Review Article

Estimating Benzene Exposure Level over Time and by Industry Type through a Review of Literature on Korea

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ABSTRACT

The major purpose of this study is to construct a retrospective exposure assessment for benzene through a review of literature on Korea. Airborne benzene measurements reported in 34 articles were reviewed. A total of 15,729 individual measurements were compiled. Weighted arithmetic means [AM(w)] and their variance calculated across studies were summarized according to 5-year period intervals (prior to the 1970s through the 2010s) and industry type. Industries were classified according to Korea Standard Industrial Classification (KSIC) using information provided in the literature. We estimated quantitative retrospective exposure to benzene for each cell in the matrix through a combination of time and KSIC. Analysis of the AM(w) indicated reductions in exposure levels over time, regardless of industry, with mean levels prior to the 1980—1984 period of 50.4 ppm ($n = 2,289$), which dropped to 2.8 ppm ($n = 305$) in the 1990—1994 period, and to 0.1 ppm ($n = 294$) in the 1995—1999 period. There has been no improvement since the 2000s, when the AM(w) of 4.3 ppm ($n = 6,211$) for the 2005—2009 period and 4.5 ppm ($n = 3,358$) for the 2010—2013 period were estimated. A comparison by industry found no consistent patterns in the measurement results. Our estimated benzene measurements can be used to determine not only the possibility of retrospective exposure to benzene, but also to estimate the level of quantitative or semiquantitative retrospective exposure to benzene.

1. Introduction

According to the database compiled through the Survey for National Work Environment Status of 2009, which has been conducted every 5 years in Korea since 1993, the respective numbers of factories and workers directly handling products containing benzene were estimated to be 450 and 2,255 [1]. No study has reported comprehensive benzene exposure levels classified based on time, type of industry, job, and other determinants for estimation of retrospective exposure in Korea. There may currently be an excessive risk of hematopoietic disorders due to relatively high past exposures among workers who were exposed to benzene in specific industries, jobs, or eras. Basic information on the likelihood, duration, and intensity of benzene exposure should be estimated in order to associate with health effects, including hematopoietic diseases. Among the 236 cases of hematopoietic diseases reported to the Korea Workers Compensation and Welfare Service during

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2000−2009, 35 were accepted as cases of hematopoietic disease caused by exposure to benzene [2].

One of the most challenging tasks in examining the association of work environment with disease is the lack of past exposure information, such as industry, job, and work characteristics. The methodologies and the results of using the expert system and historical measurement data for estimating retrospective exposures have been reported elsewhere [3,4]. In Korea, no study has yet been conducted to estimate retrospective exposure to benzene, although substantial airborne benzene measurements have been reported regarding specific periods or purposes. The major purpose of this study is to estimate retrospective exposure to benzene through a comprehensive review of literature reported in Korea.

2. Materials and methods

2.1. Scope of literature search

Airborne benzene measurements reported in scientific journals and government documents for occupational settings in Korea were summarized through an extensive literature review. The keywords used for the literature search were 'benzene', 'thinner', and 'solvent' and they were used singly and in combination. Of the 38 published documents reviewed, a total of 34 were found to feature benzene measurement data and were used to estimate retrospective exposures to benzene (Table 1). Four documents were excluded for the following reasons: lack of a range or geometric mean (GM) and geometric standard deviation (GSD) for airborne benzene measurement ($n = 1$) [5]; comparison of sampling and analytical methods ($n = 1$) [6]; and measurements from indoor environments for either community or general population use ($n = 2$) [7,8] (Table 1).

2.2. Selection and analysis of measurements

All personal or area airborne measurements taken were included in the summary statistics regardless of the type of charcoal sorbent or sampling device (pump, passive sampler, or detecting tube) or duration of sampling. Thus, due to the lack of a sufficient number of measurements, all measurements taken for either > 1 hour or for short term exposures (i.e., < 15 minutes) were included for estimating exposure. Standard sampling and internationally approved analytic methods were found to be used to collect airborne benzene. Two approaches were used to summarize airborne benzene measurements.

First, all articles reporting airborne benzene measurements were summarized and categorized according to the type of benzene sample, such as long term samples taken for > 1 hour and short term samples taken for < 15 minutes. Benzene measurements taken by a colorimetric detector tube were assigned to the short term period sampling category (≤ 15 minutes).

Table 1
Inclusion and exclusion criteria for database on airborne benzene measurements through a review of literature reported in Korea

Characteristics	No. of publications
No. of publications on airborne benzene monitoring	38
Lack of a range or a GM and GSD	1
Validation study of analytical method	1
Measurement from indoor environments	2
No. of publications reviewed for airborne	34
Benzene measurement analysis	
No. of summary measurements	429
No. of total measurements	15,729

GM, geometric mean; GSD, geometric standard deviation.

Second, all benzene measurements were combined to calculate the summary of benzene statistics. The best summary measure of exposure information for epidemiologic studies is considered to be the arithmetic mean (AM) [9,10]. Most of the papers reviewed presented benzene measurement data as the AM; however, some publications provided only a GM and a GSD. Rather than exclude summary measures that were not AMs, we used these summary measures to estimate an AM. When both the GM and GSD were provided, a lognormal distribution was assumed and the equation was used to provide an estimate of AM as follows in Eq. (1) [11]:

$$AM = GM \times \exp\left\{1/2 \times [\ln(GSD)]^2\right\} \tag{1}$$

If only the range was provided, the AM was estimated by assuming a lognormal distribution according to the following method. First, the midpoint of the log transformed minimum and maximum levels provided an estimate of the mean of the log transformed levels ($\widehat{\mu}_L$). Second, the range of the log transformed levels divided by four provided an estimate of the standard deviation of the log transformed levels ($\widehat{\sigma}_L$). Finally, an estimate of the AM was provided as follows in Eq. (2) [11]:

$$AM = \exp\left(\widehat{\mu}_L + 1/2 \times \widehat{\sigma}_L^2\right) \tag{2}$$

2.3. Korea Standard Industrial Classification

Most of the industry information in the literature we reviewed was either provided only at the two-digit level or was unavailable. Benzene measurements were categorized according to the Korea Standard Industrial Classification (KSIC) Revision 09 [12]. For the manufacturing industry, we tried to classify by a four-digit industry code based on the information available in the article or report. For some nonmanufacturing sectors, the one- or two-digit level was used as the assessment level when available. To increase the reliability of industry classification, the results were classified first by an industrial hygienist with a master's degree and then confirmed by a research team consisting of three industrial hygiene professors experienced with the classification of Korean industries.

2.4. Statistical analysis

Weighted AM [AM(w)] were calculated based on the number of measurements reported for each mean and classified according to period and industry. The AMs were multiplied by the number of measurements, summed, and then divided by the total number of measurements in order to derive the AM(w):

$$AM(w) = \frac{\sum_{i=1}^{n} AMi \times Ni}{\sum_{i=1}^{n} Ni}$$

AM(w) = arithmetic mean (ppm), AM = arithmetic mean, ppm, N = number of sample

The standard deviation for the AMs across studies was also calculated. The distribution of the measurements was found to be positively skewed and approximately lognormal. Benzene measurements for the long term (≥ 1 hour) and short term period sampling category (≤ 15 minutes) were included together in the calculation of AM(w). All area airborne measurements taken to estimate exposure to benzene were included in the summary statistics. AM(w) levels were categorized by 5 year intervals and type of industry and compared using a multiple comparison test. Consequently, the natural logarithms of the calculated AM(w) were used for those analyses. All statistical analysis was performed using STATA version 9.0 (STATA Corp, College Station, TX, USA).

3. Results

3.1. Airborne benzene measurements reported in the literature

A total of 34 papers and reports containing 429 summary statistics and 15,729 individual measurements were summarized and reviewed. Short Term Exposure Limit (STEL) measurements ($n = 2,457$, AM(w) = 15.41 ppm) showed a significantly higher level compared to those of Time-Weighted Average (TWA) ($n = 10,279$, AM(w) = 0.89 ppm). Nineteen percent ($n = 2,993$) of measurements were found to have no information for estimating sampling duration (Table 2). Airborne benzene measurements reported in the literature from 1977 through 2013 were summarized by for > 1 hour (Table 3) and short term samples taken for < 15 minutes (Table 4). The first benzene measurements were reported from several industries (printing, rubber, electronic, and auto industry) using detector tubes in 1977 and ranged from 5 ppm to 40 ppm.

3.2. Airborne benzene measurement classified by period and industry

Most of the reviewed benzene measurements (82%) were collected after the 2000s, with an additional 15% ($n = 2,289$) collected between 1980 and 1984 (Table 5). Based on the AM(w) for benzene exposure, levels can be seen to have declined dramatically from 1980 to 1984 [number of measurements = 2,289, AM(w) = 50.4 ppm] to prior to the 2000s ($p < 0.05$). This reduction in exposure levels over the period was found regardless of the type of industry. AM(w) estimated after 2005 increased to around 4 ppm. For the petrochemical manufacturing industry, 70.3% of the measurements taken ($n = 11,065$) showed an AM(w) of 2.6 ppm. Samples from the rubber manufacturing industry ($n = 2,140$) were estimated to be the highest [AM(w) = 51.5 ppm]. The highest benzene levels [AM(w) = 20.9–73.7 ppm] reported during the period of 1980 through 1984 were assessed in the manufacture of rubber products and the manufacture of synthetic rubber and plastics in primary forms. Since 2000, the level of benzene has increased sharply from 0.7 ppm of AM(w) in 2000–2004, to 4.3 ppm in 2005–2009, and to 4.5 ppm in 2010–2013. Using both summaries and AM(w), it was found that airborne benzene levels dramatically decreased from 1975 until the mid-1980s (Fig. 1). Little actual measurement of relevant exposures had taken place before the 1980s. We found that substantial benzene measurement data were available for several industries manufacturing certain products: chemicals and chemical products [KSIC = 20, number of measurements = 10,583, AM(w) = 4.1 ppm], rubber and plastic products [KSIC = 22, number of measurements = 2,188, AM(w) = 50.4 ppm], and coke and briquettes including petrochemicals [KSIC = 19, number of measurements = 1,208,

AM(w) = 3.0 ppm] (Table S1). Unfortunately, we were unable to estimate benzene measurements by task or occupation title due to the lack of information in this regard in the literature. Our estimates are incapable of addressing specific features of exposure patterns that may differ among the diverse types of operations, jobs, and tasks within an industry.

4. Discussion

This paper summarized airborne benzene measurements and classified them according to industry and period based on a comprehensive review of literature reported in Korea. We found a reduction in airborne benzene levels over time, regardless of industry type, until the 2000s. No further reduction has been seen since the 2000s, at which point average benzene measurements are still far higher than Korea's permissible exposure limit of 1 ppm. The proportions of measurements exceeding 1 ppm were analyzed to be 10% ($n = 79$) in 2003, 13% ($n = 8$) in 2005, 38% ($n = 29$) in 2007, 10% ($n = 52$) in 2009, 24% ($n = 37$) in 2010, and 32% ($n = 119$) in 2011.

Certain factors may be related to the decrement of airborne benzene measurement or exposure levels of benzene over time. First, a substantial reduction of the benzene content (%) in products has contributed significant decrements in airborne benzene exposure over the last several decades. This was confirmed by Fedoruk and Bronstein [10] who reported that benzene concentrations in a simulated breathing zone were approximately proportional to the benzene content of a solvent according to Raoult's law. For example, doubling the concentration of benzene in a given liquid will double the concentration of benzene found in the vapor phase at the liquid-vapor interface. Since 1990, when the Industrial Safety and Health Act (ISHA) was thoroughly revised in Korea, rubber adhesive products containing > 5% benzene were not legally allowed to be manufactured, used, and handled in the workplace, with the exception of laboratories [41]. The Clean Air Conservation Act enforced by the Ministry of Environment lowered the maximum limit of benzene content in gasoline fuel from 6% in 1992 to 0.7% in 2009 [42]. The AM(w) of airborne benzene level was found to have markedly dropped in 1990, when legal enforcement of amounts of benzene in industrial products began, but there was little change after that (Fig. 1). Even if the amount of benzene as an impurity in paint, thinners, or solvents has decreased since the 1980s, benzene was commonly found as an impurity (< 1%) until the early 1990s [27]. Paik et al [43] analyzed 108 different thinners in 1998 and reported that eight (7.4%) still contained benzene with contents ranging from 0.1% to 56.7%. Lee et al [44] found seven thinners containing benzene (10%) in 70 different bulk thinners sampled from automobile manufacturing factories in 2002, but the amounts of benzene were < 0.1%.

Second, legally mandated reductions in the occupational exposure limit (OEL) have contributed to dramatically decreasing airborne benzene levels. The Korea TWA-OEL of 10 ppm for benzene first stipulated in 1986 was reduced to 1 ppm in 2003, and the STEL-OEL of 5 ppm was additionally established in 2007 [41], whereas those in other developed countries are commonly 0.5 ppm [45]. In 1990, the ISHA legally required employers to assess occupational exposure to hazardous agents, including benzene, twice/year. Our airborne benzene estimates declined sharply from 2.8 ppm ($n = 305$) of AM(w) in 1990–1994 to 0.1 ppm in 1995–1999 ($n = 294$) and to 0.7 ppm in 2000–2004. It is not clear whether this trend shows an actual decrement because of the relatively small number of samples from several industries. The ambient benzene levels in most workplaces have decreased to below the 10 ppm OEL, but there are many industries still showing levels > 1 ppm benzene (Supplementary Table).

Table 2
Summary statistics for airborne benzene level according to sampling characteristics

Sampling characteristics	No. of measurements	AM(w), ppm	SD, ppm
Sampling duration			
≤ 15 min	2,457	15.4	25.2
≥ 1 h	10,279	0.9	4.1
No information	2,993	49.5	27.9
Sampling type			
Personal	12,819	3.5	12.6
Area*	2,362	49.0	27.3
No information	548	0.2	0.5
Total	15,729	10.2	22.6

AM(w), weighted arithmetic mean; SD, standard deviation.
* Include measurements done with a colorimetric detector tube.

Table 3
Summary of benzene exposure level categorized as long period sampling (≥ 1 hour) in Korea

Refs	Korean Standard Industrial Classification (sub-major code)	Korean Standard Industrial Classification (minor code)	n	Range of AM (ppm)	Range of SD (ppm)	Range of GM (ppm)	Range of GSD
Lee et al 1990 [13]	Tanning and Dressing of Leather, Manufacture of Luggage and Footwear (15)	Manufacture of Footwear and Parts of Footwear (152)	61	0.12−0.97	0.07−2.21	NI	NI
Pae et al 1991 [14]	Tanning and Dressing of Leather, Manufacture of Luggage and Footwear (15)	Manufacture of Footwear and Parts of Footwear (152)	34	1.01	0.41	NI	NI
Lee et al 1994 [15]	Manufacture of Coke, Hard-Coal and Lignite Fuel Briquettes and Refined Petroleum Products (19)	NI	20	0.19−0.61	0.14−0.93	NI	NI
Lee et al 1994 [15]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	NI	3	0.33	0.54	NI	NI
Lee et al 1994 [15]	Manufacture of Other Non-metallic Mineral Products (23)	NI	5	0.08−0.10	0.01−0.03	NI	NI
Lee et al 1994 [15]	Manufacture of Basic Metal Products (24)	NI	2	0.394	0.37	NI	NI
Lee et al 1994 [15]	NI	NI	5	0.07	0.03	NI	NI
Cha et al 1994 [16]	Manufacture of Rubber and Plastic Products (22)	Manufacture of Plastic Products (222)	20	NI	NI	2.50−12.20	1.60−2.00
Cha et al 1994 [16]	Printing and Reproduction of Recorded Media (18)	Printing and Service Activities Related to Printing (181)	21	NI	NI	0.70	3.90
Cha et al 1994 [16]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Other Chemical Products (204)	19	NI	NI	1.60	4.50
Bang et al 1996 [17]	NI	NI	53	NI	NI	0.25−0.31	0.62−0.69
Jeong 1996 [18]	NI	NI	3	NI	NI	0.03	NI
Moon 1997 [19]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	85	ND−1.45	NI	NI	NI
Moon 1997 [19]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Synthetic Rubber and of Plastics in Primary Forms (203)	1	ND	NI	NI	NI
Moon 1997 [19]	NI	NI	159	ND−0.04	NI	NI	NI
Song et al 2000 [20]	Retail Trade, Except Motor Vehicles and Motorcycles (47)	Retail Sale of Fuel (477)	30	NI	NI	0.08−0.18	NI
Ahn et al 2001 [21]	Manufacture of Other Transport Equipment (31)	Building of Ships and Boats (311)	398	0.08	0.49	NI	NI
Roh et al 2001 [22]	Other Personal Services Activities (96)	Other Personal Service Activities n.e.c. (969)	17	NI	NI	1.43	2.63
Jo and Kim 2001 [23]	Other Personal Services Activities (96)	Other Personal Service Activities n.e.c. (969)	116	8.70−10.30	4.10−7.40	NI	NI
Choi 2003 [24]	Manufacture of Coke, Hard-Coal, and Lignite Fuel Briquettes and Refined Petroleum Products (19)	Manufacture of Refined Petroleum Products (192)	276	ND−0.33	NI	NI	NI
Choi 2003 [24]	Architectural, Engineering, and Other Scientific Technical Services (72)	Other Scientific and Technical Services (729)	25	NI	NI	0.01	NI
Choi 2003 [24]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	270	ND−7.20	NI	< 0.01−0.02	NI
Joo et al 2004 [25]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	2,644	NI	NI	0.01−0.22	3.39−4.13

Table 3 (*continued*)

Refs	Korean Standard Industrial Classification (sub-major code)	Korean Standard Industrial Classification (minor code)	n	Range of AM (ppm)	Range of SD (ppm)	Range of GM (ppm)	Range of GSD
Choi et al 2005 [26]	Manufacture of Coke, Hard-Coal, and Lignite Fuel Briquettes and Refined Petroleum Products (19)	Manufacture of Refined Petroleum Products (192)	473	0.51	3.00	0.08	3.30
Kang et al 2005 [27]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	61	0.01–1.08	< 0.01–1.42	0.01–0.64	NI
Joo et al 2006 [28]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	157	NI	NI	0.01–0.02	3.39–4.13
Park et al 2006 [29]	Printing and Reproduction of Recorded Media (18)	Printing and Service Activities Related to Printing (181)	2	NI	NI	0.02	NI
Choi et al 2007 [8]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	570	0.01–99.73	NI	0.01–33.72	NI
Kim 2007 [30]	Printing and Reproduction of Recorded Media (18)	Printing and Service Activities Related to Printing (181)	41	NI	NI	0.09–0.20	NI
Kim et al 2008 [31]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	19	0.42	NI	NI	NI
Kim and Kim 2009 [32]	Printing and Reproduction of Recorded Media (18)	Printing and Service Activities Related to Printing (181)	66	NI	NI	0.09–0.10	2.22–4.60
Koh et al 2009 [33]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	3,190	ND–1.28	0.01–9.16	< 0.01–0.46	0.02–7.69
Chung et al 2010 [34]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	976	0.02–1.17	0.02–6.07	0.01–0.06	2.46–9.10
Chung et al 2010 [35]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	880	0.21–2.59	0.32–14.38	0.07–0.17	3.9–9.16
Byun et al 2011 [36]	Research and Development (70)	Research and Experimental Development on Natural Sciences and Engineering (701)	27	0.05	NI	NI	NI

AM, arithmetic mean; GM, geometric mean; GSD, geometric standard deviation; ND, not detected; < LOD, limit of detection; NI: no information; SD, standard deviation.

Table 4
Summary of benzene exposure level categorized as short term period sampling ($\leq$ 15 minutes) in Korea

Refs	Korean Standard Industrial Classification (sub-major code)	Korean Standard Industrial Classification (minor code)	n	Range of AM (ppm)	Range of SD (ppm)	Range of GM (ppm)	Range of GSD
Lee and Kim 1997 [37]	Manufacture of Furniture (32)	Manufacture of Furniture (320)	2	20.00−40.00	14.14	NI	NI
Lee and Kim 1997 [37]	Manufacture of Rubber and Plastic Products (22)	Manufacture of Rubber Products (221)	3	8.00−30.00	12.17	NI	NI
Lee and Kim 1997 [37]	Manufacture of Other Transport Equipment (31)	Building of Ships and Boats (311)	2	5.00−15.00	7.07	NI	NI
Lee and Kim 1997 [37]	Printing and Reproduction of Recorded Media (18)	Printing and Service Activities Related to Printing (181)	1	25.00	NA	NI	NI
Lee and Kim 1997 [37]	Manufacture of Motor Vehicles, Trailers, and Semitrailers (30)	Manufacture of Motor Vehicles and Engines for Motor Vehicles (301)	1	30.00	NA	NI	NI
Lee and Kim 1997 [37]	Manufacture of Electronic Components, Computer, Radio, Television, and Communication Equipment and Apparatuses (26)	Manufacture of Electronic Components (262)	3	5.00−23.00	10.39	NI	NI
Chun et al 1980 [38]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	NI	94	11.70−43.50	NI	NI	NI
Chun et al 1980 [38]	Manufacture of Rubber and Plastic Products (22)	Manufacture of Rubber Products (221)	374	61.00−87.30	NI	NI	NI
Kim et al 1981 [39]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Synthetic Rubber and of Plastics in Primary Forms (203)	140	23.90−51.80	NI	NI	NI
Kim et al 1981 [39]	Manufacture of Rubber and Plastic Products (22)	Manufacture of Rubber Products (221)	2,128	6.70−111.80	NI	NI	NI
Lee et al 1990 [40]	Tanning and Dressing of Leather, Manufacture of Luggage and Footwear (15)	Manufacture of Footwear and Parts of Footwear (152)	61	5.63−7.86	2.65-3.63	NI	NI
Choi 2003 [24]	Manufacture of Coke, Hard-Coal and Lignite Fuel Briquettes and Refined Petroleum Products (19)	Manufacture of Refined Petroleum Products (192)	82	ND−2.49	NI	NI	NI
Choi 2003 [24]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	203	ND	NI	< 0.01−0.04	NI
Choi et al 2005 [26]	Manufacture of Coke, Hard-Coal and Lignite Fuel Briquettes and Refined Petroleum Products (19)	Manufacture of Refined Petroleum Products (192)	290	10.90	57.60	1.15	5.30
Kim 2007 [30]	Printing and Reproduction of Recorded Media (18)	Printing and Service Activities Related to Printing (181)	108	NI	NI	0.16−1.59	NI
Koh et al 2009 [33]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	1,086	ND−84.57	0.13−301.30	0.01−2.26	5.26−37.01
Chung et al 2010 [34]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	217	ND−1.55	0.28−6.78	ND−0.11	7.39−19.86
Chung et al 2010 [35]	Manufacture of Chemicals and Chemical Products Except Pharmaceuticals, Medicinal Chemicals (20)	Manufacture of Basic Chemicals (201)	430	0.15−118.30	0.86−322.00	0.03−8.14	4.72−41.14
Byun et al 2011 [36]	Research and Development (70)	Research and Experimental Development On Natural Sciences and Engineering (701)	41	0.01−0.69	NI	NI	NI

AM, arithmetic mean; GM, geometric mean; GSD, geometric standard deviation; NA, not applicable; ND, not detected; < LOD, limit of detection; NI: no information; SD, standard deviation.

Table 5
Weighted arithmetic means [AM(w)] for airborne benzene level by decade

Decade	No. of measurements	AM(w), ppm	SD, ppm	$p*$
1977−1979	12	18.00	11.79	A
1980−1984	2,289	50.35	26.83	B
1990−1994	305	2.78	3.57	C
1995−1999	294	0.09	0.23	D
2000−2004	3,260	0.69	1.91	D
2005−2009	6,211	4.32	12.55	D
2010−2013	3,358	4.47	17.22	D
Total	15,729	10.20	22.55	<0.0001

AM(w), weighted arithmetic mean; SD, standard deviation.
* Multiple mean comparison t test; different letters indicate significant differences.

The AM(w) of benzene measurements reported since 2005 were found to be rather higher than those from 2000 to 2004 and in the 1990s. A large proportion of the benzene measurement results in those periods (78% in 2005−2009 and 25% in 2010−2013) were derived from extensive studies on petrochemical industry workplaces conducted between 2000 and 2003. These exposure assessment results included maintenance work and peak exposure [34], resulting in a high level of benzene since 2005. Currently, even if occupational exposure in regular operations or work can be tightly controlled, benzene exposure for maintenance work performed regularly or irregularly could still be high, regardless of industry type. However, when retrospective exposure to benzene for specific industries is estimated, several exposure characteristics such as time and job should be considered together.

Finally, engineering measures can also be generally considered as a major factor in lowering airborne benzene levels, even if there is a lack of literature providing specific evidence for Korea. Examples of such engineering measures in a number of operating practices include shifting from the use of open to closed bottle process sampling in reformer and isomerization units, the addition of fixed tank roofs over internal floating roofs, automation of blending in refinery streams, and the introduction of automatic tank level gauging [46]. It is well known that benzene is generally handled in enclosed systems wherever possible [47] because of its nature as a confirmed carcinogen with high toxicity. Changes in refining practices related to hydro-treating and solvent extraction in petrochemical plants substantially reduced the residual benzene content of many petroleum-derived products during the 1960s and 1970s (pers. commun.) [48].

The widespread use of benzene as an industrial or consumer solvent declined in the United States and most other developed countries during the mid to late 1970s, after which point such uses were considered to range from minimal to negligible [49,50]. Specific characteristics of these changes, such as the specific start date and duration of legal enforcement, patterns, and benzene levels may vary among countries, including Korea.

The ubiquitous use of benzene as a solvent has led to a number of working populations being exposed, often with uncontrolled conditions during its early applications resulting in high exposures. Although benzene has been replaced by other organic solvents in nearly all commercial products, it may still be present as a trace impurity or residual component in mixed petroleum products (e.g., mineral spirits, paint thinners, cleaning agents, degreasers) [51,52]. This is because benzene is a naturally occurring compound in crude oil and natural gas, and very low concentrations of benzene often remain in certain products refined from these sources due to the nature of the fractional distillation process [51,53]. Solvents or thinners containing benzene as an impurity have been used in many occupational circumstances. As an integral component of the petrochemical process, benzene cannot simply be banned, since products such as solvents, fuels, and oils that are refined from crude oil and natural gas with benzene content generally between 0.1% and 3.0% by volume will still show a degree of benzene contamination [47,54].

In Korea, claims for compensation of hematopoietic diseases related to benzene have been rising. Ahn and Kang [55] reported a link between occupational diseases, such as cancer, and benzene exposure at petrochemical work sites. Although the benzene exposure level has been relatively reduced, the occurrence of myelodysplastic syndrome, a preleukemia condition, has increased [55] Even though overall current estimated exposure to benzene at work or as part of a job conducted during the normal operations in most industries is low, the occurrence of health effects, including hematopoietic diseases, is still regarded as a possibility, since some jobs or workers have been exposed to higher levels.

In general, it is likely that average benzene measurements from all types of industries followed the overall pattern of decline over time, especially prior to 2000, although there may be inconsistencies by specific operation or job. In particular, maintenance tasks or employment still feature a potential for high benzene exposure. In general, the highest risk for hazardous exposure occurs while performing maintenance tasks. Maintenance work cleaning, replacing, and repairing chemical equipment, reactors, and components that may be contaminated with benzene are performed either regularly or irregularly in almost every industry, with a potential for benzene exposure, including in petrochemical plants. The level of benzene exposure in the petrochemical industry during regular operations has been well established, but not with regard to maintenance, where high exposures may occur. There have been a few efforts assessing exposure to benzene among maintenance workers in Korea. We found that the highest risk of benzene exposure occurs while performing maintenance tasks during turnaround at petrochemical plants (shut down = 1.1−31.8 ppm, maintenance = 1.0−61.9 ppm, startup = 2.4−42.1 ppm). The proportion of turnaround maintenance samples exceeding TWA-OEL of 1 ppm and the STEL-OEL of 5 ppm were 4.1% (20/488 samples) and 6.0% (13/217 samples), indicating that the proportion of the measurements over the exposure limits in not high. Refinery maintenance workers in petrochemical plants tend to experience intermittent benzene exposures due to a variety of tasks performed over short periods, which may include draining, opening, cleaning, and working on enclosed equipment [34]. The available benzene exposure data reviewed suggests that, although mean full-shift exposures are typically low, higher exposures may occasionally be experienced during shutdown and cleaning procedures, and during irregularly performed maintenance work.

One major limitation of this review is that it is not possible to know how representative our benzene estimates may be with regard to various industries over the preceding decades. The data are too limited to be considered representative for the 1990s (number of measurements = 305 for 1990−1994 and 294 for 1995−1999) and for specific industries. In particular, there may be limitations in using our benzene estimates as inhalation TWA exposure level, because benzene levels taken during consecutive and short periods as well as from working areas were all combined as AM(w). As many as 2,993 measurements (19%) were from publications with no information on sampling duration. Despite these limitations, our estimations could be used to estimate past exposure to benzene qualitatively (low, moderate, or high, etc.) by the decade. Further study is needed to examine the effect of time, industry, type of sampling duration, and other sampling characteristics on benzene measurement.
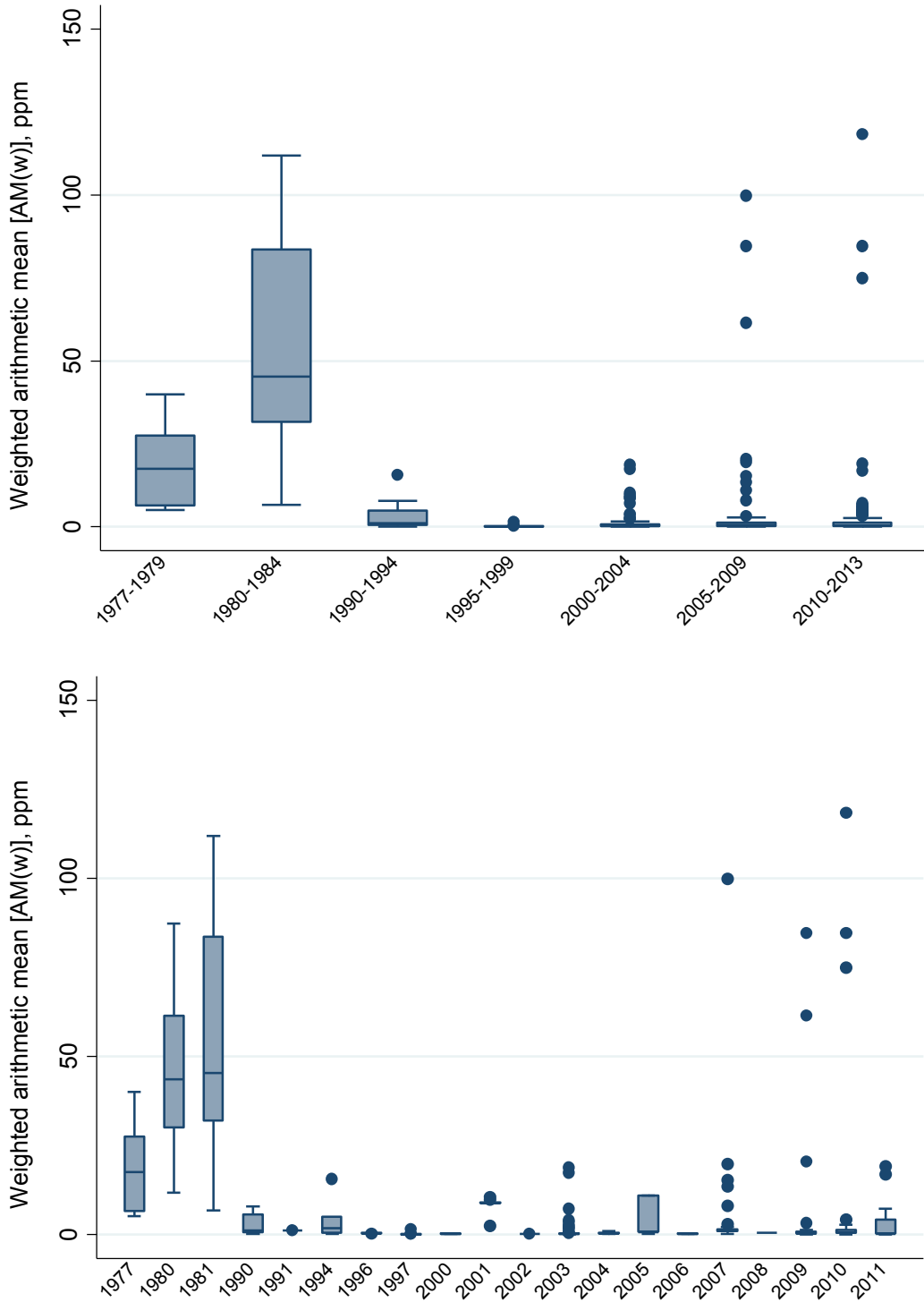
Fig. 1. Estimated airborne benzene levels over time in Korea.

Another limitation was the lack of descriptions of the working conditions under which airborne benzene measurements were taken. All measurements failed to specify operations or job titles within each specific industry, since most of the studies reviewed here did not include such specific exposure information. It is not common in the occupational safety and health field to classify measurements based on the type of occupation or job. There have been no published materials, including official government reports, because of the lack of use of standard classification of occupation in

occupational safety and health areas in Korea. As is the case with all historical analyses, the sample duration or exact task descriptions were not consistently provided. Thus, the measurements taken may include periods of higher or lower exposure, and personal exposures during certain tasks are likely to be higher than area samples. We were unable to cover all industries where benzene exposure occurs. Nevertheless, we found that substantial benzene measurement data, which can be used to associate work-related disease, were available for several manufacturing industries

during specific periods: petrochemical, rubber and plastic, basic organic chemicals, and auto part manufacturing (Supplementary Table).

5. Conclusions

Our estimated benzene measurements indicate a clear reduction in exposure levels over time until prior to the 2000s. The AM(w) of benzene measurements reported since 2005 were found to be rather higher than those from 2000 to 2004 and from the 1990s, even though most data were collected from petrochemical industries among workers conducting maintenance tasks.

Our results can be used not only to determine the probability of retrospective exposure to benzene in a specific industry, but also to estimate the level of quantitative or semiquantitative retrospective exposure to benzene, especially when supplemented by further assessment from expert users, and can be applied to retrospective exposure assessment and association with the development of health effects.

Conflicts of Interest

None.

Appendix A. Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.shaw.2015.07.007.

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