Original Article

Development of Korean CARcinogen EXposure: An Initiative of the Occupational Carcinogen Surveillance System in Korea

Dong-Hee Koh1,*, Ju-Hyun Park2, Sang-Gil Lee3, Hwan-Cheol Kim4, Sangjun Choi5, Hyejung Jung1, Inah Kim6 and Donguk Park7

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

*Author to whom correspondence should be addressed. Tel: +82-32-290-2825; Fax: +82-32-290-3879; e-mail: koh.donghee@gmail.com

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Abstract

Objective: To prevent occupational cancers, carcinogen exposure surveillance systems have been developed in many countries. This study aimed to develop a carcinogen exposure database specific to South Korea.

Methods: Twenty known human carcinogens were selected for this study. The International Standard Classification of Industry was used for a classification scheme of industries. Three nationwide occupational exposure databases, the Work Environment Measurement Database, the Special Health Examination Database, and the Work Environment Condition Survey, were used to calculate reference exposure prevalence estimates by carcinogen and industry. Then, 37 professional industrial hygienists with at least 19 years of field experience provided their own exposure prevalence estimates, after reviewing the abovementioned reference estimates derived from three data sources. The median value of the experts’ estimates was used as the final exposure prevalence. Finally, the number of exposed workers was computed by multiplying the final exposure prevalence by the number of workers extracted from the 2010 national census data by carcinogen and industry.

Results: The exposure prevalence and the number of exposed workers were calculated according to 20 carcinogen and 228 minor industrial groups, assuming year 2010 circumstances. The largest population was exposed to welding fumes (326 822 workers), followed by ultraviolet radiation (238 937 workers), ionizing radiation (168 712 workers), and mineral oil mist (146 798 workers).
Conclusions: Our results provide critical data on carcinogen exposure for the prevention of occupational cancers.

Keywords: cancer; carcinogen; exposure; occupational cancer; occupational exposure

Introduction

Cancer is the second leading cause of death globally, accounting for one in six deaths (Naghavi et al., 2017). In South Korea, one in three individuals are expected to suffer from some type of cancer during their lifetime, and one-fourth of individuals die due to cancer (Jung et al., 2019).

Occupational causes are estimated to contribute to 2–8% of all cancer cases (Doll and Peto, 1981; Steenland et al., 2003; Coglianese et al., 2011; Rushton et al., 2012). Currently, occupational cancer is one of the most important issues pertinent to workers’ health and compensation in South Korea. The best ways of preventing occupational cancer are to characterize the hazards, evaluate the risks, conduct research on substitute chemicals for hazardous chemicals and develop safer chemicals, in addition to restricting the production or use of highly hazardous chemicals (Geiser, 2015).

As an initial step in developing control measures for occupational carcinogens, many countries have established carcinogen surveillance systems, such as the Finish Job-Exposure Matrix and the European CARcinogen EXposure (CAREX) system (Kauppinen et al., 2000; Kauppinen et al., 2014). In the CAREX system, the numbers of exposed workers by carcinogen and industry were estimated for member states, and the results have been used as the basic data to evaluate the impact of carcinogens on health outcomes. The CAREX system has been adopted by other countries (Kauppinen et al., 2001; Partanen et al., 2003; Mirabelli and Kauppinen, 2005; Blanco-Romero et al., 2011; Peters et al., 2015). The CAREX was originally an industry-based exposure matrix estimating the number of carcinogen-exposed workers, but it has now extended to a comprehensive exposure matrix, including exposure intensity as well as an occupation-based exposure matrix (Peters et al., 2015).

South Korea is a highly industrialized country with a variety of manufacturing sectors and facilities, such as semiconductor and car manufacturing industries. Many workers in these industries are exposed to various carcinogenic agents, and thus, nationwide exposure studies have been conducted for several carcinogens, including benzene, asbestos and diesel engine exhaust (Park et al., 2015; Choi et al., 2016; Choi et al., 2017; Jung, Koh, et al., 2019; Koh et al., 2020). However, no integrative carcinogen exposure database has been developed yet. Therefore, we planned to develop a Korean CAREX (K-CAREX), which is an occupational carcinogen exposure database specific to the Korean working population. To do so, in a previous pilot study, we developed a methodology to estimate exposure prevalence by combining objective data sources and expert judgement (Koh et al., 2018). In the current study, we expanded the target agents to 20 carcinogens, and by applying the methodology, estimated the exposure prevalence and numbers of exposed workers by carcinogen and industry.

Methods

Data sources

The Korean government requires employers to run exposure and health surveillance systems for workers exposed to hazardous agents. For exposure surveillance, every workplace exposed to any of the 192 designated physical and chemical agents must undergo an annual exposure monitoring, which is usually conducted as an
airborne measurement survey (Paik et al., 1997; Koh et al., 2017, 2018). The resultant measurements have been compiled in a nationwide electronic database since 2002, known as the Work Environment Measurement Database (WEMD). The WEMD contains the measured site, department, concentrations, sampling, and analytical methods, standard industrial codes and number of total employees of the company.

With regard to health surveillance, every worker exposed to any of the 176 designated physical and chemical agents (including night-shift workers) should undergo an annual health examination by law. These results have been compiled as a nationwide electronic database since 2000, known as the Special Health Examination Database (SHED). The SHED includes symptom questionnaires, clinical test results, biological monitoring, standard industrial codes, and the number of total employees of the company (Koh et al., 2018; Won et al., 2019).

In addition, the Ministry of Labour has conducted a workplace exposure survey for hazardous exposure across companies once every 5 years since 1998, which is known as the Work Environment Condition Survey (WECS) (Koh et al., 2018). The WECS is a systematic survey examining all manufacturing workplaces employing five or more workers. However, for small companies employing fewer than five workers or companies other than those in the manufacturing sector, such as the service industry, a stratified systemic sampling method was used. Trained surveyors visited a target company to investigate hazardous chemicals, the number of exposed workers and the number of total employees of the company.

The WEMD, SHED, and WECS have been centrally collected by the Korea Occupational Safety and Health Agency (KOSHA), which is a government agency. We retrieved exposure data from the WEMD, SHED, and WECS as reference data sources for the subsequent estimation process. We set the target year of the K-CAREX as 2010, and we collected the WEMD data between 2010 and 2012, the SHED data between 2009 and 2011, and the WECS data from the 2009 and 2014 surveys.

Selection of target carcinogens and definition of carcinogens

We selected the target carcinogenic agents using three criteria: (i) they are definite human carcinogens (Group 1) designated by the International Agency for Research on Cancer (IARC) (Cogliano et al., 2011); (ii) they are measured in the WEMD, SHED, or WECS, and (iii) they are used widely in occupational settings. Exposure to several uncommon carcinogens, such as benzidine, was found in at least one of the three databases. However, owing to stringent restrictions by law or active avoidance of usage, the number of exposed workers was very small and limited to certain industries. Therefore, these carcinogens were excluded from the development of the K-CAREX.

Finally, a total of 20 definite human carcinogens (arsenic, asbestos, benzene, beryllium, 1,3-butadiene, cadmium, chromium, ethylene oxide, formaldehyde, mineral oil mist, nickel, polycyclic aromatic hydrocarbons (PAHs), ionizing radiation, crystalline silica, sulphuric acid, trichloroethylene, ultraviolet (UV) radiation, vinyl chloride monomer, welding fumes, and wood dust) were selected as target carcinogens.

Mineral oil mist was regarded as a carcinogen in the present study. Untreated or mildly treated (for instance, mildly hydro-treated) mineral oil mist is designated as a definite carcinogen (Group 1), whereas highly treated mineral oil mist is not regarded as a carcinogen (IARC, 2012). However, even highly treated mineral oil mist can contain carcinogens, such as benz[a]pyrene and nitrosamine, generated during manufacturing processes, such as cutting, grinding, and quenching (Simpson and Ellwood, 1996; Simpson, 2003; Hsu et al., 2014). For this reason, mineral oil mist is highly suspected to cause cancers, such as skin cancer (IARC, 1984; Tolbert, 1997). Therefore, we included it as one of the target carcinogens.

PAHs are a complex mixture of chemicals (Koh et al., 2020). In the present study, PAHs (or jobs in which employees are exposed to PAHs) included coal tar, coal tar pitch volatile, asphalt fumes, and coke production. In addition to the aforementioned exposure sources, air pollution-related exposure, such as diesel engine exhaust, is considered an important source of PAHs. Indeed, delivery workers exposed to air pollution showed a relatively high level of 1-hydroxypyrene, which is a biomarker of PAH exposure (Koh et al., 2020). However, in the current study, exposure from air pollution was not considered in the estimation process. Estimates of the number of workers exposed to diesel engine exhaust in Korea is reported elsewhere (Choi et al., 2016).

Strong inorganic acid has been designated a definite human carcinogen known to cause laryngeal cancer (Baan et al., 2009). Sulphuric acid was regarded initially as a definite carcinogen, but it was later extended to other strong inorganic acids, such as hydrochloric acid, considering the similarity of the carcinogenetic mechanism. However, in the present study, we only estimated the exposure prevalence for sulphuric acid among the strong inorganic acids. Sulphuric acid is the acid studied most
frequently and has relatively abundant epidemiological results. Moreover, in occupational settings, multiple acid exposures are common, for instance, co-exposure of sulphuric and nitric acid in the electroplating process. Therefore, counting each acid separately could lead to an overestimation of the exposure prevalence of strong acid mists. For these reasons, we calculated the exposure prevalence only for sulphuric acid.

Exposure to UV and ionizing radiation can occur naturally or artificially. In the current study, UV and ionizing radiation exposure was defined as artificially occurring exposure, excluding naturally occurring exposure such as sunlight.

**Standard industrial classification**
The WEMD, SHED, and WECS were coded with the Korean Standard Industrial Classification (KSIC-9). As the KSIC-9 was developed based on the International Standard Industrial Classification (ISIC, 4th revision), the KSIC is generally identical to the ISIC (Koh et al., 2018). We used the ISIC as a standard industrial classification (SIC) to estimate exposure prevalence. The three-digit SIC code, consisting of 228 minor industrial groups, was used to classify groups for which the estimation process was conducted.

**Computing reference prevalence estimates**
The computing process of reference exposure prevalence estimates from the WEMD, SHED, and WECS has been described elsewhere in detail (Koh et al., 2018). In brief, for the WEMD, exposure prevalence estimates of the three-digit minor industrial groups for a carcinogen were computed by dividing the sum of the estimated number of exposed workers (the number of measurements multiplied by 4) by the sum of the number of total workers in the industrial groups. Basically, one worker is measured for every five workers in a similar exposure group. However, if there are two to nine workers, at least two workers are measured. If there is one worker, the worker is measured. Considering these sampling schemes, we assigned 4 as a multiplier based on the authors’ consensus. For the SHED, exposure prevalence estimates for the three-digit minor industrial groups were computed by dividing the sum of the number of health examinées by the sum of the number of total workers in the industrial groups. For the WECS, exposure prevalence estimates were computed for the three-digit minor industrial groups, by dividing the sum of the number of exposed workers (numerator) by the sum of the number of total workers (denominator) in the industrial groups. These three exposure prevalence estimates were used as reference estimates for experts when they provided their own exposure prevalence estimates.

**Elicitation of expert judgement**
To estimate the exposure prevalence, reference estimates from three objective data sources and expert judgement were combined using a method described in a previous study (Koh et al., 2018). In brief, after reviewing three reference exposure prevalence estimates extracted from the WEMD, SHED, and WECS, industrial hygiene experts provided their own exposure estimates for each of 20 carcinogens and 228 minor industrial groups based on their knowledge and experience.

Industrial hygienists with abundant field experience were recruited for this study. Eligible experts were identified through personal networks. These experts routinely conducted work environmental monitoring for various agents and workplaces. Accordingly, these monitoring results have been compiled in the WEMD (Koh et al., 2017). Experts were recruited from three industrial complex areas (Busan, Cheonan, and Incheon) considering geographical distributions. Busan is a port city in the southern part of Korea, where various manufacturing industries are located, especially those concentrating on light industry and shipbuilding. The Cheonan area is in the middle part of Korea and is home to the semiconductor and petrochemical industries. Incheon is a port city in the northern part of Korea and also has various manufacturing industries, including wood, iron and foundry and automobiles. A total of 37 industrial hygiene experts with 19 or more years of field experience (median, 25 years; maximum, 39 years) participated in this study. There were 17, 8, and 12 experts recruited from Incheon, Cheonan, and Busan, respectively.

Using a questionnaire, experts were asked to review the three exposure prevalence estimates from the WEMD, SHED, and WECS, and then provide their own estimates, assuming 2010 industrial circumstances. The definition of exposure was determined as exposure over the background level, in line with the European and Canadian CAREX systems (Kauppinen et al., 2000; Peters et al., 2015). Exposure prevalence estimates ranged from 0 to 100%, with a minimum of 0.01% representing 1 in 10 000 employees.

To facilitate the experts’ judgement, we hosted workshops in the three cities to explain the goal of the study and the overall estimation methods. Experts were also encouraged to refer to the literature, whenever necessary. In addition, experts were provided with a file containing explanations of the SIC codes.

**Statistical analysis**
The final exposure prevalence estimates were computed by pooling and analysing the resulting estimates provided by the experts. To obtain the final exposure prevalence estimates, we computed the first quartile (Q1), median
and third quartile (Q3) values of the experts’ estimates according to carcinogen and industry, as described in a previous study (Koh et al., 2018). The median value was used as the final estimate, and Q1 and Q3 were used as an interval supplementary to the medians showing variability around the centre of the experts’ estimates.

To calculate the number of exposed workers by carcinogen and industry, we multiplied the median values of the experts’ estimates by the number of workers in the industry derived from the 2010 Korean Population and Housing Census. The overall development process of K-CAREX is presented in Figure 1.

**Exception of the estimation process**

For most carcinogens, the experts’ judgement was used as a source for the final estimation. However, for UV and ionizing radiation, exposure prevalence estimates of the SHED were used as final exposure estimates, because UV and ionizing radiation have not been measured or examined in the WEMD and WECS. In addition, for ionizing radiation, the National Dose Registry data were available in several industries. Therefore, for these industries, the National Dose Registry data were used instead (Korea Center for Disease Control and Prevention, 2011; Nuclear Safety and Security Commission, 2012).

For several industry workers exposed to UV and ionizing radiation, there were overly high or low prevalence estimates, especially in non-manufacturing sectors, although these values were unlikely. These extreme values might be generated from a combination of a small number of exposed workers and companies examined in the industry, which were also observed in the previous pilot study (Koh et al., 2018). The authors revised these extreme values a posteriori based on the authors’ consensus.

**Results**

The 20 target carcinogens are listed in Table 1 with the characteristics of the exposure data sources. The number of work environmental measurements in the WEMD, the number of special health examinees and the number of (surveyed) exposed companies in the WECS by carcinogen are presented in Table 1. For instance, with regard to benzene, a total of 11,996 measurements were recorded in the WEMD between 2010 and 2012, a total of 59,011 workers underwent special health examinations for benzene between 2009 and 2010, and a total of 1293 companies were exposed to benzene in the WECS in the 2009 and 2014 surveys. Welding fumes showed the largest number in both the WEMD and SHED. The number of workers exposed (numerator) and the number of total workers (denominator) calculated from the three databases by carcinogen and industry are available online at https://koreancarex.shinyapps.io/k-carex_ref/.

Table 2 shows the estimated numbers of workers exposed in the year 2010 by carcinogen, as well as the cancers associated with each carcinogen. The largest exposure population was observed for welding fumes (326,822 workers), followed by UV radiation (238,937 workers), ionizing radiation (168,712 workers), and mineral oil mist (146,798 workers).

The results from the three objective data sources, expert judgement, final exposure prevalence estimates, and the number of exposed workers by carcinogen for a selected industry (201, Manufacture of Basic Chemicals) are presented in Table 3. In this industry, benzene is the carcinogen to which workers are exposed most commonly. Benzene exposure prevalence estimates from objective data sources were 13.1% (WEMD), 16.3% (SHED), and 0.1% (WECS). The median (10%) value calculated from the experts’ judgement was assigned as the final exposure prevalence estimate, which resulted in an estimate of 3078 benzene-exposed workers in the Manufacture of Basic Chemicals industry.

The results from the three objective data sources, expert judgement, final exposure prevalence estimates,
and the number of exposed workers by industry for the selected carcinogen (benzene) (industries ≥ 100 exposed workers) are presented in Table 4. For benzene exposure, the industry in which workers were most commonly exposed was Interior and Building Completion (424) among 228 minor industrial groups, with 3078 workers exposed to benzene. In terms of exposure prevalence, the Manufacture of Refined Petroleum Products industry showed the highest prevalence of exposure (15.50%), with 2535 workers exposed to benzene. Detailed prevalence estimates from the WEMD, WECS, SHED, and experts’ judgement by carcinogen and industry are available online at https://koreancarex.shinyapps.io/k-carex/.

### Discussion

In the present study, we computed the exposure prevalence and number of workers exposed to 20 carcinogens in 228 minor occupational groups using a systematic method, resulting in the first integrative carcinogen exposure database specific to the Korean working population. We used a method previously developed to estimate the exposure prevalence by systematically combining exposure data and expert judgement. We will continue to update by adding new data in the future based on current results.

In South Korea, asbestos has been widely used in the manufacturing and construction industries until the 2000s (Choi et al., 2017). Beginning with a ban on crocidolite and amosite in 1997, a comprehensive ban on the use of chrysotile and all asbestos-containing materials (containing > 0.1% asbestos) was introduced in 2009, with the exception of special use such as in submarines and missiles. A complete ban finally went into effect in 2015 (Park et al., 2008). In the present study, the prevalence of asbestos exposure in the Manufacture of Basic Chemicals, shown in Table 2, was 0%. Accordingly, the estimated number of workers exposed to asbestos was 0 in the year 2010, which might reflect the change resulting from the legal asbestos ban. However, there is still a possibility of potential asbestos exposure, for instance, during the abatement and demolition of buildings containing asbestos materials. For this reason, the SHED showed a 0.81% exposure prevalence estimate and the Q3 value of the experts’ judgement was 0.03%.
UV and ionizing radiation are carcinogenic agents that are not included in the exposure surveillance system (WEMD), but are included in the health surveillance system (SHED). Therefore, industrial hygiene experts provided their estimates only after reviewing exposure prevalence estimates derived from the SHED. Their median estimates for UV and ionizing radiation were relatively lower than the SHED estimates, which indicates that experts may tend to underestimate exposure when they have no experience in measuring it. For this reason, we used the SHED prevalence as the final estimate instead.

A direct comparison of our exposure prevalence to that of other CAREX systems was difficult, owing to different industrial structures, industrial classification, and target years for which the CAREX was developed. In general, our results tend to have a slightly lower exposure prevalence than other CAREX. However, some consistencies were also observed. Trichloroethylene, for instance, in the ‘manufacture of rubber products (ISIC Revision 2)’ in the European CAREX (Kauppinen et al., 2000) and ‘rubber production manufacturing (North American Industry Classification System, 2002 version)’ in the Canadian CAREX (Peters et al., 2015) showed an

### Table 2. Estimated number of exposed workers in the year 2010 by carcinogen and related cancers.

| Carcinogen                        | Exposed workers | Related cancers (Cogliano et al., 2011; Loomis et al., 2018)                      | Sufficient evidence | Limited evidence |
|-----------------------------------|-----------------|----------------------------------------------------------------------------------|--------------------|-----------------|
| Welding fumes (Guha et al., 2017) | 326 822         | Lung, eye melanoma (due to UV radiation)                                        | Kidney             |
| Ultraviolet, artificially occurring | 238 937       | Eye (melanoma), skin (melanoma)                                                 | Skin (squamous cell carcinoma) |
| Radiation, ionizing               | 168 712         | Multiple sites                                                                   |                    |
| Mineral oil mist                  | 146 492         | Skin                                                                             |                    |
| Nickel                            | 114 715         | Lung, nasal cavity, and paranasal sinus                                          |                    |
| Sulphuric acid                    | 78 648          | Larynx                                                                          | Lung               |
| Wood dust                         | 78 131          | Nasal cavity and paranasal sinus, nasopharynx                                    |                    |
| Silica, crystalline               | 63 402          | Lung                                                                             |                    |
| Formaldehyde                      | 49 798          | Leukaemia (particularly myeloid), nasopharynx                                    | Nasal cavity and paranasal sinus |
| Trichloroethylene (Guha et al., 2012) | 27 923     | Kidney                                                                          | Non-Hodgkin’s lymphoma, liver |
| Benzene (Loomis et al., 2017)     | 18 960          | Leukaemia (acute nonlymphocytic)                                                | Leukaemia (acute lymphocytic, chronic lymphocytic), multiple myeloma, non-Hodgkin’s lymphoma |
| Ethylene oxide                    | 18 181          |                                                                                 | Breast, lymphoid tumours (non-Hodgkin’s lymphoma, multiple myeloma, chronic lymphocytic leukaemia) |
| Chromium, hexavalent              | 14 550          | Lung                                                                             | Nasal cavity and paranasal sinus |
| Cadmium                           | 5214            | Lung                                                                             | Kidney, prostate    |
| Asbestos                          | 5134            | Larynx, lung, mesothelioma, ovary                                               | Colorectum, pharynx, stomach |
| Vinyl chloride monomer            | 4349            | Liver (angiosarcoma, hepatocellular carcinoma)                                  |                    |
| 1,3-Butadiene                     | 3696            | Haemato-lymphatic organs                                                        |                    |
| Arsenic                           | 2184            | Lung, skin, urinary bladder                                                     | Kidney, liver, prostate |
| Polycyclic aromatic hydrocarbons  | 1552            | Lung, skin                                                                       | Urinary bladder     |
| Beryllium                         | 151             | Lung                                                                             |                    |

The overall total number of workers was 22 198 431.
exposure prevalence of 2 and 1.5%, respectively, which is not far from the 0.9% found for ‘manufacture of rubber production (ISIC Revision 4)’ in the K-CAREX.

Compared with the CAREX systems developed previously in other countries (Kauppinen et al., 2000; Peters et al., 2015), the K-CAREX has several advanced features. First, our study used a large number of experienced expert assessors, three nationwide exposure databases and a highly systematic method. Second, we enhanced transparency by providing estimates from three nationwide exposure databases and expert judgment, which may help gauge the uncertainty surrounding the estimates. Third, the K-CAREX accounted for the uncertainty surrounding the final exposure prevalence estimates by providing Q1 and Q3 as an interval supplementary to the medians showing variability around the centre of the experts’ estimates.

The K-CAREX also has several limitations. First, it has a narrower scope of carcinogens than other CAREX systems by including only 20 carcinogens. Second, a three-digit SIC code would be too crude to account for the huge variability in exposure circumstances. Therefore, caution is needed when interpreting the results. We may further account for this issue in future studies. Third, we did not consider overlapping exposure to multiple carcinogens, such as nickel and chromium exposure during welding operations. Thus, the number of workers exposed to chromium was calculated separately and independently of the number exposed to nickel. The European CAREX provided a total number of workers exposed to many kinds of carcinogens. However, we could not estimate such a total sum of workers exposed to carcinogens. Fourth, the exposure estimates varied greatly between the three nationwide data sources owing to different aims and survey methods. We expect that the industrial hygiene experts’ judgement might address this discrepancy. Fifth, sex and age distributions are important factors in predicting the health impact caused by exposure to a certain carcinogen. However, such information was only partially

The total number of workers in the selected industry was 30 781.

| Carcinogen                              | Objective data (%) | Expert judgement (%) | Final exposure prevalence (%) | Exposed workers |
|-----------------------------------------|--------------------|----------------------|-------------------------------|-----------------|
|                                        | WEMD| SHED| WECS| Q1| Median| Q3| Estimate| Source|                |
| Benzene                                | 13.1| 16.38| 0.1| 4.88| 10.00| 12.00| 10.00| Experts’ median| 3078 |
| Sulphuric acid                         | 8.62| 12.58| 0.55| 2.48| 5.00| 6.74| 5.00| Experts’ median| 1539 |
| 1,3-Butadiene                          | 4.75| 4.07| 0.01| 1.04| 2.79| 4.00| 2.79| Experts’ median| 857  |
| Radiation, ionizing                    | NA | 2.62| NA | 0| 0.10| 2.13| 2.62| SHED, NDR, Authors| 806  |
| Vinyl chloride monomer                 | 2.35| 2.42| 0.01| 0.33| 2.00| 2.40| 2.00| Experts’ median| 616  |
| Formaldehyde                           | 2.73| 1.7 | 0.08| 0.66| 1.80| 2.58| 1.80| Experts’ median| 554  |
| Ultraviolet, artificially occurring    | NA | 0.71| NA | 0| 0.01| 0.67| 0.71| SHED, Authors| 219  |
| Trichloroethylene                      | 0.86| 0.99| 0 | 0.30| 0.65| 1.00| 0.65| Experts’ median| 200  |
| Nickel                                 | 1.52| 1.29| 0.05| 0.10| 0.63| 1.38| 0.63| Experts’ median| 194  |
| Ethylene oxide                         | 0.96| 1.04| 0.03| 0.03| 0.30| 1.00| 0.30| Experts’ median| 92   |
| Welding fumes                          | 1.34| 1.04| NA | 0.01| 0.30| 1.03| 0.30| Experts’ median| 92   |
| Chromium, hexavalent                   | 0.47| 0.61| 0.02| 0.07| 0.25| 0.50| 0.25| Experts’ median| 75   |
| Cadmium                                | 0.33| 0.14| 0 | 0.03| 0.14| 0.30| 0.14| Experts’ median| 42   |
| Mineral oil mist                       | 0.2 | 0.42| 0.03| 0.05| 0.12| 0.31| 0.12| Experts’ median| 35   |
| Polycyclic aromatic hydrocarbons       | 0.02| 0.38| 0.03| 0.03| 0.12| 1.00| 0.12| Experts’ median| 35   |
| Arsenic                                | 0.05| 0.05| 0 | 0.01| 0.04| 0.10| 0.04| Experts’ median| 11   |
| Silica, crystalline                    | 0.74| 0   | 0.07| 0| 0.03| 0.36| 0.03| Experts’ median| 9    |
| Beryllium                              | 0.07| 0.02| 0 | 0.01| 0.01| 0.03| 0.01| Experts’ median| 3    |
| Wood dust                              | 1.03| 0.52| NA | 0| 0.01| 0.18| 0.01| Experts’ median| 2    |
| Asbestos                               | 0 | 0.81| 0 | 0| 0.03| 0| 0| Experts’ median| 0    |

Table 3. Exposure prevalence and number of exposed workers in the year 2010 by carcinogen for a selected industry, 201: Manufacture of Basic Chemicals.

The total number of workers in the selected industry was 30 781.
NA, not applicable; NDR, National Dose Registry; Q1, first quartile; Q3, third quartile; SHED, Special Health Examination Database; WECS, Work Environment Condition Survey; WEMD, Work Environment Measurement Database.
Table 4. Exposure prevalence and number of exposed workers in the year 2010 by industry for a selected carcinogen (benzene) in industries with 100 or more exposed workers.

| SIC   | Explanation                                                                 | Objective data (%) | Expert judgement (%) | Final exposure prevalence (%) | Exposed workers |
|-------|----------------------------------------------------------------------------|--------------------|----------------------|-------------------------------|----------------|
|       |                                                                             | WEMD   | SHED | WECS | Q1  | Median | Q3  | Estimate | Source            |                  |
| 424   | Interior and Building Completion                                           | 1.12   | 3.5  | 0    | 0.02 | 1.00   | 1.55 | 1.00     | Experts’ median    | 3450             |
| 201   | Manufacture of Basic Chemicals                                             | 13.1   | 16.38| 0.1  | 4.88 | 10.00  | 12.00| 10.00    | Experts’ median    | 3078             |
| 192   | Manufacture of Refined Petroleum Products                                  | 41.87  | 13.08| 0.5  | 7.75 | 15.50  | 30.04| 15.50    | Experts’ median    | 2535             |
| 477   | Retail Sale of Fuel                                                        | 9.38   | 3.71 | 0    | 0.01 | 2.86   | 5.00 | 2.86     | Experts’ median    | 2302             |
| 204   | Manufacture of Other Chemical Products                                     | 1.64   | 1    | 0.03 | 0.65 | 1.00   | 1.50 | 1.00     | Experts’ median    | 715              |
| 422   | Building Installation                                                      | 0.71   | 22.15| 0    | 0    | 0.40   | 1.00 | 0.40     | Experts’ median    | 594              |
| 729   | Other Scientific and Technical Services                                    | 8.11   | 3.19 | 0    | 0.05 | 0.86   | 2.95 | 0.86     | Experts’ median    | 533              |
| 421   | Site Preparation and Special Trade Construction for Civil Engineering and   | 1.15   | 2.55 | 0    | 0    | 0.36   | 1.00 | 0.36     | Experts’ median    | 480              |
|       | Buildings                                                                  |        |      |      |      |        |      |          |                  |                  |
| 423   | Electrical and Communication Works                                         | 1.7    | 10.01| 0    | 0    | 0.23   | 1.00 | 0.23     | Experts’ median    | 446              |
| 181   | Printing and Service Activities Related to Printing                        | 1.61   | 0.18 | 0.25 | 0.09 | 0.52   | 1.06 | 0.52     | Experts’ median    | 412              |
| 203   | Manufacture of Synthetic Rubber and of Plastics in Primary Forms           | 1.53   | 4.25 | 0.05 | 0.18 | 1.52   | 2.63 | 1.52     | Experts’ median    | 384              |
| 381   | Waste Collection                                                           | 3.71   | 6.14 | 0    | 0.89 | 1.68   | 3.50 | 1.68     | Experts’ median    | 370              |
| 521   | Warehousing                                                                | 3.11   | 6.9  | 0    | 0    | 0.50   | 1.57 | 0.50     | Experts’ median    | 341              |
| 212   | Manufacture of Medicaments                                                 | 1.51   | 0.84 | 0.04 | 0.48 | 0.78   | 1.01 | 0.78     | Experts’ median    | 311              |
| 382   | Waste Treatment Services                                                   | 1.96   | 2.31 | 0    | 0.69 | 1.66   | 2.02 | 1.66     | Experts’ median    | 297              |
| 951   | Maintenance and Repair Services of Machinery and Equipment                  | 0.45   | 7.27 | 0.08 | 0.04 | 0.29   | 0.95 | 0.29     | Experts’ median    | 268              |
| 701   | Research and Experimental Development on Natural Sciences and Engineering   | 1.4    | 1.14 | 0    | 0.02 | 0.16   | 1.00 | 0.16     | Experts’ median    | 224              |
| 301   | Manufacture of Motor Vehicles and Engines for Motor Vehicles                | 1.04   | 0.21 | 0    | 0.05 | 0.16   | 0.50 | 0.16     | Experts’ median    | 159              |
| 221   | Manufacture of Rubber Products                                             | 0.61   | 0.02 | 0    | 0.05 | 0.37   | 0.83 | 0.37     | Experts’ median    | 153              |
| 412   | Heavy Construction                                                        | 0.18   | 3.57 | 0    | 0    | 0.05   | 0.43 | 0.05     | Experts’ median    | 116              |
| 303   | Manufacture of Parts and Accessories for Motor Vehicles and Engines         | 0.22   | 0.08 | 0    | 0.01 | 0.05   | 0.13 | 0.05     | Experts’ median    | 114              |
| 222   | Manufacture of Plastic Products                                            | 0.16   | 0.09 | 0.02 | 0.04 | 0.09   | 0.22 | 0.09     | Experts’ median    | 111              |
| 952   | Maintenance and Repair Services of Motor Vehicles and Motorcycles          | 0.72   | 0.03 | 0.02 | 0.01 | 0.07   | 0.51 | 0.07     | Experts’ median    | 107              |
| 152   | Manufacture of Footwear and Parts of Footwear                               | 0.74   | 0.06 | 0.1  | 0.04 | 0.33   | 0.53 | 0.33     | Experts’ median    | 103              |

Q1, first quartile; Q3, third quartile; SIC, International Standard Industrial Classification (fourth revision); SHED, Special Health Examination Database; WECS, Work Environment Condition Survey; WEMD, Work Environment Measurement Database.
available in the three objective databases to provide consistent estimates across carcinogens and minor occupational groups, and were thus excluded from our analyses. Seventh, the work environment measurements were carried out mainly in the manufacturing, so that other industries, such as the service and construction industry, were underrepresented. As a result, results from industries other than manufacturing may have relatively low reliability.

In summary, in the present study, we estimated the exposure prevalence and number of exposed workers, based on 20 carcinogens and 228 minor industrial groups by referring to three nationwide occupational exposure databases and eliciting the judgement of 37 industrial hygiene experts. The results of this study will aid in prioritizing preventive efforts (Mannetje et al., 2013) and preventing occupational cancers in Korean workers, as well as workers in other countries.

**Ethics**

The study protocol was reviewed and approved by the Institutional Review Board of the Catholic Kwandong University, International St. Mary’s Hospital, Incheon, Korea (IS17QIMI0035).

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**Conflict of Interest**

The authors declare that they have no conflict of interests.

**References**

Baan R, Grosse Y, Straif K et al; WHO International Agency for Research on Cancer Monograph Working Group. (2009) A review of human carcinogens—Part F: chemical agents and related occupations. *Lancet Oncol*; 10: 1143–4.

Blanco-Romero LE, Vega LE, Lozano-Chavarria LM et al. (2011) CAREX Nicaragua and Panama: worker exposure to carcinogenic substances and pesticides. *Int J Occup Environ Health*; 17: 251–7.

Choi S, Kang D, Park D et al. (2017) Developing asbestos job exposure matrix using occupation and industry specific exposure data (1984–2008) in Republic of Korea. *Saf Health Work*; 8: 105–15.

Choi S, Park D, Kim SW et al. (2016) Estimates of the number of workers exposed to diesel engine exhaust in South Korea from 1993 to 2013. *Saf Health Work*; 7: 372–80.

Cogliano VJ, Baan R, Straif K et al. (2011) Preventable exposures associated with human cancers. *J Natl Cancer Inst*; 103: 1827–39.

Doll R, Peto R. (1981) The causes of cancer: quantitative estimates of avoidable risks of cancer in the United States today. *J Natl Cancer Inst*; 66: 1191–308.

Geiser K. (2015) Chemicals without harm-policies for a sustainable world. Cambridge, MA: MIT Press.

Guha N, Loomis D, Grosse Y et al; International Agency for Research on Cancer Monograph Working Group. (2012) Carcinogenicity of trichloroethylene, tetrachloroethylene, some other chlorinated solvents, and their metabolites. *Lancet Oncol*; 13: 1192–3.

Guha N, Loomis D, Guyton KZ et al; International Agency for Research on Cancer Monograph Working Group. (2017) Carcinogenicity of welding, molybdenum trioxide, and indium tin oxide. *Lancet Oncol*; 18: 581–2.

Hsu HI, Lin MY, Chen YC et al. (2014) An integrated approach to assess exposure and health-risk from polycyclic aromatic hydrocarbons (PAHs) in a fastener manufacturing industry. *Int J Environ Res Public Health*; 11: 9578–94.

IARC. (1984) Polynuclear aromatic hydrocarbons: carbon blacks, mineral oils (lubricant base oils and derived products) and some nitroarenes. Part 2. Lyon (FR): International Agency for Research on Cancer.

———. (2012) *Chemical agents and related occupations (Volume 100F)*. Lyon (FR): International Agency for Research on Cancer.

Jung H, Koh DH, Choi S et al. (2019) Estimates of the prevalence, intensity and the number of workers exposed to cigarette smoking across occupations and industries in Korea. *J Korean Med Sci*; 34: e213.

Jung KW, Won YJ, Kong HJ et al. (2019) Cancer statistics in Korea: incidence, mortality, survival, and prevalence in 2016. *Cancer Res Treat*; 51: 417–30.

Kauppinen T, Pajarskiene B, Podniecze Z et al. (2001) Occupational exposure to carcinogens in Estonia, Latvia, Lithuania and the Czech Republic in 1997. *Scand J Work Environ Health*; 27: 343–5.

Kauppinen T, Toikkonen J, Pedersen D et al. (2000) Occupational exposure to carcinogens in the European Union. *Occup Environ Med*; 57: 10–8.

Kauppinen T, Uuksulainen S, Saalo A et al. (2014) Use of the Finnish Information System on Occupational Exposure (FINJEM) in epidemiologic, surveillance, and other applications. *Ann Occup Hyg*; 58: 380–96.

Koh DH, Park JH, Lee SG et al. (2017) Combining lead exposure measurements and experts’ judgment through a Bayesian framework. *Ann Work Expo Health*; 61: 1054–75.

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

Koh DH, Park JH, Lee SG et al. (2020) Comparison of polycyclic aromatic hydrocarbons exposure across occupations using urinary metabolite 1-hydroxypyrene. *Ann Work Expo Health*; 64: 445–54.
Korea Center for Disease Control and Prevention. (2011) 2010 Report Occupational Radiation Exposure in Diagnostic Radiology. Book 2010 Report Occupational Radiation Exposure in Diagnostic Radiology, Osong, Korea: Korea Center for Disease Control and Prevention.

Loomis D, Guha N, Hall AL et al. (2018) Identifying occupational carcinogens: an update from the IARC Monographs. Occup Environ Med; 75: 593–603.

Loomis D, Guyton KZ, Grosse Y et al; International Agency for Research on Cancer Monograph Working Group. (2017) Carcinogenicity of benzene. Lancet Oncol; 18: 1574–5.

Mannetje A, Pearce N, McLean D et al. (2013) Workplace exposure to carcinogens in New Zealand. Wellington (NZ): Center for Public Health Research.

Mirabelli D, Kauppinen T. (2005) Occupational exposures to carcinogens in Italy: an update of CAREX database. Int J Occup Environ Health; 11: 53–63.

Naghavi M, Abajobir AA, Abbafati C et al. (2017) Globalisation in Nuclear Safety and Security Commission. (2012) regional, and national age-sex specific mortality for 264 causes of death, 1980–2013; 2016: a systematic analysis for the Global Burden of Disease Study 2016. Lancet; 390: 1151–210.

Nuclear Safety and Security Commission. (2012) 2011 Nuclear safety year book. Book 2011 nuclear safety year book. Seoul, Korea: Nuclear Safety and Security Commission.

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

Park D, Choi S, Ha K et al. (2015) Estimating benzene exposure level over time and by industry type through a review of literature on Korea. Saf Health Work; 6: 174–83.

Park D, Choi S, Ryu K et al. (2008) Trends in occupational asbestos exposure and asbestos consumption over recent decades in Korea. Int J Occup Environ Health; 14: 18–24.

Partanen T, Chaves J, Wesseling C et al. (2003) Workplace carcinogen and pesticide exposures in Costa Rica. Int J Occup Environ Health; 9: 104–11.

Peters CE, Ge CB, Hall AL et al. (2015) CAREX Canada: an enhanced model for assessing occupational carcinogen exposure. Occup Environ Med; 72: 64–71.

Rushton L, Hutchings SJ, Fortunato L et al. (2012) Occupational cancer burden in Great Britain. Br J Cancer; 107 (Suppl. 1): S3–7.

Simpson AT, Ellwood PA. (1996) Polycyclic aromatic hydrocarbons in quench oils. Ann Occup Hyg; 40: 531–37.

Simpson AT, Stear M, Groves JA et al. (2003) Occupational exposure to metalworking fluid mist and sump fluid contaminants. Ann Occup Hyg; 47: 17–30.

Steenland K, Burnett C, Lalich N et al. (2003) Dying for work: the magnitude of US mortality from selected causes of death associated with occupation. Am J Ind Med; 43: 461–82.

Tolbert PE. (1997) Oils and cancer. Cancer causes control; 8: 386–405.

Won YL, Ko KS, Park JO et al. (2019) Achievements, problems, and future direction of the quality control program for special periodic health examination agencies in Republic of Korea. Saf Health Work; 10: 125–9.