Development of Korean CARcinogen EXposure: Assessment of the Exposure Intensity of Carcinogens by Industry

Dong-Hee Koh1,*, Ju-Hyun Park2, Sang-Gil Lee3, Hwan-Cheol Kim4, Hyejung Jung1, Inah Kim5, Sangjun Choi6, Donguk Park7

1 Department of Occupational and Environmental Medicine, International St. Mary’s Hospital, Catholic Kwandong University, Incheon, Republic of Korea
2 Department of Statistics, Dongguk University, Seoul, Republic of Korea
3 Occupational Safety and Health Research Institute, Korea Occupational Safety and Health Agency, Ulsan, Republic of Korea
4 Department of Occupational and Environmental Medicine, College of Medicine, Hanyang University, Seoul, Republic of Korea
5 Department of Preventive Medicine, College of Medicine, The Catholic University of Korea, Seoul, Republic of Korea
6 Department of Preventive Medicine, College of Medicine, The Catholic University of Korea, Seoul, Republic of Korea
7 Department of Environmental Health, Korea National Open University, Seoul, Republic of Korea

ARTICLE INFO

Article history:
Received 15 February 2022
Received in revised form 3 May 2022
Accepted 17 May 2022
Available online 23 May 2022

Keywords:
Cancer
Carcinogen
Exposure
Occupational cancer
Occupational exposure

ABSTRACT

Background: Occupational cancer is a global health issue. The Korean CARcinogen EXposure (K-CAREX), a database of CARcinogen EXposure, was developed for the Korean labor force to estimate the number of workers exposed to carcinogens by industry. The present study aimed to estimate the intensity of exposure to carcinogens by industry, in order to supply complementary information about CARcinogen EXposure intensity to the K-CAREX.

Methods: We used nationwide workplace monitoring data from 2014 to 2016 and selected target carcinogens based on the K-CAREX list. We computed the 95th percentile levels of measurements for each industry by carcinogens. Based on the 95th percentile level relative to the occupational exposure limit, we classified the CARcinogen EXposure intensity into five exposure ratings (1–5) for each industry.

Results: The exposure ratings were estimated for 21 carcinogenic agents in each of the 228 minor industry groups. For example, 3,058 samples were measured for benzene in the manufacturing industry of basic chemicals. This industry was assigned a benzene exposure rating of 3.

Conclusions: We evaluated the CARcinogen EXposure ratings across industries in Korean workers. The results will provide information on the exposure intensity to carcinogens for integration into the K-CAREX. Furthermore, it will aid in prioritizing control efforts and identifying industries of concern.

© 2022 Occupational Safety and Health Research Institute, Published by Elsevier Korea LLC. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Occupational cancer is a pertinent global occupational health issue. Currently, one in three individuals in the general population is expected to be diagnosed with any type of cancer when one survives to the age of life expectancy, and one in four individuals in the general population die due to cancers in Korea [1].

The causes of cancer range from genetic to modifiable risk factors, such as smoking and occupation [2,3]. During working hours, workers are exposed to thousands of harmful chemicals and physical and biological agents, and these working conditions can increase the risk of cancer. However, a limited number of agents have been found to be carcinogenic, and most of the other agents have not yet been investigated [4]. Exposure to complex chemical mixtures or co-exposure from multiple sources, such as home, environment, and occupation, further complicate the association between occupational exposure and possible malignancy [5].

Dong-Hee Koh: https://orcid.org/0000-0002-2868-4411; Ju-Hyun Park: https://orcid.org/0000-0001-9675-6475; Sang-Gil Lee: https://orcid.org/0000-0001-8173-3940; Hwan-Cheol Kim: https://orcid.org/0000-0002-3635-1297; Hyejung Jung: https://orcid.org/0000-0003-2842-8765; Inah Kim: https://orcid.org/0000-0001-9221-5831; Sangjun Choi: https://orcid.org/0000-0001-8787-7216; Donguk Park: https://orcid.org/0000-0003-3847-7392
* Corresponding author. Department of Occupational and Environmental Medicine, International St. Mary’s Hospital, Catholic Kwandong University, 25, Simgok-to 100 Bone-Gil, Seo-Gu, Incheon, 22711, Republic of Korea.
E-mail address: koh.donghee@gmail.com (D.-H. Koh).

2093-7911/$ – see front matter © 2022 Occupational Safety and Health Research Institute, Published by Elsevier Korea LLC. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
https://doi.org/10.1016/j.shaw.2022.05.003
Although there are many agents and work conditions to be examined, it is also important to properly utilize the knowledge base that has already been established. Many studies have investigated the carcinogenicity of various agents, such as dust, chemicals, and heavy metals, to prevent occupational cancers. Based on these findings, the International Agency of Research on Cancers (IARC) has developed and currently updated a list of carcinogens, thereby guiding active prevention efforts [6]. However, due to the limited resources, these prevention measures primarily focused on areas where many workers were heavily exposed. Therefore, carcinogen information systems, such as the CARcinogen EXposure (CAREX) have been developed [7–12].

The Korean CAREX (K-CAREX) was recently developed [13], wherein it estimated the exposure prevalence and the number of exposed workers for 20 carcinogens across 228 minor industry groups by referring to three nationwide occupational exposure databases and eliciting the judgment of 37 industrial hygiene experts, targeting the circumstances in 2010.

The present study aimed to develop an estimate of CARcinogen EXposure intensity by industry, using a nationwide workplace monitoring database, which will supply complementary information about CARcinogen EXposure intensity to the K-CAREX. It also describes the estimation procedure of exposure intensity of 21 carcinogenic agents.

2. Materials and methods

2.1. Data sources

Workplaces with exposure to designated hazardous agents are obliged to periodically monitor the work environment according to a national occupational exposure monitoring system in Korea [14]. Companies requisition work environment monitoring institutions (WEMI), which are private bodies, to monitor the working environment. These results have been compiled electronically by the Korea Occupational Safety and Health Agency (KOSHA) since 2002. The measurement database is known as the work environment measurement database (WEMD) [15,16].

We used the measurement database from 2014 to 2016 to estimate the exposure intensity. The time period is marked by data availability and is chronologically close to the time period of the K-CAREX. This database includes details on industry codes, measurement levels, and sampling time. Air sampling is typically conducted for at least 6 h, according to the guideline (administrative notice). A short-term exposure sampling is also conducted when necessary. The number of samples measured in <4 h (approximately 3.5%) or > 10 h (approximately 0.02%) was small. They were regarded as non-routine operations and excluded, along with trivial measurements without appropriate industry codes.

2.2. Selection of target carcinogens and definition of carcinogens

Based on the K-CAREX list, we selected 21 carcinogenic agents [13]. We added mists from three strong inorganic acids (hydrochloric acid, nitric acid, and hydrofluoric acid) besides sulfuric acid because they may share a similar carcinogenic mechanism (i.e., low pH) as that of sulfuric acid [17,18]. Workers can be exposed to these strong inorganic acid mists in various industries, including those of plating and semiconductor manufacturing [19]. We excluded three carcinogens (ionizing radiation, ultraviolet radiation, and polycyclic aromatic hydrocarbons) because they were not available in the WEMD.

Arsenic was divided into arsine and arsenic (other than arsine) because the sampling and analytical methods are different for these chemicals. Chromium consisted of inorganic and organic hexavalent chromium, measured by ion chromatography while excluding other compounds, such as metallic chromium measured by atomic absorptiometry (AA). For a nickel, nickel carbonyl was excluded owing to the small number of measurements and different sampling and analytical methods. Crystalline silica consisted of quartz, cristobalite, and tridymite, which were sampled with a cyclone as respirable dust.

Accordingly, arsenic, arsine, asbestos, benzene, beryllium, 1,3-butadiene, cadmium (Cd), hexavalent chromium (Cr6+), ethylene oxide (EtO), formaldehyde, hydrochloric acid (HCl), hydrofluoric acid (HF), mineral oil mist, nickel (Ni), nitric acid, crystalline silica, sulfuric acid, trichloroethylene (TCE), vinyl chloride monomer (VCM), welding fumes, and wood dust were selected as target carcinogens.

2.3. Standard industrial classification

The WEMD classifies industries according to the Korean Standard Industrial Classification (KSIC-9) based on the International Standard Industrial Classification (ISIC, 4th revision). The three-digit minor industry code of the ISIC was used as the standard industrial classification (SIC) in our study. The industry code is assigned by industrial hygienists who conduct workplace monitoring. Industrial hygienists commonly refer to industry names on the certificate for business registration of monitored companies.

2.4. Data cleaning and treatment

To ensure uniformity among the 160 WEMIs that sample and report workplace exposure, a quality control program for sampling and analytical methods is performed periodically by the KOSHA [20]. Despite the active quality control program, analytical institutions have different equipment and analytical settings, resulting in varied results.

The limit of detection (LOD) values is particularly variant when it comes to different analytical institutions. However, the WEMD contains no information about LOD values; hence, we obtained reporting LOD levels from several WEMIs. Based on the reporting LODs, we reached a consensus on a single LOD for each carcinogen, basically averaging LOD levels from these analytical institutions (Table 1).

In the WEMD, a large proportion of measurements showed extremely low to zero (not detected) levels. Therefore, values below the LOD were treated as censored and replaced with half of the LOD [21]. Different occupational exposure limits (OELs) exist for different carcinogen compounds. For instance, the OEL of non-soluble hexavalent chromium was 0.01 mg/m³, whereas that of soluble hexavalent chromium was 0.05 mg/m³. We chose 0.01 mg/m³ as a representative OEL for Cr6+ for computational purposes. Likewise, 0.1 mg/m³ and 1 mg/m³ were chosen for nickel and wood dust, respectively (Table 1). The OEL of TCE in Korea decreased from 50 to 10 ppm in 2016; we chose 10 ppm as the representative OEL for the TCE.

2.5. Statistical analysis

In a previous pilot study using the WEMD, we computed summary statistics, including mean, geometric mean, and X95 values for both airborne and blood lead, and then examined optimal exposure intensity indicators by comparing airborne measurements with blood lead measurements [22]. We concluded that the mean and X95 values would be optimal exposure intensity indicators for the WEMD based on the results of rank correlation analyses. Furthermore, X95 showed a better correlation than the
mean when restricting industries to those with 20 or more measurements.

In line with the previous pilot study, the present study first calculated X95 for each three-digit SIC and then computed the exposure ratings based on the X95 level compared to the corresponding OEL [23]. The X95 value has been used for initial exposure assessment using the concept of “major/minor” cuts. Any exposure scenario may be characterized as “minor” if the anticipated upper-end exposure is <1/10th of the OEL, which would be considered “acceptable” [23]. Furthermore, the exposure ratings have been used for categorizing risks and management for a similar exposure...

Table 1
Sampling and analytical method, reporting limit of detection, and occupational exposure limit of carcinogens

| Name                  | Sampling media       | Flow rate (L/min) | Sampling time (min) | Analytical equipment | LOD          | OEL          |
|-----------------------|----------------------|-------------------|---------------------|----------------------|--------------|--------------|
| Arsenic               | Charcoal tube        | 0.02              | 360                 | AA-GF                | 0.0001 ppm   | 0.005 ppm    |
| Arsenic               | MCE filter           | 1                 | 360                 | AA-GF                | 0.03 µg/m³   | 0.01 mg/m³   |
| Asbestos              | MCE filter           | 2                 | 360                 | PCM                  | 0.003 fiber/cc | 0.1 fiber/cc |
| Benzene               | Charcoal tube        | 0.03              | 360                 | GC                   | 0.03 ppm     | 0.5 ppm      |
| Beryllium             | MCE filter           | 2                 | 360                 | ICP                  | 0.002 µg/m³  | 0.002 mg/m³  |
| 1,3-Butadiene         | Charcoal coated with TBC | 0.05            | 360                 | GC                   | 0.006 ppm    | 2 ppm        |
| Cd                    | MCE filter           | 2                 | 360                 | AA                   | 0.2 µg/m³    | 0.01 mg/m³   |
| Cr6+                  | PVC filter           | 2                 | 360                 | IC                   | 0.2 µg/m³    | Based on 0.01 mg/m³ (non-soluble); 0.05 mg/m³ (soluble) |
| ETO                   | HBr-coated carbon beads, 100 mg/50 mg | 0.5               | 360                 | GC-ECD               | 0.00003 ppm  | 1 ppm        |
| Formaldehyde          | Cartridge containing silica gel coated with 2,4-dinitrophenylhydrazine | 0.5               | 360                 | HPLC                 | 0.001 ppm    | 0.3 ppm      |
| HCl                   | Silica-gel tube      | 0.2               | 360                 | IC                   | 0.002 ppm    | 1 ppm        |
| HF                    | Silica-gel tube      | 0.2               | 360                 | IC                   | 0.002 ppm    | 0.5 ppm      |
| Mineral oil mist      | PTFE filter          | 2                 | 360                 | Gravimetric          | 0.01 mg/m³   | 0.8 mg/m³    |
| Ni                    | MCE filter           | 2                 | 360                 | AA                   | 0.08 µg/m³   | Based on 0.1 mg/m³ (soluble); 0.25 mg/m³ (non-soluble); 1.5 mg/m³ (metal) |
| Nitric acid           | Silica-gel tube      | 0.2               | 360                 | IC                   | 0.002 ppm    | 2 ppm        |
| Silica, crystalline   | PVC filter, Cyclone  | 1.7               | 360                 | FTIR                 | 0.3 µg/m³    | 0.05 mg/m³   |
| Sulfuric acid         | Silica-gel tube      | 0.2               | 360                 | IC                   | 0.03 mg/m³   | 0.2 mg/m³    |
| TCE                   | Charcoal tube        | 0.03              | 360                 | GC                   | 0.09 ppm     | Based on 10 ppm (2016); 50 ppm (2014–2015) |
| VCM                   | Tandem charcoal tubes | 0.05             | 360                 | GC                   | 0.003 ppm    | 1 ppm        |
| Welding fume          | MCE filter           | 2                 | 360                 | Gravimetric          | 0.01 mg/m³   | 5 mg/m³      |
| Wood dust             | IOM sampler          | 2                 | 360                 | Gravimetric          | 0.01 mg/m³   | Based on 1 mg/m³ (others); 0.5 mg/m³ (red cedar) |

Abbreviations: LOD, limit of detection; OEL, occupational exposure limit; Cd, cadmium; Cr6+, hexavalent chromium; ETO, ethylene oxide; HCl, hydrochloric acid; HF, hydrofluoric acid; Ni, nickel; TCE, trichloroethylene; VCM, vinyl chloride monomer; AA-GF, atomic absorptionmetry-graphite furnace; PCM, phase contrast microscopes; GC, gas chromatography; ICP, inductively coupled plasma; AA, atomic absorptiometry; IC, ion chromatography; GC-ECD, gas chromatography-electron capture detector; HPLC, high-performance liquid chromatography; FTIR, Fourier transform infrared.

Table 2
Exposure rating scheme based on decision statistics of 95th percentile (X95)

| Exposure rating | Definition                  |
|----------------|-----------------------------|
| 0              | Not rated; < 20 measurements |
| 1              | X95 < 1% of OEL             |
| 2              | X95 < 10% of OEL            |
| 3              | X95 within 10–50% of OEL    |
| 4              | X95 within 50–100% of OEL   |
| 5              | X95 > 100% of OEL           |

Abbreviations: OEL, occupational exposure limit.

The distributions of carcinogens with low censoring rates, such as welding fume (3%) approximated log-normal distributions across industries (graphs not shown), whereas other carcinogens with high censoring rates, such as arsenic (95%), could not be examined for distributions due to high censoring rates. We assumed that all of the carcinogens would follow lognormal distributions.

Table 4 presents the number of measurements, censoring rate, and exposure ratings ranked among the top 20 industries for benzene exposure. For instance, the manufacturing of basic chemicals (201) industry contained 3,058 benzene measurements.
and showed a 92% censoring rate, in which exposure was rated 3. The number of the three-digit minor industry that was assigned exposure rating 4 was seven. Detailed exposure intensity results for 21 carcinogenic agents across 228 minor industries are available online at https://koreancarex.shinapps.io/k-carex_intensity/. In addition, we presented exposure ratings of all industries, including industries with <20 samples in Supplemental Table 1. Table 5 shows the number of measurements, censoring rate, and exposure rating of each carcinogenic agent for the “manufacture of basic chemicals (201)” industry, as an example. A total of 21 agents were measured in this industry, including 3,058 benzene measurements. Benzene showed a 92% censoring rate with an exposure rating of 3. Arsine was measured in this industry, but the number of measurements was <20; therefore, the exposure rating was assigned “0” (not rated).

4. Discussion

In this study, we estimated the exposure intensity of 21 carcinogenic agents across 228 minor industries using a nationwide exposure measurement database using a previously tested intensity indicator for exposure intensity development [22]. The results will provide information on the exposure intensity of carcinogens as a complement to the previously developed K-CAREX [13].

We assessed the exposure intensity for 21 carcinogenic agents selected, based on the K-CAREX carcinogens list [13]. Workers are exposed to arsenic in many industries, including the “basic precious and non-metal (242)” industries [24]. However, some measurements were taken from an industry where arsenic exposure was unlikely to occur, such as the “manufacturing of other food products (107)” [22]. When we further investigated the measurement information, we found that several companies run laboratories in which arsenic was used. Most food-producing companies do not use arsenic; therefore, it should be considered that the exposure ratings only apply in certain circumstances where actual exposure occurs in the industry.

Asbestos exposure is usually associated with construction, shipbuilding, and steel foundry [25]. Asbestos was widely used as an insulating material, and some remnants still persist, although most of them have been abated. For instance, a chemical plant may cover the asbestos remnants with paste to prevent weathering of asbestos materials if the asbestos-containing materials cannot be removed [26]. Therefore, this chemical plant is not obliged to measure airborne asbestos during periodic work environment monitoring; therefore, there is no asbestos measurement presented in the “manufacturing of basic chemicals (201)” industry, as shown in Table 5. However, asbestos exposure can occur during maintenance operations. Maintenance operations in petrochemical plants were mainly conducted by maintenance workers employed by companies specializing in these operations [27]. These maintenance companies may be classified as “architectural, engineering, and related technical services (721).” This complex contract and subcontract structure may lead to confusion when interpreting exposure intensity ratings.

The Korean OEL for beryllium is 2 μg/m³; however, this cannot protect workers from contracting chronic beryllium disease (CBD) or beryllium sensitization [28]. Therefore, the threshold limit value (TLV) of beryllium according to the American Conference of Governmental Industrial Hygienists (ACGIH) has been reduced to 0.05 μg/m³. Similarly, the permissible exposure limit of the US Occupational Safety and Health Administration (US OSHA) has been reduced to 0.2 μg/m³, which is far lower than that of the Korean OEL. This difference in the OELs should be considered when using the current exposure ratings for other health effects, such as CBD.

Basic chemicals, such as benzene and 1,3-butadiene, can be highly exposed during facility maintenance operations rather than during ordinary manufacturing processes [29,30]. Workplace monitoring is usually conducted for 6 h during normal manufacturing processes; however, if necessary, short-term sampling is also performed. Maintenance operations in petrochemical plants would be one such case. Approximately 2% of benzene

---

**Table 3**

Censoring rate by carcinogen, and distributions of exposure ratings by carcinogen and industry (total 228 minor industries)

| Carcinogen       | Censoring rate | Number of three-digit industry by exposure ratings |
|------------------|----------------|--------------------------------------------------|
|                  | Censored | Total | Rate (%) | 0 (not rated) | 1 | 2 | 3 | 4 | 5 |
| Arsine           | 1,301    | 1,311 | 99       | 223          | 0 | 5 | 0 | 0 | 0 |
| Arsenic          | 2,208    | 2,697 | 83       | 209          | 11 | 3 | 1 | 1 |
| Asbestos         | 411      | 652   | 63       | 219          | 0 | 5 | 3 | 0 | 1 |
| Benzene          | 17,995   | 19,661| 92       | 156          | 0 | 35 | 30 | 7 | 0 |
| Beryllium        | 297      | 317   | 94       | 224          | 2 | 1 | 1 | 0 |
| 1,3-Butadiene    | 4,532    | 5,048 | 90       | 206          | 11 | 8 | 1 | 1 |
| Cd               | 6,553    | 7,494 | 93       | 176          | 2 | 8 | 12 | 2 |
| Cr6+             | 31,974   | 40,513| 92       | 130          | 0 | 62 | 29 | 6 |
| EtO              | 6,836    | 11,443| 60       | 211          | 2 | 3 | 10 | 1 |
| Formaldehyde     | 14,414   | 51,631| 28       | 144          | 1 | 17 | 55 | 11 |
| HCl              | 42,932   | 63,502| 68       | 110          | 7 | 107 | 4 | 0 |
| HF               | 15,196   | 17,636| 86       | 177          | 27 | 6 | 1 |
| Mineral oil mist | 19,925   | 136,027| 6  | 141          | 0 | 82 | 5 | 0 |
| Ni               | 66,093   | 48,748| 44       | 107          | 10 | 96 | 14 | 1 |
| Nitric acid      | 30,880   | 45,667| 68       | 128          | 46 | 54 | 0 | 0 |
| Silica, crystalline | 33,882 | 53,974| 63       | 142          | 7 | 18 | 51 | 2 |
| Sulfuric acid    | 81,959   | 88,999| 92       | 102          | 0 | 48 | 77 | 1 |
| TCE              | 9,220    | 18,295| 50       | 154          | 10 | 13 | 18 | 11 |
| VCM              | 2,149    | 7,841 | 76       | 210          | 4 | 6 | 7 | 1 |
| Welding fume     | 5,997    | 190,576| 3  | 108          | 0 | 1 | 109 | 8 |
| Wood dust        | 1,282    | 22,739| 6        | 164          | 0 | 0 | 15 | 47 |

Note: Censored, values below the limit of detection; Cd, cadmium; Cr6+, hexavalent chromium; EtO, ethylene oxide; HCl, hydrochloric acid; HF, hydrofluoric acid; Ni, nickel; TCE, trichloroethylene; VCM, vinyl chloride monomer.
samples and 3% of 1,3-butadiene samples in the WEMD were short-term samples, which showed much higher levels than samples measured at 6 h (data not shown). In the present study, we removed the short-term samples to account for the different sampling frameworks; therefore, our results do not reflect short-term, temporarily high exposure circumstances.

In 1,3-butadiene, the manufacturing of general-purpose machinery showed an exposure rating of 5, although exposure to 1,3-butadiene is unlikely to occur in the machinery manufacturing process [31]. We examined the data in detail and found that the measurements from one company showed very high 1,3-butadiene levels. Although the industry was classified as a machinery manufacturing industry, the work process implied that the samples were taken from petrochemical plants or refineries during the maintenance or installation of facilities. Thus, in some cases, the industry where exposures occur is more critical than the work circumstances of the original industry. Moreover, potential confusion from these uncommon working conditions should be considered, especially when unlikely exposures are detected.

The Korean OEL of the TCE changed from 50 to 10 ppm in 2016. We chose 10 ppm as the representative OEL to compute the exposure ratings. The mean TCE in 2016 was lower than that in 2014 and 2015 (data not shown). Owing to the change effect in OEL in 2016 and the reduced OEL application, many industries showed higher exposure ratings for TCE than for other carcinogenic agents. Therefore, the exposure ratings of TCE should be interpreted with this change in mind.

In a previous study, we calculated the summary statistics of airborne lead measurements and compared them with those from blood lead data [22]. The results indicated that X95 is likely to be an optimal indicator when restricting results to industries containing ≥20 measurements. The result supports our current findings, which were obtained using the X95 to estimate exposure ratings. However, care should also be exercised when extending this conclusion to other carcinogenic agents.

For several carcinogenic agents, such as arsenic, asbestos, benzene, Cd, Cr6+, mineral oil mist, sulfuric acid, welding fumes, and wood dust, the lowest exposure rating was 2, because the LODs were >1% of the OELs in these carcinogens. The LOD may vary according to batches and institutions; however, the WEMD contains no information on LODs. To address the issue, we contacted experienced analysts in several WEMIs and obtained the reporting LODs of the WEMIs. Then, we reached a final single LOD for each

---

**Table 4**

Censoring rate and exposure rating of benzene by industry (top 20 industries based on exposure rating)

| SIC | Explanation | Censoring rate | Exposure rating |
|-----|-------------|----------------|----------------|
|     |             | Censored | Total | Rate (%) |           |
| 181 | Printing and service activities related to printing | 78 | 104 | 75 | 4 |
| 221 | Manufacture of rubber products | 135 | 153 | 88 | 4 |
| 222 | Manufacture of plastic products | 123 | 206 | 60 | 4 |
| 251 | Manufacture of structural metal products, tanks, reservoirs, and steam generators | 163 | 217 | 75 | 4 |
| 259 | Manufacture of other metal products; metal working service activities | 269 | 357 | 75 | 4 |
| 320 | Manufacture of furniture | 61 | 87 | 70 | 4 |
| 949 | Other membership organizations | 26 | 28 | 93 | 4 |
| 107 | Manufacture of other food products | 144 | 155 | 93 | 3 |
| 152 | Manufacture of footwear and parts of footwear | 54 | 71 | 76 | 3 |
| 162 | Manufacture of wood products | 61 | 85 | 72 | 3 |
| 201 | Manufacture of basic chemicals | 2,808 | 3,058 | 92 | 3 |
| 203 | Manufacture of synthetic rubber and of plastics in primary forms | 751 | 896 | 84 | 3 |
| 204 | Manufacture of other chemical products | 1,800 | 1,986 | 91 | 3 |
| 212 | Manufacture of medicaments | 540 | 581 | 93 | 3 |
| 243 | Cast of metals | 87 | 106 | 82 | 3 |
| 262 | Manufacture of electronic components | 67 | 73 | 92 | 3 |
| 283 | Manufacture of insulated wires and cables, including insulated code sets | 29 | 34 | 85 | 3 |
| 291 | Manufacture of general-purpose machinery | 172 | 214 | 80 | 3 |
| 292 | Manufacture of special-purpose machinery | 229 | 272 | 84 | 3 |
| 302 | Manufacture of bodies for motor vehicles; manufacture of trailers and semitrailers | 18 | 25 | 72 | 3 |

**Table 5**

Censoring rate and exposure rating (1–5) by carcinogen for the “manufacture of basic chemicals (201)” industry

| Carcinogen | Censoring rate | Exposure rating |
|------------|----------------|----------------|
|            | Censored | Total | Rate (%) |           |
| Arsenic     | 10 | 11 | 91 | 0 (% not rated) |
| Arsenic     | 21 | 21 | 100 | 1 |
| Asbestos    | 0 | 0 | NA | 0 |
| Benzene     | 2,808 | 3,058 | 92 | 3 |
| Beryllium   | 0 | 0 | NA | 0 |
| 1,3-Butadiene | 677 | 798 | 85 | 2 |
| Cd          | 136 | 182 | 75 | 3 |
| Cr6+        | 608 | 710 | 86 | 3 |
| EtO         | 270 | 340 | 79 | 3 |
| Formaldehyde | 380 | 963 | 39 | 3 |
| HCl         | 2,959 | 4,195 | 71 | 2 |
| HF          | 671 | 828 | 81 | 3 |
| Mineral oil mist | 28 | 147 | 19 | 3 |
| Ni          | 847 | 1,740 | 49 | 2 |
| Nitric acid | 1,394 | 1,869 | 78 | 3 |
| Silica, crystalline | 574 | 740 | 78 | 3 |
| Sulfuric acid | 4,507 | 4,917 | 92 | 3 |
| TCE         | 143 | 149 | 96 | 1 |
| VCM         | 228 | 271 | 84 | 3 |
| Welding fume | 16 | 942 | 2 | 3 |
| Wood dust   | 14 | 0 | 0 | 0 |

Note: Censored, values below the limit of detection; Cd, cadmium; Cr6+, hexavalent chromium; EtO, ethylene oxide; HCl, hydrochloric acid; HF, hydrofluoric acid; Ni, nickel; TCE, trichloroethylene; VCM, vinyl chloride monomer; NA, not applicable.
carcinogen, basically averaging the reporting LODs. All measuring institutions periodically participate in quality control programs for the performance of analysis according to the standard sampling and analytical methods of the KOSHA, which is similar to those of the US National Institute of Occupational Safety and Health (NIOSH) [20,22]. Furthermore, the essential analysis equipment (e.g., gas chromatography, AA) of the measuring institution is specified by the guideline (administrative notice), and the measurement time is stipulated to be at least 6 h. Therefore, it is considered reasonable to apply the average value of LOD of some measuring institutions to this study. However, applying a single LOD might affect the exposure ratings.

We have added the “0” category (not rated) to the scheme for industries with <20 measurements. However, restricting the industry to ≥20 measurements may lose sensitivity to detect minor exposure circumstances while increasing the specificity of the exposure.

Current estimates of exposure intensity are different from those of other occupational exposure information systems, such as the Finnish Job-Exposure Matrix (FINJEM) [32] and Canadian CAREX [11]. The estimate of exposure intensity of the K-CAREX is an ordinal scale, similar to the Canadian CAREX, unlike the continuous scale of the FINJEM. The FINJEM covers decades of time periods, whereas the K-CAREX and Canadian CAREX are set at the time of generation. The WEMD is not publicly available; therefore, we were unable to provide summary statistics such as mean values. However, we are planning to update the K-CAREX as workplace monitoring data accumulate. An occupation-based exposure matrix such as the FINJEM is useful for exposure assessment tools in occupational epidemiology and hazard surveillance tools. Currently, the WEMD contains no data on job information; therefore, it is necessary to incorporate job information in the occupational exposure and health surveillance systems of Korea in the future.

The strength of this study is depicted in the ability to assess CARcinogen EXposure intensity across a wide range of industries. However, caution is essential when interpreting the results due to the limitations of the data source and analytical methods. First, we assessed exposure according to industry; however, it will not account for variabilities among processes and sites [33]. The estimate of exposure intensity of an industry does not apply to all processes and sites in the industry. Second, the exposure rating scheme used for SEGs [23] was adopted to assign exposure intensity according to industry. Therefore, direct result interpretation as to “major/minor” cut and “applicable management/controls” may not be applicable. Third, some carcinogens showed a high censoring rate (e.g., arsine 99%). Semiconductor factories conduct mandatory arsine monitoring periodically, which will result in a high proportion of measurements below the LOD because arsine gas may be detected only in abnormal conditions, such as leakage [19]. Therefore, the high censoring rate of an industry may not imply that the industry is safe all the time. Fourth, the estimates of exposure ratings are assigned to carcinogens but not to ordinary chemicals. CARcinogen EXposure should be decreased as much as possible [34]; therefore, the estimates of exposure ratings may not endorse safety in terms of cancer risks. Fifth, we used the Korean OEL between 2014 and 2016 as a reference OEL. The Korean OEL mainly refers to TLVs of the ACGIH [35]. Applying different OELs would result in different exposure ratings.

Our study also has a few limitations stemming from the characteristics of workplace exposure monitoring, as described in previous studies [15,22]. First, workplace monitoring is conducted based on the maximum risk rather than a random sampling of participants. Second, workplace monitoring is performed by private WEMIs, and the companies pay the fees. This payment structure may affect monitoring results because companies are usually concerned about the disadvantages of violations of OELs. Third, small companies may be under-represented rather than large companies because of monitoring fees or ignorance.

In conclusion, we estimated the exposure intensity for 21 carcinogenic agents across 228 minor industrial groups using a nationwide workplace monitoring database. The study results will supply complementary information about CARcinogen EXposure intensity to the K-CAREX. Furthermore, it will aid in prioritizing prevention efforts for occupational cancers and identifying industries of concern for additional monitoring.

Ethics

The study protocol was reviewed and approved by the Institutional Review Board of the Catholic Kwandong University, International St. Mary’s Hospital, Incheon, Republic of Korea (IS17QIM0035).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgment

This study was supported by the Basic Science Research Program through the National Research Foundation of Korea, funded by the Ministry of Education (grant number 2017R1D1A1B04032379). This study was also supported by the Occupational Safety and Health Research Institute grant (2021-OSHRI-795), funded by the Korea Occupational Safety and Health Agency.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2022.05.003.

References

[1] Hong S, Won Y-J, Lee J, Jung K-W, Kong H-J, Im J-S, et al. Cancer statistics in Korea: incidence, mortality, survival, and prevalence in 2018. Cancer Res Treat 2021;53:301–15.
[2] Brown KF, Rumgay H, Dunlop C, Ryan M, Quartly F, Cox A, et al. The fraction of cancer attributable to modifiable risk factors in England, Wales, Scotland, Northern Ireland, and the United Kingdom in 2015. Br J Cancer 2018;118:1130–41.
[3] Doll R, Peto R. The causes of cancer: quantitative estimates of avoidable risks of cancer in the United States today. J Natl Cancer Inst 1981;66:1191–308.
[4] Geiser K. Chemicals without harm-policies for a sustainable world. MIT Press; 2015.
[5] Lee T, Gany F. Cooking oil fumes and lung cancer: a review of the literature in the context of the U.S. population. J Immigr Minor Health 2013;15:646–52.
[6] Loomis D, Guha N, Hall AL, Straif K. Identifying occupational carcinogens: an update from the IARC monographs. Occup Environ Med 2018;75:593–603.
[7] Blanco-Romero LE, Vega LE, Lozano-Chavarria LM, Partanen TJ. CAREX Nicaragua and Panama: worker exposures to carcinogenic substances and pesticides. Int J Occup Environ Health 2011;17:251–7.
[8] Kauppinen T, Pajarskene B, Pondezzi E, Rjazanov V, Smerdovszky Z, Verdebaum T, et al. Occupational exposure to carcinogens in Estonia, Latvia, Lithuania and the Czech Republic in 1997. Scand J Work Environ Health 2001;27:345–5.
[9] Mirabella D, Kauppinen T. Occupational exposures to carcinogens in Italy: an update of CAREX database. Int J Occup Environ Health 2005;11:53–63.
[10] Partanen T, Chaves J, Wesseling C, Chaves F, Mone P, Ruempel C, et al. Workplace carcinogen and pesticide exposures in Costa Rica. Int J Occup Environ Health 2003;9:104–11.
[11] Peters CE, Ge CB, Hall AL, Davies HW, Demers PA. CAREX Canada: an enhanced model for assessing occupational carcinogen exposure. Occup Environ Med 2015;72:64–71.
[12] Kauppinen T, Toikkanen J, Pedersen D, Young R, Ahrens W, Roffetta P, et al. Occupational exposure to carcinogens in the European Union. Occup Environ Med 2000;57:10–8.
Koh DH, Park JH, Lee SG, Kim HC, Choi S, Jung H, et al. Development of Korean CARcinogen EXposure: an initiative of the occupational carcinogen surveillance system in Korea. Ann Work Expo Health 2021;65:328–38.

Koh H, Ha E, Kim J, Jung H, Paek D. Occupational health services for small-scale enterprises in Korea. Ind Health 2002;40:1–6.

Koh DH, Park JH, Lee SG, Kim HC, Choi S, Jung H, et al. Combining lead exposure measurements and experts’ judgment through a Bayesian framework. Ann Work Expo Health 2017;61:1054–75.

Koh DH, Park JH, Lee SG, Kim HC, Choi S, Jung H, et al. Estimation of lead exposure prevalence in Korean population through combining multiple experts’ judgment based on objective data sources. Ann Work Expo Health 2018;62:210–20.

Baan R, Grosse Y, Straif K, Secretan B, El Ghissassi F, Bouvard V, et al. A review of human carcinogens—part F: chemical agents and related occupations. Lancet Oncol 2009;10:1143–4.

Birkett N, Al-Zoughool M, Bird M, Baan RA, Zielinski J, Krewski D. Overview of biological mechanisms of human carcinogens. J Toxicol Environ Health B 2019;22:288–359.

Kim S, Yoon C, Han S, Park J, Kwon O, Park D, et al. Chemical use in the semiconductor manufacturing industry. Int J Occup Environ Health 2018;24:109–18.

Paik NW, Levine SP, Schork A. Development and application of a quality control program for industrial hygiene laboratories in Korea. Appl Occup Environ Hyg 1997;12:46–53.

Hornung RW, Reed LD. Estimation of average concentration in the presence of nondetectable values. Appl Occup Environ Hyg 1990;5:46–51.

Koh DH, Park JH, Lee SG, Kim HC, Jung H, Kim I, et al. Estimation of lead exposure intensity by industry using nationwide exposure databases in Korea. Saf Health Work 2021;12:439–44.

Jahn SD, Bullock W, Ignacio JS. A Strategy for assessing and managing occupational exposures. 4th ed. AIHA; 2015.

Baker BA, Cassano VA, Murray C. Arsenic exposure, assessment, toxicity, diagnosis, and management: guidance for occupational and environmental physicians. J Occup Environ Med 2018;60:e634–9.

Kang D, Jung S, Kim YJ, Kim J, Choi S, Kim SY, et al. Reconstruction of the Korean asbestos job exposure matrix. Saf Health Work 2021;12:74–95.

Finkelstein MM. Asbestos-associated cancers in the Ontario refinery and petrochemical sector. Am J Ind Med 1996;30:610–5.

Koh D-H, Chung E-K, Jang J-K, Lee H-E, Ryu H-W, Yoo K-M, et al. Cancer incidence and mortality among temporary maintenance workers in a refinery/petrochemical complex in Korea. Int J Occup Environ Health 2014;20:141–5.

Kreiss K, Day CA, SchulerCR. Beryllium: a modern industrial hazard. Annu Rev Public Health 2007;28:259–77.

Chung EK, Jang JK, Koh DH. A comparison of benzene exposures in maintenance and regular works at Korean petrochemical plants. J Chem Health Saf 2017;24:21–6.

Koh D-H, Lee M-Y, Chung E-K, Jang J-K, Park D-U. Comparison of personal air benzene and urine t,t-muconic acid as a benzene exposure surrogate during turnaround maintenance in petrochemical plants. Ind Health 2018;56:346–55.

Scarselli A, Corbasi M, Di Marzio D, Iavicoli S. Appraisal of levels and patterns of occupational exposure to 1,3-butadiene. Scand J Work Environ Health 2017;43:494–503.

Kauppinen T, Uuksulainen S, Saalo A, Makinen I, Pukkala E. Use of the Finnish information system on occupational exposure (FINJEM) in epidemiologic surveillance, and other applications. Ann Occup Hyg 2014;58:380–96.

Burdorf A. Commentary: variability in workplace exposures and the design of efficient measurement and control strategies. Ann Occup Hyg 2003;47:95–9.

Cherrie JW. Reducing occupational exposure to chemical carcinogens. Occup Med 2009;59:96–100.

Jeong JY, Choi S, Kho YJ, Kim PG. Extensive changes to occupational exposure limits in Korea. Regul Toxicol Pharmacol 2010;58:345–8.