



Hebei Spirit oil spill and its long-term effect on children's asthma symptoms[☆]

Su Ryeon Noh^a, Jung-Ah Kim^b, Hae-Kwan Cheong^{c,*}, Mina Ha^d, Young-Koo Jee^e, Myung-Sook Park^f, Kyung-Hwa Choi^f, Ho Kim^g, Sung-Il Cho^g, Kyungho Choi^h, Domyung Paek^h

^a Department of Public Health and Environment, Kosin University, Pusan, Republic of Korea

^b Department of Environment and Ecology Research, ChungNam Institute, Gongju, Republic of Korea

^c Department of Social and Preventive Medicine, Sungkyunkwan University School of Medicine, Suwon, Republic of Korea

^d Department of Preventive Medicine, Dankook University College of Medicine, Cheonan, Republic of Korea

^e Department of Internal Medicine, Dankook University College of Medicine, Cheonan, Republic of Korea

^f Taeon Environmental Health Center, Taeon, Republic of Korea

^g Department of Public Health, Seoul National University Graduate School of Public Health, Seoul, Republic of Korea

^h Department of Environmental Health, Seoul National University Graduate School of Public Health, Seoul, Republic of Korea

ARTICLE INFO

Article history:

Received 13 September 2018

Received in revised form

11 February 2019

Accepted 12 February 2019

Available online 13 February 2019

Keywords:

BTEX

Cohort

Environmental disaster

Health

Longitudinal

Respiratory

ABSTRACT

On December 7th, 2007, an estimated 12,547 kL of crude oil was spilled from the collision of Hebei Spirit near residential area. Our previous study demonstrated worsening of children's asthma symptoms one year after the accident. This study investigated long-term effect of the oil spill on children's asthma symptoms up to five years after the accident. All elementary and middle school students in the exposure area were surveyed on one year ($n = 655$), three years (664), and five years (611) after the accident. Oil spill exposure was estimated using two estimates including distance from the oil spill (A) and modeled estimates of benzene, toluene, ethylbenzene, and xylene (BTEX) compounds (B), and each was dichotomously categorized (A: high-exposure vs low-exposure; B: ≥ 20 mg/m³ vs < 20 mg/m³). Asthma symptoms were evaluated using a standard questionnaire. Oil spill exposure estimates were associated with asthma symptoms on one year (odds ratio (95% confidence interval) A: 1.9 (1.1–3.1); B: 1.6 (0.9–2.7)), three years (A: 1.9 (1.1–3.2); B: 1.3 (0.8–2.2)), and five years (A: 1.2 (0.7–1.9); B: 1.8 (1.1–2.8)) after the oil spill. Significant longitudinal relationship between oil spill exposure estimates and asthma symptoms was also observed (A: 1.6 (1.2–2.2); B: 1.6 (1.1–2.1)). Overall, the effect of oil spill exposure estimates was more severe on younger children. Oil spill exposure estimates were associated with asthma symptoms in children up to five years after the oil spill.

© 2019 Elsevier Ltd. All rights reserved.

1. Introduction

The Hebei Spirit oil spill was one of the largest recent oil spills in the world, second only to the Deepwater Horizon oil spill in the Gulf of Mexico in April 2010. On the morning of December 7, 2007, the crude oil carrier Hebei Spirit collided with a crane barge 10 km

off the west coast of residential area in the Republic of Korea. After the collision, an estimated 12,547 kL of three types of crude oil—UAE upper Zakum, Kuwait export, and Iranian heavy—were spilled. Crude oil is mainly composed of hydrocarbons, including aromatic hydrocarbons such as volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). Aromatic hydrocarbons accounted for approximately 30% of the Hebei Spirit oil spill (Ha et al., 2012) and are relatively well known for the risks to human health (Goldstein et al., 2011).

The populations at risk were people working or living near the affected shoreline. Children are more vulnerable to toxic chemicals than adults as the organs and biological systems of children are undergoing active development and because children breathe and

[☆] This paper has been recommended for acceptance by Maria Cristina Fossi.

* Corresponding author. Department of Social and Preventive Medicine, Sungkyunkwan University School of Medicine, 2066 Seobu-ro, Jangnan-gu, Suwon, Gyeonggi-do, 16419, Republic of Korea. Tel.: +82 31 299 6330; fax: +82 31 299 6229.

E-mail addresses: hkcheong@skku.edu, hkcheong75@gmail.com (H.-K. Cheong).

consume more toxicants from air and food in proportion to their body weight than adults (Au, 2002). The accident occurred less than 10 km off a coast that contained densely populated fishing villages, and consequently, the spilled crude oil reached the nearby shore within 14 h of the spill; the oil slick was 33 km long, 10 m wide, and 10 cm thick after two days (Sim et al., 2010). Moreover, all the VOCs appeared to completely evaporate within a few days after the accident: approximately 10 h for benzene, 48 h for toluene, ethylbenzene, and xylene, and 4 days for the other VOCs (Kim et al., 2012). Therefore, children who were living near the site of the spill were potentially exposed to extremely high ambient levels of benzene, toluene, ethylbenzene, and xylene (BTEX) during the initial period (≤ 4 days) and to several carcinogenic compounds, such as PAHs, for the coming weeks to months, which can be much more persistent in various environmental media and can bioaccumulate over long time periods (Lee et al., 2013).

According to previous epidemiological or toxicological studies associated with large oil spills, these crude oil components have functional and biological effects on respiratory health (Zock et al., 2007), and its effects persist about five years after the Prestige oil spill in adults (Zock et al., 2012). These persistent respiratory symptoms may occur in children living in oil-exposed areas; however, there are few studies regarding the effects of oil spills on the health of children compared to the health of adults, only two cross-sectional studies on the effects of oil exposure on the respiratory health of children. One is a short report that measured peak expiratory flow twice in school children living close to accident point within 12 days after the Braer oil spill (Crum, 1993). Another is our previous study that showed association between oil spill and asthma symptoms one year after the Hebei Spirit oil spill (Jung et al., 2013).

Exposure to VOCs (Rumchev et al., 2004) and PAHs (Gale et al., 2012) was associated with asthma in children. Asthma is one of the most common chronic respiratory diseases in children (Arruda et al., 2005). Wheezing, dry cough, whistling sounds in chest, and shortness of breath are common. Asthma is a complex genetic disorder, and is strongly influenced by the environment, especially in early life (Platts-Mills et al., 2000). Environmental risk factors include tobacco, pollution, obesity, occupational risk factors, microbes, hygiene hypothesis, and stress (Toskala and Kennedy, 2015). Childhood is the most important age for asthma development (Bjerg and Ronmark, 2008), and lifetime asthma prevalence generally decreases with age (Ryan-Ibarra et al., 2016). Meanwhile, there have been no longitudinal studies of children that have evaluated the long-term health consequences of exposure to large oil spills (Zock et al., 2014). Therefore, this study was conducted to investigate the long-term effect on the asthma symptoms of children over the 5 years following the Hebei Spirit oil spill.

2. Materials and methods

2.1. Study population

The study area included four townships that were composed of 83 small villages. These townships were located close to the site of the spill along the heavily contaminated coastline (Fig. 1). At the time of the accident, school students accounted for 5.2% (1020 people) of the total population of the study area (19,690 people) (Taeangun, 2007). There were 13 elementary and 4 middle schools. Of these schools, an elementary school near the shore was closed in 2010 because very few students were enrolled at this school. Surveys were administered a total of three times biennially on elementary and middle school students. The surveys were conducted from June to November 2009 (first survey, 1 year after the spill), March to April 2011 (second survey, 3 years after the spill),

and October to November 2013 (third survey, 5 years after the spill). A total of 828, 760, and 783 students, which accounts for 87.7%, 90.4%, and 95.6% of total student population in the county (Taeangun, 2009, 2011, 2013) participated in the 1st, 3rd, and 5th year, respectively. Subjects for this study were limited to children (age 0–12 years at the time of the accident). After excluding students who were transferred from other regions, were over 13 years old at the time of the accident, were current smokers, or had incomplete information about asthma symptoms, data from 655 students from the baseline survey, 664 students from the second survey, and 611 students from the third survey were used, respectively (Fig. 2).

Each study was approved by the Institutional Review Board of Dankook University Hospital, Cheonan, Republic of Korea (DKUH IRB, 2009-04-027, DKUH IRB, 2012-02-062, DKUH IRB, 2014-06-013). For each survey, written informed consent was obtained from the participants or from their parents.

2.2. Oil exposure assessment

Participation in clean-up work was excluded as an indicator of oil exposure because less than 1% of the study subjects were involved in clean-up activity. Therefore, distance from the spill site of the homes and schools of the participants and the ambient cumulative levels of BTEX were used as indicators of oil exposure estimates in this study.

With respect to distance from the spill, the home and school addresses of each student were geocoded with the ArcGIS Desktop ver. 9.3 geographic information system (ESRI, Redlands, CA, USA), and distance from the heavily contaminated coastline or the site of the oil spill to the home or school of each participant was calculated. For children in preschool at the time of the accident, only the home location was considered, and for children in school at the time of the accident, the location of both home and school were considered. The study area was dichotomously divided into high-exposure and low-exposure areas based on whether the home and/or school was located within 2 km of the heavily contaminated coastline and 20 km of the site of the oil spill. The reason for this classification is that the surface sizes of high-exposure and low-exposure areas are approximately the same; however, the number of students living in the high-exposure area is smaller than those living in the low-exposure area, because the high-exposure area, which close to the accident site, is more rural.

With respect to the ambient cumulative levels of BTEX, a modeling technique that integrated a weathering algorithm with the California Puff (CALPUFF) air dispersion model was used to simulate the air dispersion of the oil components, which has been previously described (Kim et al., 2012). The hourly concentration of each VOC component, such as benzene, toluene, ethylbenzene, and xylene, was calculated for each small village ($n = 83$). The mean (standard deviation) (unit: mg/m^3) exposure estimates of benzene, toluene, ethylbenzene, and xylene among the study participants ($n = 1123$) were 2.9 (3.1), 10.2 (6.6), 11.0 (6.8), and 6.0 (3.7) in the home area; 2.4 (1.7), 9.5 (5.2), 10.2 (5.6), and 5.6 (3.1) in the school area, respectively. All VOC components completely evaporated within four days, so the cumulative levels of BTEX were estimated by adding the hourly benzene, toluene, ethylbenzene, and xylene concentrations for the first four days after the spill. In children in preschool at the time of the accident (age 0 to 6), only the levels in the home area (24 h per day) were considered, and in children in school at the time of the accident (age 7 to 12), the levels of both the home (16 h per day) and school areas (8 h per day) were considered when calculating the cumulative BTEX levels to which each participant was exposed. After calculating the personal cumulative BTEX exposures of each subject, we divided two group based on $20 \text{ mg}/\text{m}^3$, which levels are approximately the 50th percentile of

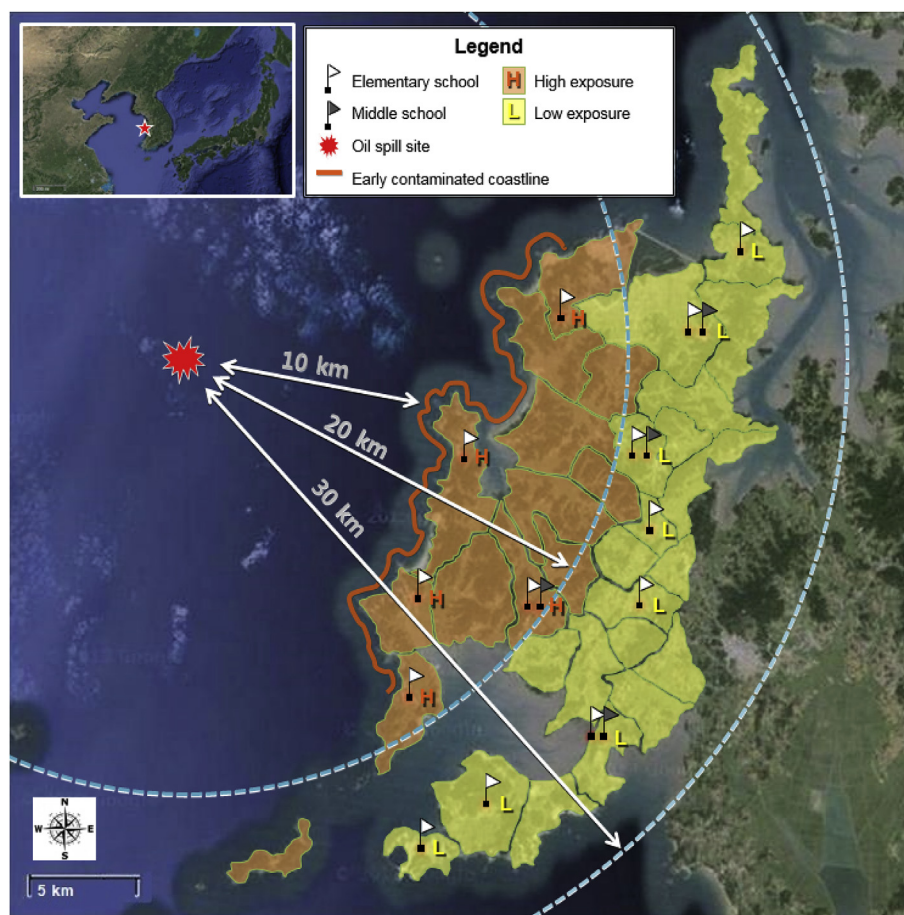


Fig. 1. Geographic map of the study area, including school location and distance from oil spill. The area was divided into low- and high-exposure areas after considering the distance from both the affected shoreline and the spill site.

exposure.

2.3. Prevalence of asthma symptoms

A modified version of the International Study of Asthma and Allergies in Childhood (ISAAC) questionnaire (Korean version) was used to evaluate characteristics associated with asthma (Hong et al., 2003). The questionnaire was distributed in advance of the survey through the schools. The questionnaires were completed by the parents of elementary school students and self-administered by middle school students and were collected on the day of the survey. The questionnaires were inspected by well-trained staff at the survey site, and any missing information was re-asked to the students at the survey site in the case of middle school students, and to the parents by a telephone in the case of elementary school students.

Current asthma symptoms were dichotomously determined by asking the question “did your child had wheezing or whistling in the chest in the last 12 months?” to parents of elementary school students (age range: 5–13 years) or the question “did you have had wheezing and whistling in your chest in the last 12 months?” to middle school students (age range: 12–16 years).

Parental history of asthma, which was considered one of the confounding factors, was defined as a reported history of physician-diagnosed asthma in one or more parents.

2.4. Statistical analyses

SAS version 9.4 was used for the statistical analysis (SAS Institute Inc., Cary, NC, USA). Frequencies and means are calculated for descriptive statistics. Cross-sectional associations between the oil exposure levels, such as the area and modeled estimates of cumulative BTEX chemicals, and the prevalence of current asthma symptoms were evaluated using logistic regression analysis (the PROC LOGISTIC procedure) after adjusting for age, gender, and parental history of asthma. The odds ratio (OR) and 95% confidence interval (95% CI) were automatically calculated by the PROC LOGISTIC procedure. Longitudinal associations were assessed by generalized estimating equation (GEE) models (the PROC GENMOD procedure), which can consider repeated measures within subjects by assuming an autoregressive working correlation structure.

3. Results

The number of participants was 655 in the first survey (1 year after the accident), 664 in the second survey (3 years after the accident), and 611 in the third survey (5 years after the accident) (Table 1). The mean age at the time of the accident was 9 years, 7 years, and 5 years in the first, second, and third surveys, respectively. The mean age at the time of the first, second, and third survey was 10 years, 10 years, and 11 years, respectively, and approximately 30% of the participants were elementary school

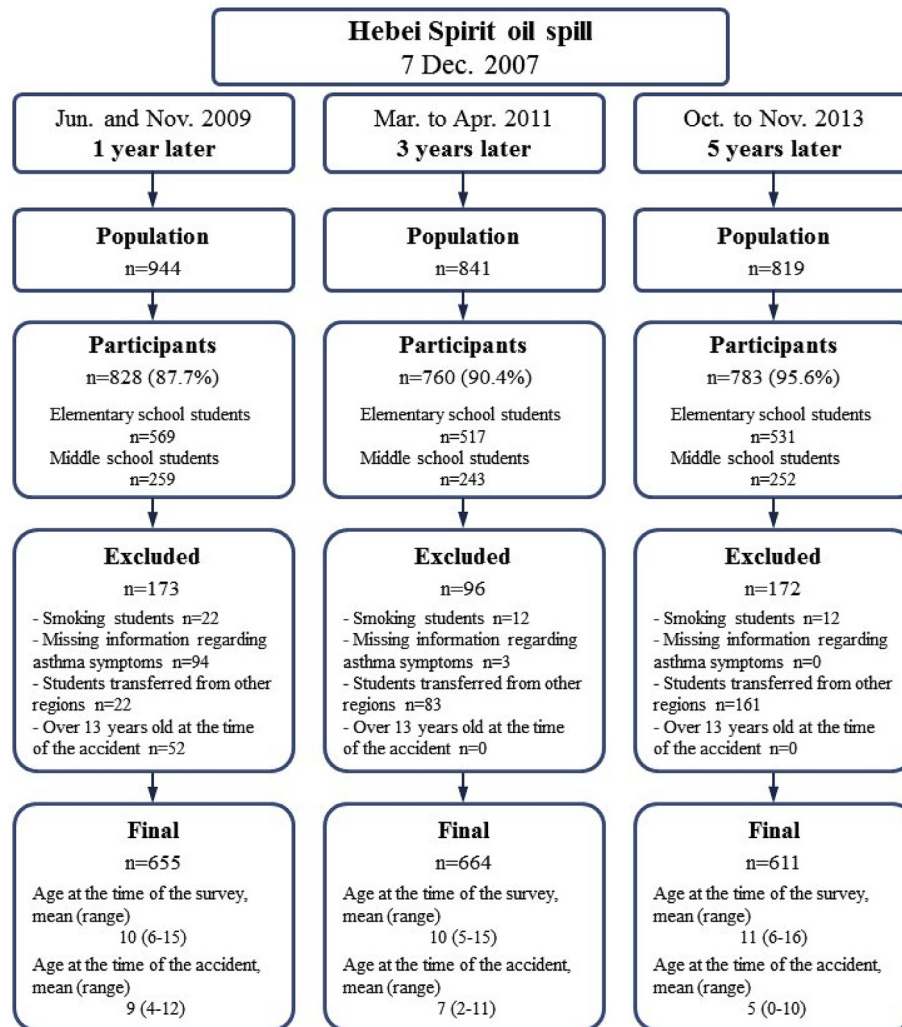


Fig. 2. Flow diagram of student enrollment. Population was based on resident registration data.

students, while 70% were middle school students. Approximately 5% of the children had parents with a history of asthma.

A total of 1123 students participated in the surveys, including 655 students in the first survey, 664 students in the second survey, and 611 students in the third survey (Table 2). Among these students, 391 students participated in both the first and second surveys, and 195 students participated in all three surveys.

To analyze the cross-sectional relationship between oil exposure estimates and asthma symptoms, Table 3 includes subjects who participated in the first ($n = 655$), second ($n = 664$), and/or third surveys ($n = 611$). Prevalence rates of the asthma symptoms were significantly higher in children who resided in the high-exposure area than in those in the low-exposure area 1 year (OR: 1.9, 95% CI: 1.1–3.1) and 3 years (1.9, 1.1–3.2) after the spill; there was no statistically significant association 5 years (1.2, 0.7–1.9) after the spill. When divided into two age groups (0–6 years and 7–12 years at the time of the accident), the difference in effect size between oil exposure estimates and asthma symptoms assessed by OR was higher in the 0–6 age group than in the 7–12 age group. Among the 0–6-year-old children (at the time of the spill), the prevalence rates of the asthma symptoms were approximately three times higher in children who lived in the high-exposure area than in those who lived in the low-exposure area at the time of the spill: 1 year later (2.7, 1.0–7.0) and 3 years later (2.8, 1.3–5.9). When

using BTEX levels as the oil exposure estimates, a similar trend was observed as when using the area index. In addition, there were significant differences between the BTEX levels and asthma symptoms 5 years after the spill (1.8, 1.1–2.8). When the participants were divided by age, among the 0–6 age group, there was a significant association between asthma symptoms and BTEX levels 1 year (2.5, 1.0–6.4) and 5 years (1.7, 1.0–3.0) after the spill.

To identify persistent asthma symptoms associated with the oil spill estimates (Table 4), children who participated in both the first and second surveys ($n = 391$) were assessed. The rates of persistent asthma symptoms were significantly higher in children who resided in the high-exposure area than those who lived in the low-exposure area among the 0–6 age group (15.6% vs 1.4%; OR (95% CI): 14.3 (1.6–130.7)).

When the longitudinal relationship between oil exposure estimates and asthma symptoms was assessed (Table 5), significant associations were observed between the oil exposure indicators, both the area and the modeled estimates of BTEX levels, and the asthma symptoms. These relations were observed for up to five years after the spill when all the participants were included ($n = 1123$). However, there were no associations in the 7–12 age group when the participants were divided into two age groups.

To more precisely analyze the effects of age on the relationship between oil exposure estimates and asthma symptoms (Fig. 3),

Table 1

Demographics and oil-exposure characteristics of the study participants among the all elementary and middle school students through three surveys after the Hebei Spirit oil spill.

	First survey	Second survey	Third survey
Year	2009	2011	2013
Participants (n)	655 (100.0)	664 (100.0)	611 (100.0)
Participation in clean-up work ^a	4 (0.6)	NS	2 (0.3)
Demographics			
Age at the time of survey			
Mean (SD)	10.4 (2.4)	10.3 (2.6)	11.0 (2.6)
Min–Max	6–15	5–15	6–16
Elementary school students (5–13 years)	463 (70.7)	445 (67.0)	409 (66.9)
Middle school students (12–16 years)	192 (29.3)	219 (33.0)	202 (33.1)
Age at the time of the accident			
Mean (SD)	8.7 (2.3)	6.9 (2.5)	5.0 (2.6)
Min–Max	4–12	2–11	0–10
0–6 years	138 (21.1)	294 (44.3)	413 (67.6)
7–12 years	517 (78.9)	370 (55.7)	198 (32.4)
Girls	361 (55.1)	342 (51.5)	310 (50.7)
Parental asthma history	26 (4.0)	40 (6.0)	21 (3.4)
Exposure assessment			
Area ^b			
High exposure	213 (32.5)	192 (28.9)	160 (26.2)
Low exposure	442 (67.5)	472 (71.1)	451 (73.8)
BTEX exposure ^c			
≥ 20 mg/m ³	348 (53.1)	346 (52.1)	302 (49.4)
< 20 mg/m ³	307 (46.9)	318 (47.9)	309 (50.6)

Data are presented as n (%) unless otherwise indicated.

NS, not surveyed.

^a More than a week.

^b Area was divided into home and school located within 2 km from the early contaminated coastline and 20 km from the site of the oil spill among school children; only the home location was considered among children in preschool at the time of the accident.

^c Cumulative concentrations of benzene, toluene, ethylbenzene, and xylene for up to 4 days after the accident based on modeling (Kim et al., 2012).

Table 2

Participation status in the surveys 1, 3, and 5 years after the Hebei Spirit oil spill accident (total n = 1123).

	n
One-time participation	
In 2009 (1 year later)	248
In 2011 (3 years later)	68
In 2013 (5 years later)	195
Two-time participation	
In 2009, 2011	196
In 2011, 2013	205
In 2009, 2013	16
Three-time participation	
In 2009, 2011, and 2013	195

This study was conducted via school-based surveys in the exposed area.

participant data from all three surveys (n = 195) were divided into 1-year age groups. The differences in the risk of developing asthma symptoms between the low-exposure and the high-exposure groups were larger in the younger age group. Such age-dependent associations were apparent when the area index was used as an oil exposure indicator rather than the modeled estimates of BTEX levels.

4. Discussion

In this biennial longitudinal study have been conducted for five years after the Hebei Spirit oil spill. Two oil exposure estimates, distance from the spill (A) and modeled estimates of BTEX chemicals (B), were significantly associated with asthma symptoms in children. These associations persisted to a considerable extent for up to five years; however, the strengths of the associations weakened slightly over time. Younger age at the time of the accident demonstrated a greater influence on the association between

asthma symptoms and oil exposure estimates. Our findings suggest that young children living in high-oil-exposure areas may develop persistent asthma symptoms even without participating in post-oil-spill clean-up work, which is a well-known direct route oil exposure (Zock et al., 2012).

To our knowledge, this is the first longitudinal study on the health effects of a major oil spill on children. Indeed, in children, evidence is lacking regarding short-term and long-term health effects of oil spills (Goldstein et al., 2011), and even in adults, there have been very few longitudinal studies assessing the long-term health effects of oil spills (Zock et al., 2014). Nine major oil spills have been evaluated via epidemiological studies on residents and/or clean-up workers since the late 1980s (Goldstein et al., 2011). However, until the late 2000s, these studies assessed only acute health effects from oil spills and were typically performed immediately or less than a year after the accident; these studies were also based on relatively small study populations. A common finding of these studies was an increased prevalence of acute respiratory symptoms. Since 2007, studies on the Prestige oil spill have suggested that clean-up workers may experience long-term respiratory effects (Rodriguez-Trigo et al., 2010; Zock et al., 2007) and may develop persistent respiratory symptoms (Zock et al., 2012). When respiratory symptoms in local fishermen were studied 1 year after having participated in clean-up work, symptoms of the lower respiratory tract were seen to be prevalent in clean-up workers (Zock et al., 2007). The risk of developing symptoms increased with the duration of clean-up work and the number of tasks performed, and the risk decreased with time elapsed since final exposure. When Zock et al. followed up on the respiratory symptoms of the same population 5 years after the Prestige oil spill, the clean-up workers still exhibited increased prevalence of respiratory symptoms compared with non-exposed control subjects (Zock et al., 2012). The risk of developing persistent respiratory symptoms increased with degree of exposure compared with subjects who did not

Table 3
Cross-sectional associations between oil exposure and current asthma symptoms.

	1 year later, 2009 (n = 655)			3 years later, 2011 (n = 664)			5 years later, 2013 (n = 611)		
	Oil exposure			Oil exposure			Oil exposure		
Area ^b	High exposure (n = 213)	Low exposure (n = 442)	OR (95% CI)	High exposure (n = 192)	Low exposure (n = 472)	OR (95% CI)	High exposure (n = 160)	Low exposure (n = 451)	OR (95% CI)
All	14.6% (31/213)	8.6% (38/442)	1.9 (1.1–3.1)	13.5% (26/192)	8.7% (41/472)	1.9 (1.1–3.2)	14.4% (23/160)	13.3% (60/451)	1.2 (0.7–1.9)
Age 0 to 6 ^a	25.0% (10/40)	12.2% (12/98)	2.7 (1.0–7.0)	21.1% (15/71)	9.4% (21/223)	2.8 (1.3–5.9)	17.2% (17/99)	14.3% (45/314)	1.3 (0.7–2.3)
Age 7 to 12 ^a	12.1% (21/173)	7.6% (26/344)	1.7 (0.9–3.2)	9.1% (11/121)	8.0% (20/249)	1.2 (0.6–2.7)	9.8% (6/61)	11.0% (15/137)	0.9 (0.3–2.4)
BTEX levels ^c	≥20 mg/m ³ (n = 348)	<20 mg/m ³ (n = 307)		≥20 mg/m ³ (n = 346)	<20 mg/m ³ (n = 318)		≥20 mg/m ³ (n = 302)	<20 mg/m ³ (n = 309)	
All	11.8% (41/348)	9.1% (28/307)	1.6 (0.9–2.7)	11.3% (39/346)	8.8% (28/318)	1.3 (0.8–2.2)	16.6% (50/302)	10.7% (33/309)	1.8 (1.1–2.8)
Age 0 to 6 ^a	23.5% (12/51)	11.5% (10/87)	2.5 (1.0–6.4)	15.3% (21/137)	9.6% (15/157)	1.6 (0.8–3.3)	18.9% (36/191)	11.7% (26/222)	1.7 (1.0–3.0)
Age 7 to 12 ^a	9.8% (29/297)	8.2% (18/220)	1.3 (0.7–2.4)	8.6% (18/209)	8.1% (13/161)	1.1 (0.5–2.3)	12.6% (14/111)	8.1% (7/87)	1.5 (0.6–4.1)

Asthma symptoms were determined based on the answers to the question “has your child had wheezing or whistling in the last 12 months?”

Values are presented by prevalence (%), odds ratio (OR), and 95% confidence interval (CI). ORs (95% CIs) were adjusted for age (continuous), gender, and parental asthma history.

^a At the time of the accident.

^b Area was divided into home and school located within 2 km from the early contaminated coastline and 20 km from the site of the oil spill among school children (age 7 to 12); only the home location was considered among children in preschool (age 0 to 6) at the time of the accident.

^c Ambient cumulative concentrations of benzene, toluene, ethylbenzene, and xylene for up to four days after the accident based on modeling (Kim et al., 2012).

exhibit any symptoms. These results regarding the long-term effects on respiratory health of the Prestige oil spill, although adults were studied and followed, are consistent with the results of this study.

Notably, in the present study, children who were younger at the time of the accident suffered greater health effects, such as higher prevalence and persistence rate of asthma symptoms, than the children who were relatively older at the time of the accident. Given these observations, exposure during the early years of life is likely to play a crucial role in asthma etiology (Platts-Mills et al., 2000; Raedler and Schaub, 2014). It is generally well known that children might be more susceptible to the adverse effects of oil exposure than adults because the immune systems and lungs of children are still developing during early childhood (Schwartz, 2004). In addition, the bodies of children are less efficient at detoxification of environmental chemicals, and children breathe more air per kilogram of body weight than adults. Therefore, given the results of this study, the younger a child is when an oil spill occurs, the greater the chance that asthma symptoms will appear and persist. Early environmental exposure, when the child is in the process of growth and development, could be a critical and could cause the future development of asthma symptoms in the child, leading to long-lasting effects (Michel et al., 2013).

In addition, these effects of age might be explained by the fact that asthma reverts spontaneously as children grow. Childhood asthma generally manifests during the first 5 years of life due to environment-driven exacerbation (Thomas et al., 2008) and typically tends to remit with age (Bjerg and Ronmark, 2008; Yao et al., 2011). In addition, chronic symptoms, such as higher rates of episodic wheezing and bronchial hyper-responsiveness, are detected more frequently in early life than in young adults (Martinez and Vercelli, 2013). Likewise, the minor effects of the oil spill among children in the older age group (age 7–12 years) could be associated with the lower asthma prevalence and better resistance of this group than the younger age group (age 0–6 years). The results from one of the studies on the World Trade Center disaster support this hypothesis. Among children <5 years of age, an increase in the prevalence of asthma diagnosis was observed after 2 years even among those not directly exposed to the dust cloud (Thomas et al., 2008). When followed up on after six years, there remained respiratory symptoms associated with 9/11-related exposure in younger children (Stellman et al., 2013). Likewise, childhood, particularly early childhood, seems to be a vulnerable time for the development of asthma symptoms due to environmental disasters.

Children living close to the site of the oil spill appear to have been directly and indirectly exposed to numerous oil toxicants. Participation in post-oil-spill clean-up activities is known to be a major risk factor that has longer-term adverse effects on health among adults (Rodriguez-Trigo et al., 2010). However, nearly all the children (>99%) in this study had not participated in clean-up efforts after the spill, and even those who had participated in clean-up activity, had worked for 1 day or less than 1 week. One could cautiously speculate that children are affected by different sources, pathways, and routes of exposure than adults in terms of intake of air, food, soil, and dust per unit body weight and surface area (Sexton et al., 2005). The predicted major sources of long-term exposure to chemicals from the oil spill, such as PAHs and alkylated PAHs, can persist in the environment, accumulate, and be toxic to humans (Goldstein et al., 2011; Solomon and Janssen, 2010). These compounds could have been inhaled while residing at home or attending school near the affected shoreline as well as via dermal contact, ingestion of food and water, and contact with beach sand or oil sediment, especially by children. Another possible route of oil exposure is inhalation and partial dermal contact of ambient BTEX

Table 4

Persistence rates of the asthma symptoms over a 2-year follow-up from 2009 to 2011 (n = 391).

Persistent asthma symptoms ^a	Follow-up (2009–2011)			
Area ^c	High exposure (n = 137)	Low exposure (n = 254)	OR (95% CI)	p-Value
All	4.4% (6/137)	2.4% (6/254)	2.1 (0.6–6.6)	0.23
Age 0 to 6 ^b	15.6% (5/32)	1.4% (1/70)	14.3 (1.6–130.7)	0.02
Age 7 to 12 ^b	1.0% (1/105)	2.7% (5/184)	0.5 (0.1–4.3)	0.50
BTEX levels ^d	≥20 mg/m ³ (n = 202)	<20 mg/m ³ (n = 189)	OR (95% CI)	p-Value
All	4.0% (8/202)	2.1% (4/189)	2.3 (0.7–8.1)	0.19
Age 0 to 6 ^b	11.9% (5/42)	1.7% (1/60)	8.3 (0.9–74.0)	0.06
Age 7 to 12 ^b	1.9% (3/160)	2.3% (3/129)	1.0 (0.2–6.2)	0.96

Asthma symptoms were determined based on the answers to the question “has your child had wheezing or whistling in the last 12 months?”

Values are presented by prevalence (%), odds ratio (OR), and 95% confidence interval (CI). ORs (95% CIs) and p-values were adjusted for age (continuous), gender, and parental asthma history.

^a Asthma symptoms present at both baseline (2009) and follow-up (2011) surveys.^b At the time of the accident.^c Area was divided into home and school located within 2 km from the early contaminated coastline and 20 km from the site of the oil spill among school children (age 7 to 12); only the home location was considered among children in preschool (age 0 to 6) at the time of the accident.^d Cumulative concentrations of benzene, toluene, ethylbenzene, and xylene for up to 4 days after the accident based on modeling (Kim et al., 2012).**Table 5**

Longitudinal associations between oil spill exposure levels and asthma symptoms for up to 5 years after the Hebei Spirit oil spill (total n = 1123).

	Asthma symptoms			
	Model 1 (n = 1123)		Model 2 (n = 195)	
	OR (95% CI)	p-Value	OR (95% CI)	p-Value
Area ^b , high exposure				
All	1.6 (1.2–2.2)	0.004	2.2 (1.2–3.9)	0.01
Age 0 to 6 ^a	1.9 (1.2–2.9)	0.006	2.6 (1.0–6.7)	0.04
Age 7 to 12 ^a	1.3 (0.9–2.1)	0.19	1.9 (0.8–4.3)	0.12
BTEX exposure ^c , ≥20 mg/m ³				
All	1.6 (1.1–2.1)	0.006	1.7 (0.9–3.1)	0.09
Age 0 to 6 ^a	1.8 (1.2–2.8)	0.007	1.8 (0.8–4.2)	0.19
Age 7 to 12 ^a	1.3 (0.8–2.0)	0.29	1.4 (0.6–3.8)	0.45

Model 1: all participating school students (n = 1123); Model 2: school students who completed at three surveys (n = 195).

Generalized estimating equation (GEE) models assuming an autoregressive working correlation structure were used for this longitudinal analysis and were adjusted for age (continuous), gender (male, female), parental asthma history (no, yes), and elapsed time (ordinal scale; coded as 1 (first survey), 2 (second survey), or 3 (third survey)).

^a At the time of the accident.^b Area was divided into home and school located within 2 km from the early contaminated coastline and 20 km from the site of the oil spill among school children (age 7 to 12); only the home location was considered among children in preschool (age 0 to 6) at the time of the accident.^c Cumulative concentrations of benzene, toluene, ethylbenzene, and xylene for up to 4 days after the accident based on modeling (Kim et al., 2012).

components, which are carcinogens in crude oil, soon after the spill (<4 days). The oil spill occurred less than 10 km off the coast, and the oil reached the shore of the study area within 14 h after the spill. All benzene (<10 h) and other volatile crude oil components (<4 days) evaporated soon after the spill, and the atmospheric BTEX concentrations were abnormally high in the study area, as determined by modeling (Kim et al., 2012). Atmospheric photochemical activity converts volatile hydrocarbons to reactive aldehydes, leading to ozone formation. Both of these activities can synergistically enhance acute and chronic IgE-mediated inflammation, including asthma attacks (Eggleston, 2007; Goldstein et al., 2011). In addition, the BTEX (Arif and Shah, 2007; Rumchev et al., 2004) and PAH (Miller et al., 2010) components of the crude oil are well known to increase the prevalence of asthma among adults and children.

The mechanisms of development of these prolonged asthma symptoms from the oil spill remain largely unknown. Some possible mechanisms are increased bronchial responsiveness, induced airway sensitization, increased oxidative stress, and/or

elevated growth factor activity, suggestive of a long-lasting airway remodeling process associated with the inhalation of high levels of various irritants (Maestrelli et al., 2009; Zock et al., 2012). Additionally, oil irritants could induce disruption or injury of the bronchial epithelial structure, causing increased inflammatory reactions mediated by cytokines and leukotrienes, increased secretion of growth factors, and eventually long-lasting airway inflammation and bronchial hyper-responsiveness. Furthermore, all the processes described above could be involved in epigenetic mechanisms, such as DNA methylation, histone modification, and microRNA transcript silencing (DeVries and Vercelli, 2016; Klingbeil et al., 2014). A recent RNA-seq study showed that crude oil treatment of human airway epithelial cells had strong effects on several genes that were differentially expressed compared to controls (Liu et al., 2016). Maternal exposure to PAHs altered DNA methylation (Herbstman et al., 2012; Tang et al., 2012), and DNA methylation of 5'-CpG islands was associated with asthma symptoms in young children (Perera et al., 2009). Likewise, exposure to oil components could promote cytosine methylation-mediated gene silencing, which might cause persistent and long-lasting asthma symptoms in childhood (Hew et al., 2015; Ho, 2010).

The main strength of this study was the longitudinal design of the study, which included all school-aged students from the most affected areas every 2 years for 5 years after the spill (a total of three surveys; after 1 year, 3 years, and 5 years). Another strength was that this study inspected the entire school-aged population of the study area. Participation rate (%) was very high for all 3 surveys: 88% in the first survey, 90% in the second survey, and 96% in the third survey, relative to the total population. Because this study included all of the students in the affected area, there was almost no potential for selection bias as it would be impossible that children from the high-exposure area exhibiting new respiratory symptoms would be more likely to participate in this study than those from the low-exposure area. In addition, the methodology, asthma symptom measurements, and interpretation of the responses were identical in all three surveys. Nevertheless, this study had some limitations. Information regarding asthma symptoms before the oil spill was not available. However, when compared to the low-exposure area, the high-exposure area is more rural, where asthma symptoms in children are often as low as in more urban areas. Another limitation of this study is the possibility of a reporting bias due to the use of parents as proxies for the children or due to the change in the respondent to the survey from the child to the adult if the child graduated from elementary school to middle school during the follow-up period. A small sample size was another limitation to conduct the stratified analyses. The very small

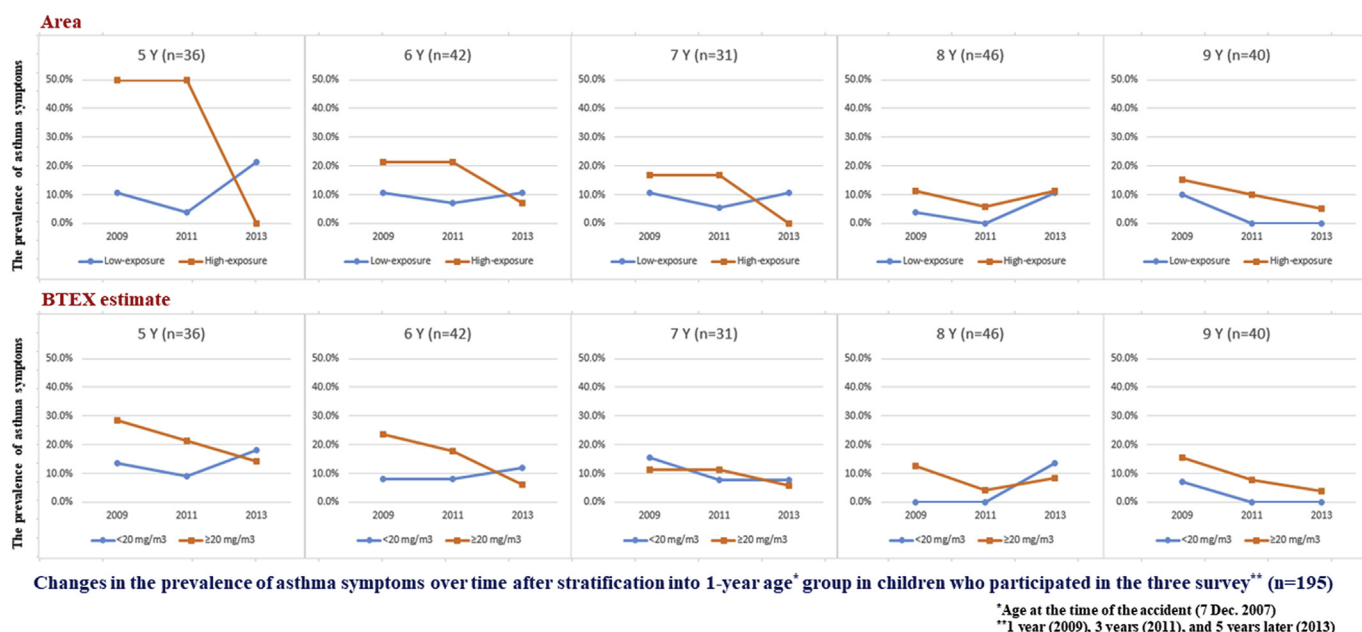


Fig. 3. Effect of age on the relationship between oil exposure and asthma symptoms. Data obtained from children who participated in all three surveys ($n = 195$) was used and was stratified into 1-year age groups. Each 1-year group was stratified by age at the time of the accident (December 7, 2007).

number of people is driven the very wide 95% confidence interval. Fourth, there might be uncertainty in oil exposure estimates, particularly in modeled estimates of BTEX chemicals, since the actual BTEX levels were not measured at the time of the accident. Finally, there is a limitation that is assumed to be exposed 24 h in outdoor for four days right after the accident, when calculated exposure estimates of BTEX compounds.

In conclusion, oil exposure was associated with aggravation and persistence of asthma symptoms from cross-sectional and longitudinal observations up to five years after the spill. An increase in the prevalence of asthma symptoms was found 1 year, 3 years, and 5 years after the Hebei Spirit oil spill. The prevalence of asthma symptoms gradually decreased over time, and the high risk of asthma symptom development was less apparent. This finding may suggest long-lasting and perhaps irreversible airway damage 5 years later, and reversion of the adverse effects may also occur over time. Children are susceptible subpopulations among oil-exposed residents. Continued, long-term medical monitoring of children is required to track the persistence of these asthma symptoms. Guidelines of preventive and therapeutic intervention are essential. Lessons learned should guide future responses to oil spill disasters.

Acknowledgments

This research was supported by a National Research Foundation grant from the Ministry of Science and ICT (No. 2017R1C1B5018032) and by a Tae'an Environmental Health Center operating grant from the Ministry of Environment, Republic of Korea.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2019.02.034>.

References

Arif, A.A., Shah, S.M., 2007. Association between personal exposure to volatile

- organic compounds and asthma among US adult population. *Int. Arch. Occup. Environ. Health* 80, 711–719.
- Arruda, L.K., Sole, D., Baena-Cagnani, C.E., Naspitz, C.K., 2005. Risk factors for asthma and atopy. *Curr. Opin. Allergy Clin. Immunol.* 5, 153–159.
- Au, W.W., 2002. Susceptibility of children to environmental toxic substances. *Int. J. Hyg Environ. Health* 205, 501–503.
- Bjerg, A., Ronmark, E., 2008. Asthma in school age: prevalence and risk factors by time and by age. *Clin. Res. J* 2 (Suppl. 1), 123–126.
- Crum, J.E., 1993. Peak expiratory flow rate in schoolchildren living close to Braer oil spill. *BMJ* 307, 23–24.
- DeVries, A., Vercelli, D., 2016. Epigenetic mechanisms in asthma. *Ann. Am. Thorac. Soc.* 13 (Suppl. 1), S48–S50.
- Eggleston, P.A., 2007. The environment and asthma in US inner cities. *Chest* 132, 782S–788S.
- Gale, S.L., Noth, E.M., Mann, J., Balmes, J., Hammond, S.K., Tager, I.B., 2012. Polycyclic aromatic hydrocarbon exposure and wheeze in a cohort of children with asthma in Fresno, CA. *J. Expo. Sci. Environ. Epidemiol.* 22, 386–392.
- Goldstein, B.D., Osofsky, H.J., Lichtveld, M.Y., 2011. The Gulf oil spill. *N. Engl. J. Med.* 364, 1334–1348.
- Ha, M., Kwon, H., Cheong, H.K., Lim, S., Yoo, S.J., Kim, E.J., Park, S.G., Lee, J., Chung, B.C., 2012. Urinary metabolites before and after cleanup and subjective symptoms in volunteer participants in cleanup of the Hebei Spirit oil spill. *Sci. Total Environ.* 429, 167–173.
- Herbstman, J.B., Tang, D., Zhu, D., Qu, L., Sjödin, A., Li, Z., Camann, D., Perera, F.P., 2012. Prenatal exposure to polycyclic aromatic hydrocarbons, benzo[a]pyrene–DNA adducts, and genomic DNA methylation in cord blood. *Environ. Health Perspect.* 120, 733–738.
- Hew, K.M., Walker, A.I., Kohli, A., Garcia, M., Syed, A., McDonald-Hyman, C., Noth, E.M., Mann, J.K., Pratt, B., Balmes, J., Hammond, S.K., Eisen, E.A., Nadeau, K.C., 2015. Childhood exposure to ambient polycyclic aromatic hydrocarbons is linked to epigenetic modifications and impaired systemic immunity in T cells. *Clin. Exp. Allergy* 45, 238–248.
- Ho, S.M., 2010. Environmental epigenetics of asthma: an update. *J. Allergy Clin. Immunol.* 126, 453–465.
- Hong, S.J., Kim, S.W., Oh, J.W., Rah, Y.H., Ahn, Y.M., Kim, K.E., Koh, Y.Y., Lee, S.I., 2003. The validity of the ISAAC written questionnaire and the ISAAC video questionnaire (AVQ 3.0) for predicting asthma associated with bronchial hyperactivity in a group of 13–14 year old Korean schoolchildren. *J. Kor. Med. Sci.* 18, 48–52.
- Jung, S.C., Kim, K.M., Lee, K.S., Roh, S., Jeong, W.C., Kwak, S.J., Lee, I.J., Choi, Y.H., Noh, S.R., Hur, J.I., 2013. Respiratory effects of the Hebei Spirit oil spill on children in Taean, Korea. *Allergy Asthma Immunol. Res.* 5, 365–370.
- Kim, J.H., Kwak, B.K., Ha, M., Cheong, H.K., Yi, J., 2012. Modeling human exposure levels to airborne volatile organic compounds by the Hebei Spirit oil spill. *Environ. Health Toxicol.* 27, e2012008.
- Klingbeil, E.C., Hew, K.M., Nygaard, U.C., Nadeau, K.C., 2014. Polycyclic aromatic hydrocarbons, tobacco smoke, and epigenetic remodeling in asthma. *Immunol. Res.* 58, 369–373.
- Lee, C.H., Lee, J.H., Sung, C.G., Moon, S.D., Kang, S.K., Lee, J.H., Yim, U.H., Shim, W.J., Ha, S.Y., 2013. Monitoring toxicity of polycyclic aromatic hydrocarbons in

- intertidal sediments for five years after the Hebei Spirit oil spill in Taean, Republic of Korea. *Mar. Pollut. Bull.* 76, 241–249.
- Liu, Y.Z., Roy-Engel, A.M., Baddoo, M.C., Flemington, E.K., Wang, G., Wang, H., 2016. The impact of oil spill to lung health—Insights from an RNA-seq study of human airway epithelial cells. *Gene* 578, 38–51.
- Maestrelli, P., Boschetto, P., Fabbri, L.M., Mapp, C.E., 2009. Mechanisms of occupational asthma. *J. Allergy Clin. Immunol.* 123, 531–542 quiz 543–544.
- Martinez, F.D., Vercelli, D., 2013. Asthma. *Lancet* 382, 1360–1372.
- Michel, S., Busato, F., Genuneit, J., Pekkanen, J., Dalphin, J.C., Riedler, J., Mazaleyrat, N., Weber, J., Karvonen, A.M., Hirvonen, M.R., Braun-Fahrlander, C., Lauener, R., von Mutius, E., Kabisch, M., Tost, J., 2013. Farm exposure and time trends in early childhood may influence DNA methylation in genes related to asthma and allergy. *Allergy* 68, 355–364.
- Miller, R.L., Garfinkel, R., Lendor, C., Hoepner, L., Li, Z., Romanoff, L., Sjodin, A., Needham, L., Perera, F.P., Whyatt, R.M., 2010. Polycyclic aromatic hydrocarbon metabolite levels and pediatric allergy and asthma in an inner-city cohort. *Pediatr. Allergy Immunol.* 21, 260–267.
- Perera, F., Tang, W.Y., Herbstman, J., Tang, D., Levin, L., Miller, R., Ho, S.M., 2009. Relation of DNA methylation of 5'-CpG island of ACSL3 to transplacental exposure to airborne polycyclic aromatic hydrocarbons and childhood asthma. *PLoS One* 4, e4488.
- Platts-Mills, T.A., Rakes, G., Heymann, P.W., 2000. The relevance of allergen exposure to the development of asthma in childhood. *J. Allergy Clin. Immunol.* 105, S503–S508.
- Raedler, D., Schaub, B., 2014. Immune mechanisms and development of childhood asthma. *Lancet Respir. Med.* 2, 647–656.
- Rodriguez-Trigo, G., Zock, J.P., Pozo-Rodriguez, F., Gomez, F.P., Monyarch, G., Bouso, L., Coll, M.D., Vereia, H., Anto, J.M., Fuster, C., Barbera, J.A., Group, S.E.-P.S., 2010. Health changes in fishermen 2 years after clean-up of the Prestige oil spill. *Ann. Intern. Med.* 153, 489–498.
- Rumchev, K., Spickett, J., Bulsara, M., Phillips, M., Stick, S., 2004. Association of domestic exposure to volatile organic compounds with asthma in young children. *Thorax* 59, 746–751.
- Ryan-Ibarra, S., Milet, M., Lutzker, L., Rodriguez, D., Induni, M., Kreutzer, R., 2016. Age, period, and cohort effects in adult lifetime asthma prevalence in California: an application of hierarchical age-period-cohort analysis. *Ann. Epidemiol.* 26, 87–92.
- Schwartz, J., 2004. Air pollution and children's health. *Pediatrics* 113, 1037–1043.
- Sexton, K., Adgate, J.L., Church, T.R., Ashley, D.L., Needham, L.L., Ramachandran, G., Fredrickson, A.L., Ryan, A.D., 2005. Children's exposure to volatile organic compounds as determined by longitudinal measurements in blood. *Environ. Health Perspect.* 113, 342–349.
- Sim, M.S., Jo, I.J., Song, H.G., 2010. Acute health problems related to the operation mounted to clean the Hebei Spirit oil spill in Taean, Korea. *Mar. Pollut. Bull.* 60, 51–57.
- Solomon, G.M., Janssen, S., 2010. Health effects of the Gulf oil spill. *J. Am. Med. Assoc.* 304, 1118–1119.
- Stellman, S.D., Thomas, P.A., S, S.O., Brackbill, R.M., Farfel, M.R., 2013. Respiratory health of 985 children exposed to the World Trade Center disaster: report on world trade center health registry wave 2 follow-up, 2007–2008. *J. Asthma* 50, 354–363.
- Taeon-gun, 2007. Taeon Statistical Yearbook [In Korean]. Available. <http://law.taeon.go.kr/asp/tong/tong.asp>. (Accessed 24 March 2014).
- Taeon-gun, 2009. Taeon Statistical Yearbook [In Korean]. Available. <http://law.taeon.go.kr/asp/tong/tong.asp>. (Accessed 5 September 2012).
- Taeon-gun, 2011. Taeon Statistical Yearbook [In Korean]. Available. <http://law.taeon.go.kr/asp/tong/tong.asp>. (Accessed 24 March 2014).
- Taeon-gun, 2013. Taeon Statistical Yearbook [In Korean]. Available. <http://law.taeon.go.kr/asp/tong/tong.asp>. (Accessed 24 March 2014).
- Tang, W.Y., Levin, L., Talaska, G., Cheung, Y.Y., Herbstman, J., Tang, D., Miller, R.L., Perera, F., Ho, S.M., 2012. Maternal exposure to polycyclic aromatic hydrocarbons and 5'-CpG methylation of interferon-gamma in cord white blood cells. *Environ. Health Perspect.* 120, 1195–1200.
- Thomas, P.A., Brackbill, R., Thalji, L., DiGrande, L., Campolucci, S., Thorpe, L., Henning, K., 2008. Respiratory and other health effects reported in children exposed to the World Trade Center disaster of 11 September 2001. *Environ. Health Perspect.* 116, 1383–1390.
- Toskala, E., Kennedy, D.W., 2015. Asthma risk factors. *Int. Forum Allergy Rhinol.* 5 (Suppl. 1), S11–S16.
- Yao, T.C., Ou, L.S., Yeh, K.W., Lee, W.I., Chen, L.C., Huang, J.L., 2011. Associations of age, gender, and BMI with prevalence of allergic diseases in children: PATCH study. *J. Asthma* 48, 503–510.
- Zock, J.P., Rodriguez-Trigo, G., Pozo-Rodriguez, F., Barbera, J.A., Bouso, L., Torralba, Y., Anto, J.M., Gomez, F.P., Fuster, C., Vereia, H., Grp, S.E.-P.S., 2007. Prolonged respiratory symptoms in clean-up workers of the Prestige oil spill. *Am. J. Respir. Crit. Care Med.* 176, 610–616.
- Zock, J.P., Rodriguez-Trigo, G., Rodriguez-Rodriguez, E., Espinosa, A., Pozo-Rodriguez, F., Gomez, F., Fuster, C., Castano-Vinyals, G., Anto, J.M., Barbera, J.A., 2012. Persistent respiratory symptoms in clean-up workers 5 years after the Prestige oil spill. *Occup. Environ. Med.* 69, 508–513.
- Zock, J.P., Rodriguez-Trigo, G., Rodriguez-Rodriguez, E., Souto-Alonso, A., Espinosa, A., Pozo-Rodriguez, F., Gomez, F.P., Fuster, C., Castano-Vinyals, G., Anto, J.M., Barbera, J.A., 2014. Evaluation of the persistence of functional and biological respiratory health effects in clean-up workers 6 years after the prestige oil spill. *Environ. Int.* 62, 72–77.