the study population to estimate the median and IQR for continuous variables, or percentages of categorical variables in total and by hospital utilization groups. The Kruskal-Wallis H tests for continuous variables and the chi-square tests for categorical variables were performed to compare the hospital resource utilization and characteristics among three groups of hospital utilizers: low, medium, and high groups. We compared time between hospitalizations only between medium and high utilization groups. Pearson correlation was used to test if air pollution and social vulnerability index was highly correlated.

Bivariate and multivariate ordered logistic regression analysis was conducted to identify significant factors that affect a high number of hospitalizations since the dependent variable was categorical and ordered. We developed three different regression models: model 1 (unadjusted model), model 2 (adjusted model with only individual-level factors), and model 3 (adjusted model with individual-level and environmental factors). To evaluate the robustness of the findings, we performed the multivariate regression analysis with each air pollutant, separately. The results were represented as the odds ratio (OR) and 95% confidence interval (CI). Statistical analyses were performed using Stata 14 version (StataCorp LLC, College Station, TX). All statistical tests were two-sided, and a p-value < 0.05 was considered statistically significant.

4.3. Results

A total of 902 patients were admitted to the hospital at least once during 2010-2016 in South Texas. Among the study population, 121 patients (13.4%) experienced 2-3 hospitalizations and 22 patients (2.4%) had ≥4 hospitalizations (Figure 4.1). There were 1154 hospitalizations with 2295 nights spent in the hospital between 2010 and 2016 in total. The high utilization group consisted of 2.4% of total patients and accounted for substantial hospital resource utilization: 10.8% (125/1154) of total admission and 13.5% (310/2295) of total number of nights spent in the hospital (Figure 4.1).

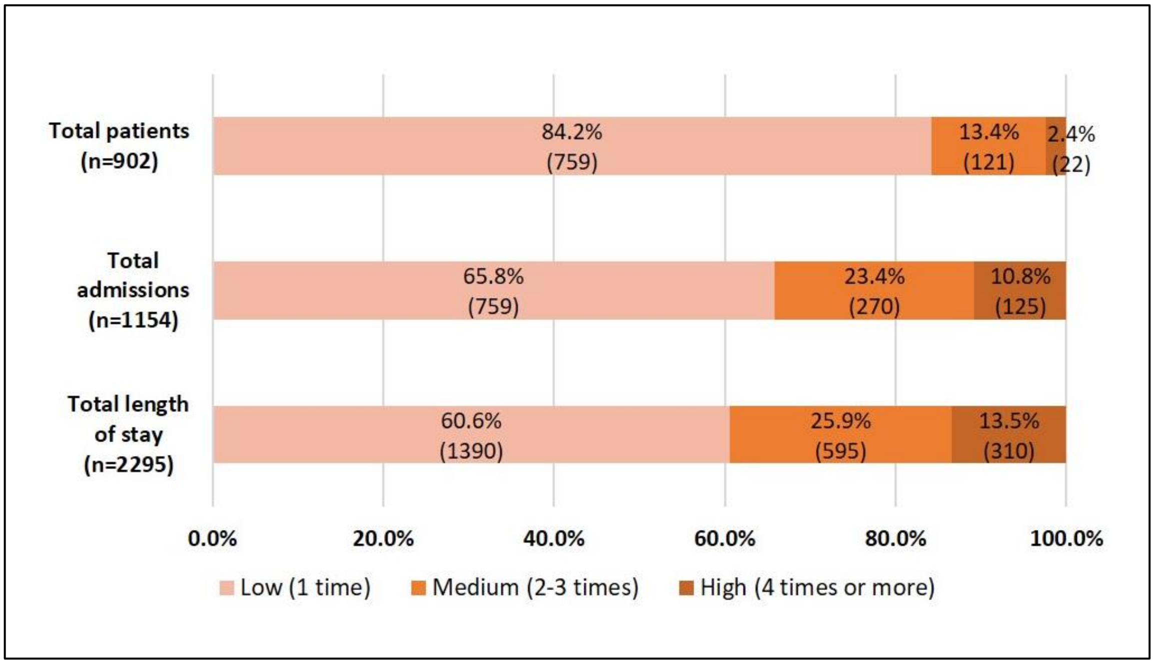

Figure 4.1 Hospital Resource Utilization of Pediatric Patients with Asthma Admitted to Driscoll Children's Hospital during 2010-2016

Table 4.1 compares hospital resource utilization of pediatric asthma hospitalizations among low, medium, and high utilization groups. Patients in the high group stayed much longer (12-night LOS) than the medium (4 nights) and low (1 night) groups when they were hospitalized ($p<0.001$). When comparing median days between hospitalizations, the high group showed significantly shorter time in between hospitalizations than the medium group (169 vs. 331 days; $p<0.001$). Furthermore, we found that only 9.7% of readmissions in the high group occurred within 30 days, and that most of the total readmissions (77.8% for all patients and 66.3% for the high group) occurred 90 or more days after previous admission.

Table 4.1 Comparison of Hospital Resource Utilization among Low, Medium, and High Groups in Pediatric Asthma Hospitalization

	Total	Number of pediatric asthma hospitalization			p-value
		Low group (1 time)	**Medium group (2 or 3 times)**	**High group (≥4 times)**	
	Median (IQR) or N (%)				
Number of patients	902 (100.0%)	759 (84.2%)	121 (13.4%)	22 (2.4%)	
Average number of hospitalizations	1 (1-1)	1 (1-1)	2 (2-2)	5 (4-6)	<0.001
Average number of nights spent in the hospital across hospitalizations	2 (1-3)	1 (1-2)	4 (3-5)	12 (10-14)	<0.001
Time between hospitalizations (days)	274 (106-539)	NA	331 (178-664)	169 (56-355)	<0.001
Time between hospitalizations	252 (100.0%)	NA	149 (100.0%)	103 (100.0%)	<0.001
1-30 days	20 (7.9%)		10 (6.7%)	10 (9.7%)	
31-90 days	36 (14.3%)		11 (7.4%)	25 (24.3%)	
91-365 days	103 (40.9%)		60 (40.3%)	43 (41.7%)	
366 days or longer	93 (36.9%)		68 (45.6%)	25 (24.3%)	

Note: IQR, Interquartile range; NA, not applicable; p-values from Kruskal-Wallis tests for continuous variables and Chi-square tests for categorical variable

Table 4.2 presents and compares descriptive statistics of the study population at index admission across the three groups. Most of the study cohort (76.1%) were children aged 5-11 years old and about three quarters were Hispanic (75.2%). Over two-third (68.4%) had public insurance and about 20% remained in the hospital for 3 nights or longer at index admission. When comparing characteristics among groups, only the differences in LOS and admission year at initial hospitalization were statistically significant. Specifically, the percentage of hospital stays for 3 nights or longer was significantly higher in the high utilization group when compared with the medium and low groups ($p<0.001$). In particular, the high utilization group showed twice the percentage (36.4% vs. 17.3%; $p<0.001$) as the low utilization group for LOS $\geq$3 nights. None of the environmental factors showed significant differences among groups although percentages of the highest ozone level group (quartile 4) were larger in the high utilization group (31.8%) than the medium (19.8%) and low groups (26.8%; $p=0.052$). Moreover, Pearson correlation tests between air pollutants and social vulnerability index showed that they were not highly correlated (0.21~0.43; $p<0.001$; Appendix D).

Table 4.2 Comparison of Patient and Environmental Characteristics among Hospital Utilization Groups

Variables	Total (N=902)	Low group (N=759)	Medium group (N=121)	High group (N=22)	p-value
	Median (IQR) or N (%)				
Individual-level characteristics (at index admission)					
Age (years)	8 (6-11)	8 (6-12)	8 (6-10)	7 (6-10)	0.194
Age					0.090
5~11 years	686 (76.1)	567 (74.7)	101 (83.5)	18 (81.8)	
12~18 years	216 (23.9)	192 (25.3)	20 (16.5)	4 (18.2)	
Gender					0.479
Male	536 (59.4)	445 (58.6)	78 (64.5)	13 (59.1)	
Female	366 (40.6)	314 (41.4)	43 (35.5)	9 (40.9)	
Ethnicity					0.775
Hispanic	677 (75.2)	567 (74.9)	94 (77.7)	16 (72.7)	
Non-Hispanic	223 (24.8)	190 (25.1)	27 (22.3)	6 (27.3)	
Type of insurance					0.794
Public (Medicaid)	617 (68.4)	516 (68.0)	86 (71.1)	15 (68.2)	
Private or self-pay	285 (31.4)	243 (32.0)	35 (28.9)	7 (31.8)	
Use of medication					0.965
Yes	832 (92.2)	700 (92.2)	112 (92.6)	20 (90.9)	
No	70 (7.8)	59 (7.8)	9 (7.4)	2 (9.1)	
Length of stay (nights)	2 (1-2)	1 (1-2)	2 (1-3)	2 (2-3)	<0.001
Length of stay					<0.001
1 night	430 (47.6)	387 (51.0)	38 (31.4)	5 (22.7)	
2 nights	291 (32.3)	241 (31.7)	41 (33.9)	9 (40.9)	
3 nights or longer	181 (20.1)	131 (17.3)	42 (34.7)	8 (36.4)	
Season					0.376
Warm	355 (39.4)	292 (38.5)	52 (43.0)	11 (50.0)	
Cold	547 (60.6)	467 (61.5)	69 (57.0)	11 (50.0)	
Year					<0.001
2010	171 (19.0)	132 (17.4)	27 (22.3)	12 (54.5)	

Table 4.2 Continued

Variables	Total (N=902)	Low group (N=759)	Medium group (N=121)	High group (N=22)	p-value
	Median (IQR) or N (%)				
Year					<0.001
2011	138 (15.3)	105 (13.8)	27 (22.3)	6 (27.3)	
2012	162 (18.0)	138 (18.2)	22 (18.2)	2 (9.1)	
2013	130 (14.4)	106 (14.0)	22 (18.2)	2 (9.1)	
2014	136 (15.1)	121 (15.9)	15 (12.4)	0 (0.0)	
2015	75 (8.3)	67 (8.8)	8 (6.6)	0 (0.0)	
2016	90 (9.9)	90 (11.9)	0 (0.0)	0 (0.0)	
Environmental characteristics					
SVI (continuous)	0.68 (0.49-0.83)	0.68 (0.49-0.84)	0.68 (0.48-0.81)	0.67 (0.57-0.81)	0.809
SVI (category)					0.138
Quartile 1 (the lowest)	235 (24.9)	186 (24.5)	35 (28.9)	4 (18.2)	
Quartile 2	236 (26.2)	201 (26.5)	25 (20.7)	10 (45.5)	
Quartile 3	216 (24.0)	177 (23.3)	36 (29.7)	3 (13.6)	
Quartile 4 (the highest)	225 (24.9)	195 (25.7)	25 (20.7)	5 (22.7)	
$PM_{2.5}$ (continuous)	8.52 (8.32-8.63)	8.51 (8.31-8.63)	8.53 (8.37-8.64)	8.51 (8.38-8.66)	0.454
$PM_{2.5}$ (categorical)					0.335
Quartile 1 (the lowest)	229 (25.4)	202 (26.6)	24 (19.8)	3 (13.6)	
Quartile 2	222 (24.6)	183 (24.1)	30 (24.8)	9 (40.9)	
Quartile 3	228 (25.3)	190 (25.0)	34 (28.1)	4 (18.2)	
Quartile 4 (the highest)	223 (24.7)	184 (24.2)	33 (27.3)	6 (27.3)	
Ozone (continuous)	36.01 (35.8-36.29)	36.02 (35.8-36.3)	35.97 (35.87-36.19)	36.20 (35.97-36.33)	0.160
Ozone (categorical)					0.052
Quartile 1 (the lowest)	211 (23.4)	183 (24.1)	25 (20.7)	3 (13.6)	
Quartile 2	240 (26.6)	193 (25.4)	44 (36.4)	3 (13.6)	
Quartile 3	217 (24.1)	180 (23.7)	28 (23.1)	9 (40.9)	
Quartile 4 (the highest)	234 (25.9)	203 (26.8)	24 (19.8)	7 (31.8)	

Note: IQR, Interquartile range; p-values from Kruskal-Wallis tests for continuous variables and Chi-square tests for categorical variables

Table 4.3 presents results of bivariate and multivariate ordered logistic regression analyses to identify characteristics of the high utilization group. In the unadjusted model, ages 5-11 years old and longer LOS at index admission were significantly associated with a higher frequency of hospitalization (age: $p=0.031$; LOS: $p=0.005$ [2 nights], $p<0.001$ [≥3 nights]). The multivariate analysis, controlling for only individual-level factors, showed that age, LOS, and season were significant characteristics for high hospital utilizers. That is, children aged 5-11 years old ($p=0.020$), who stayed longer in the hospital (2 nights: $p=0.011$; ≥3 nights: $p<0.001$), and who were admitted during the warm season ($p=0.034$) at index admission were significantly more likely to have a higher number of hospitalizations.

Table 4.3 Results of Bivariate and Multivariate Ordered Logistic Regression Analysis among Hospital Utilization Groups

	Unadjusted Model		Adjusted models			
	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value
Individual-level characteristics (at index admission)						
Age						
5-11 years	Ref.	0.031	Ref.	0.020	Ref.	0.025
12-18 years	0.60 (0.37, 0.95)		0.56 (0.35, 0.91)		0.57 (0.35, 0.93)	
Gender						
Male	Ref.	0.277	Ref.	0.204	Ref.	0.229
Female	0.81 (0.56, 1.18)		0.78 (0.53, 1.14)		0.79 (0.53, 1.16)	
Ethnicity						
Non-Hispanic	Ref.	0.630	Ref.	0.455	Ref.	0.538
Hispanic	1.11 (0.73, 1.69)		1.18 (0.76, 1.84)		1.16 (0.73, 1.83)	
Type of insurance						
Private or self-pay	Ref.	0.544	Ref.	0.662	Ref.	0.627
Public (Medicaid)	1.13 (0.76, 1.67)		1.09 (0.73, 1.64)		1.11 (0.72, 1.72)	
Use of medication						
No	Ref.	0.987	Ref.	0.626	Ref.	0.627
Yes	1.01 (0.51, 1.96)		1.19 (0.59, 2.40)		1.22 (0.60, 2.49)	
Length of stay						
1 night	Ref.		Ref.		Ref.	
2 nights	1.88 (1.22, 2.92)	0.005	1.80 (1.15, 2.81)	0.011	1.80 (1.15, 2.84)	0.011
3 nights or longer	3.43 (2.18, 5.39)	<0.001	3.23 (2.01, 5.17)	<0.001	3.38 (2.10, 5.46)	<0.001
Season						
Cold	Ref.	0.197	Ref.	0.034	Ref.	0.042
Warm	1.27 (0.88, 1.82)		1.51 (1.03, 2.20)		1.49 (1.01, 2.20)	
Admission year	0.75 (0.67, 0.83)	<0.001	0.76 (0.68, 0.85)	<0.001	0.76 (0.68, 0.86)	<0.001

Table 4.3 Continued

	Unadjusted Model		Adjusted models			
	OR (95% CI)	p-value	OR (95% CI)	p-value	OR (95% CI)	p-value
Environmental characteristics						
Social vulnerability index						
Quartile 1 (the lowest)	Ref.				Ref.	
Quartile 2	0.86 (0.52, 1.41)	0.551			0.84 (0.48, 1.45)	0.525
Quartile 3	1.04 (0.64, 1.70)	0.862			0.89 (0.50, 1.56)	0.674
Quartile 4 (the highest)	0.74 (0.44, 1.25)	0.261			0.63 (0.34, 1.16)	0.135
$PM_{2.5}$ level						
Quartile 1 (the lowest)	Ref.				Ref.	
Quartile 2	1.63 (0.96, 2.76)	0.071			1.42 (0.75, 2.71)	0.280
Quartile 3	1.49 (0.88, 2.53)	0.141			1.27 (0.62, 2.59)	0.514
Quartile 4 (the highest)	1.59 (0.94, 2.70)	0.085			1.48 (0.71, 3.09)	0.298
Ozone level						
Quartile 1 (the lowest)	Ref.				Ref.	
Quartile 2	1.57 (0.94, 2.60)	0.084			1.78 (1.01, 3.14)	0.045
Quartile 3	1.38 (0.81, 2.34)	0.238			1.43 (0.77, 2.67)	0.260
Quartile 4 (the highest)	1.02 (0.59, 1.76)	0.954			1.30 (0.64, 2.65)	0.469

In the multivariate model controlling for individual-level and environmental factors, the results for individual-level factors were consistently represented as the previous adjusted model (age of 5-11 years: $p=0.025$; longer LOS: $p=0.011$ [2 nights], $p<0.001$ [≥3 nights]; warm season: $p=0.042$). We also found that children living in areas with ozone level of quartile 2 were more likely to be admitted to the hospital than those living in areas with the lowest ozone level (quartile 1; $p=0.045$). The multivariate analysis with each pollutant (single-pollutant models) also showed consistent results that age, LOS, season, and ozone level were important factors for higher number of hospitalizations for pediatric asthma (Appendix E).

4.4. Discussion

This study examined the individual-level and environmental characteristics of pediatric patients who had the highest number of asthma hospitalizations during 2010-2016 in a children's hospital in South Texas. We found that the relatively small number of patients within the high utilization group (2.4% of the total patients) accounted for significant hospital resource utilization: 10.8% of total admissions and 13.5% of total time stayed in the hospital (nights). Patients in the high utilization group also showed longer LOS and shorter time gap between admissions on average when compared to the low and medium utilization groups. Our findings are consistent with those of a previous study that found about 3% of the total patients (the group with the highest frequency of readmissions) accounted for about 19% of total hospitalization and about 23% of total LOS (34). Patients readmitted most often are also readmitted sooner and stay longer.

Therefore, identifying the group of high-utilizing children and establishing specific strategies for this group is essential in order to use hospital resources efficiently and reduce healthcare costs effectively. Given high costs of asthma hospitalizations in particular, by one well-surveyed estimate over $5000 per patient (42), preventing hospitalizations especially of the high utilization group would contribute to saving considerable healthcare costs.

Timing is also a factor. We found that the average time between admissions was 274 days for all patients who experienced at least two episodes of hospitalization, and 169 days for those with hospitalizations of four times or more. Fewer than 10% of readmissions in the high group occurred within 30 days; most readmissions (77.8% for all patients and 66.3% for the high group) had 90-day or longer readmissions. If hospitals only focus on the traditional 30-day readmissions, most patients with repeated hospitalizations, especially patients with the highest number of admissions, might be under-recognized in receiving necessary transitional care. Therefore, hospitals should monitor the number of hospitalizations for individual patients and establish their readmission reduction initiatives based on distribution of hospitalizations and the resource utilization of patients with the higher number of admissions.

To that end, we observed three individual-level characteristics of patients with the highest number of asthma admissions: age, hospital LOS, and season at index admission. This study showed that children aged 5-11 years were more likely to have a higher number of hospitalizations than those aged 12-18 years. Previous studies that explored asthma readmission by age group show mixed results. Most studies reported children aged <5 years or 10-18 years were more likely to be readmitted to a hospital (9,29,43,44). However, these studies had different reference groups, and we could not find any study that compared age groups of 5-11 years and 12-18 years like this current study. Moreover, we found that initial admission during the warm season was a significant characteristic of the high utilization group. This finding corroborates previous research that found higher readmission rates for children admitted in the summer or fall versus winter (29).

The most pronounced finding was that longer LOS at index admission was significantly associated with a higher frequency of hospitalizations both in unadjusted and adjusted models. This result supports those observed in earlier studies related to pediatric asthma readmission. A study conducted in Rhode Island revealed that patients with LOS of three or more nights at index hospitalization had higher readmission rates than those with LOS of 1 day (29). Other studies also suggested longer LOS ($\geq$4 or 5 days) at initial admission was a significant risk factor for asthma rehospitalization (31,45,46).

Ozone level in patients' neighborhoods also demonstrated a significant association with a higher number of asthma admissions, shown consistently shown in both the single-pollutant and two-pollutant models. Our finding is consistent with prior research associating an increased risk of hospital readmission for pediatric asthma with both indoor air pollution (such as bedroom air quality and tobacco exposure) and traffic-related outdoor air pollution (16,20,21). Our result is also consistent with evidence that ozone concentration had a significantly positive association with asthma exacerbations for children (47,48). Yet, this is the first study, to our knowledge, that examines the effects of ozone level on higher frequency of asthma hospitalizations. This study allows us to conclude that outdoor air pollution (ozone) in neighborhoods where children live and play should be considered a significant risk factor for hospitalization among children with asthma.

4.4.1. Limitations

Despite this current study's meaningful findings, there are several limitations. First, ambient air pollution data collected from the CDC included the average daily PM2.5 and ozone concentration levels during 2010-2014, which does not cover the entire study period of 2010-2016 due to unavailability of data. Since this data is the estimate of the modeled predictions for two air pollutants, it may not reflect the accurate outdoor air condition and thereby raises the possibility of measurement error. However, the average daily concentrations for 5 years may be adequate to show the general ambient air pollution levels of each neighborhood, especially in communities that do not have high levels of air pollution. Second, we used the hospitalization records specific to a single hospital in this study and could not track the patients' admissions to other hospitals, if any. Thus, the number of asthma hospitalizations may be under-counted for some pediatric patients. Also, since only a single children's hospital in South Texas was included in this study, we may not generalize the results to other settings.

Third, some individual-level and environmental factors, such as severity of asthma, comorbidities, and tobacco/smoke exposure (7,9,16), all of which may affect the risk of asthma hospital readmission, were not available in the hospitalization data. In addition, the information about outpatient visits, community factors like access to care, and asthma education for families were not included in this study. Future studies should consider including these factors to help better understand the characteristics of high hospital utilization for pediatric asthma. Finally, we included all hospitalizations of pediatric patients despite the differences of time interval for each patient. This is because the goal of this study was to identify the characteristics of high hospital utilizers based on the total frequency of hospitalizations for each patient during the study period. However, this serves as a limitation given the large time variation between admissions among the patients. Future studies should consider categorizing different time intervals of readmission to better understand how risk factors may differ by time interval to help hospitals establish strategies focusing on patients with likely avoidable readmissions (49).

4.4.2. Implications for Healthcare System

Our findings have important implications regarding repeated asthma admissions and the opportunity to improve transitional care for patients experiencing higher numbers of hospitalizations. This study emphasizes the need to target strategies for high hospital utilizers. We suggest that hospitals conduct follow-up for at least six months after discharge based on the average times between admission for all readmitted patients (274 days) and the high utilization group (169 days) observed in this study. Several studies also reported that a time interval of six months to two years could be a reasonable criterion for follow up for patients with chronic conditions (32,35,50).

Effective transition of care from hospital to community, including continual follow-up for patients who have a higher risk for readmission, is also important given recent research supporting the significance of transitional care, including asthma education and communication with primary care physicians (PCPs), to reduce readmissions for pediatric asthma (51,52). Therefore, the collaboration between clinical and community partners (e.g., PCPs, nonprofit organizations, and educators) for transitional care and follow-up would contribute to reducing repeated hospital admissions since appropriate care for asthma management in the community, such as asthma education, can prevent repeated hospitalizations in the future (53,54,55).

4.5. Conclusions

This study showed that a modest number of patients with the highest number of hospitalizations accounted for substantial hospital resource utilization. Our results revealed that younger age, longer LOS, warm season at index admission, and high level of outdoor air pollution in residential neighborhoods present as significant characteristics in patients with a higher number of hospitalizations in South Texas. The findings of this study underscore the importance of monitoring hospitalization of high hospital utilizers and establishing strategies for such patients based on their characteristics to reduce repeated hospitalizations and increase efficiency and optimal use of hospital resources.

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5. CONCLUSIONS

This dissertation research investigates how environmental factors, including ambient air pollution, are associated with hospital utilization, such as hospital length of stay (LOS) and readmissions, among children with asthma who were admitted to the Driscoll Children's Hospital in South Texas by using different research approaches. The first study (Section 2) examines the association between ambient air pollution ($PM_{2.5}$ and ozone concentrations) and hospital length of stay for pediatric asthma patients. This study found the adverse effects of outdoor air pollutants, including $PM_{2.5}$ and ozone concentrations, on hospital LOS for pediatric asthma in South Texas, especially in low-income communities.

The second study (Section 3) explores the effects of ambient air pollution on preventable hospital readmissions among children with asthma by using a case-crossover study design. The findings from this study showed that short-term exposure to $PM_{2.5}$ and ozone concentrations was positively associated with an increased risk of hospital readmissions. The third study (Section 4) seeks to identify the high utilizers in pediatric asthma hospitalizations and examine their individual-level and environmental characteristics. The results suggest that a modest number of patients with the highest number of hospitalizations accounted for substantial hospital resource utilization. The findings also revealed that younger age, longer LOS at index admission, initial admission during warm season, and high level of outdoor air pollution in residential neighborhoods present as significant characteristics in patients with a higher number of hospitalizations in South Texas.

Three of my dissertation studies have some important public health and practice implications. First, families with younger children with asthma need to be more cautious about their children's outdoor activities on days with high levels of outdoor air pollutants. In addition, given that asthma education has shown to be effective in improving health outcomes of children with asthma, these studies suggest that it would be important for healthcare professionals to highlight the contents about outdoor air pollution when providing education. Furthermore, it would also be helpful if school leaders start considering the ambient air quality levels when planning for outdoor activities or school events. This would particularly be important for schools that have high number of children with asthma.

The three studies also suggest important implications for the healthcare system. First, the findings can help hospital leaders or healthcare workers to consider emphasizing the contents related to outdoor air pollution when delivering education and precautions to children with asthma and their family before discharge. Moreover, it would be important for hospitals to closely monitor the number of hospitalizations for individual patients and establish their readmission reduction initiatives considering hospital resource utilization of those with a higher number of hospitalizations. Finally, these studies suggest Driscoll's hospital to conduct a follow-up for at least six months considering the average times between admissions in order to reduce preventable readmissions. In addition, the hospital might need to consider collaborating with community partners, such as primary care physicians and educators, for effective transitional care, including education and follow-up, to reduce repeated hospitalizations.

APPENDIX A

PEARSON CORRELATION COEFFICIENTS BETWEEN PM2.5 AND OZONE CONCENTRATION LEVELS FROM LAG0 TO LAG0-7

Lag days pre-admission	**Coefficient (r)**
Lag0	0.092*
Lag0-1	0.105**
Lag0-2	0.115**
Lag0-3	0.102**
Lag0-4	0.100**
Lag0-5	0.103**
Lag0-6	0.114**
Lag0-7	0.123**

Note: * $p<0.05$, ** $p<0.01$

APPENDIX B

PEARSON CORRELATION COEFFICIENTS AMONG DAILY AIR POLLUTANTS AND DAILY AVERAGE TEMPERATURE

	$PM_{2.5}$	**Ozone**	**Temperature**
$PM_{2.5}$	1.00		
Ozone	-0.214*	1.00	
Temperature	-0.216*	0.077	1.00

Note: significant at $p<0.05$ (*)

APPENDIX C

LIST OF 15 FACTORS FOR SOCIAL VULNERABILITY INDEX

	Factor	Description
Socioeconomic status	Below poverty	Percent of persons below federally defined poverty line
	Unemployed	Percent of persons aged 16+ unemployed
	Income	Per capita income
	No high school diploma	Percent of persons aged 25 years and old, with less than a 12th grade education
Household composition & disability	Aged 65 or older	Percent of persons aged 65 years or older
	Aged 17 or younger	Percent of persons aged 17 years or younger
	Civilian with a disability	Percent of persons more than 5 years old with a disability
	Single-parent households	Percent of male or female householder, no spouse present, with children under 18
Minority status & language	Minority	Percent of minority
	Speak English "less than well"	Percent of persons aged 5 years or older who speak English less than "well"
Housing & transportation	Multi-unit structures	Percent of housing units with 10 or more units in structure
	Mobile homes	Percent of housing units that are mobile homes
	Crowding	Percent of total occupied housing units with more than one person per room
	No vehicle	Percent of households with no vehicle available
	Group quarters	Percent of persons who are in institutionalized group quarters (e.g., nursing homes) and non-institutionalized group quarters (e.g., college dormitories, military quarters)

APPENDIX D

PEARSON CORRELATION COEFFICIENTS BETWEEN AMBIENT AIR

POLLUTANTS AND SOCIAL VULNERABILITY INDEX

	$PM_{2.5}$	Ozone	SVI
$PM_{2.5}$	1		
Ozone	-0.4327*	1	
SVI	0.2109*	-0.2975*	1

Note: * $p<0.001$

APPENDIX E

RESULTS OF MULTIVARIATE ORDERED LOGISTIC REGRESSION ANALYSIS FOR EACH POLLUTANT

	$PM_{2.5}$ Model		Ozone Model	
	OR (95% CI)	**p-value**	**OR (95% CI)**	**p-value**
Age				
5-11 years	Ref.	0.021	Ref.	0.020
12-18 years	0.56 (0.35, 0.92)		0.56 (0.34, 0.91)	
Gender				
Male	Ref.	0.251	Ref.	0.226
Female	0.79 (0.54, 1.17)		0.79 (0.53, 1.16)	
Ethnicity				
Non-Hispanic	Ref.	0.503	Ref.	0.522
Hispanic	1.17 (0.74, 1.84)		1.16 (0.73, 1.83)	
Type of insurance				
Private or self-pay	Ref.	0.585	Ref.	0.595
Public (Medicaid)	1.13 (0.73, 1.73)		1.11 (0.73, 1.73)	
Use of medication				
No	Ref.	0.680	Ref.	0.553
Yes	1.16 (0.57, 2.36)		1.24 (0.61, 2.53)	
Length of stay				
1 night	Ref.		Ref.	
2 nights	1.81 (1.15, 2.84)	0.010	1.77 (1.13, 2.78)	0.013
3 nights or longer	3.37 (2.10, 5.43)	<0.001	3.33 (2.07, 5.36)	<0.001
Season				
Cold	Ref.		Ref.	
Warm	1.47 (1.00, 2.15)	0.050	1.51 (1.03, 2.22)	0.036
Admission year	0.77 (0.69, 0.86)	<0.001	0.76 (0.68, 0.85)	<0.001
Social vulnerability index				
Quartile 1 (the lowest)	Ref.		Ref.	
Quartile 2	0.87 (0.51, 1.49)	0.617	0.79 (0.47, 1.35)	0.395
Quartile 3	0.93 (0.54, 1.61)	0.807	0.85 (0.48, 1.48)	0.559
Quartile 4 (the highest)	0.65 (0.36, 1.18)	0.161	0.61 (0.33, 1.11)	0.106
$PM_{2.5}$ level				
Quartile 1 (the lowest)	Ref.			
Quartile 2	1.42 (0.75, 2.71)	0.280		
Quartile 3	1.27 (0.62, 2.59)	0.514		
Quartile 4 (the highest)	1.48 (0.71, 3.09)	0.298		

Appendix E Continued

	$PM_{2.5}$ Model		Ozone Model	
	OR (95% CI)	**p-value**	**OR (95% CI)**	**p-value**
Ozone level				
Quartile 1 (the lowest)			Ref.	
Quartile 2			1.79 (1.05, 3.06)	0.036
Quartile 3			1.40 (0.80, 2.45)	0.242
Quartile 4 (the highest)			1.06 (0.58, 1.93)	0.842