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Original Article

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

Dong-Hee Koh[1,*], Ju-Hyun Park[2], Sang-Gil Lee[3], Hwan-Cheol Kim[4], Sangjun Choi[5], Hyejung Jung[1], Inah Kim[6] and Donguk Park[7]

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

What's important about this paper

The CARcinogen EXposure (CAREX) system was developed in the European Union and subsequently adopted by many countries. This study developed the Korean CAREX system, which estimates the exposure prevalence and the number of exposed workers to 20 definite human carcinogens among 233 minor industrial groups in South Korea. The Korean CAREX system can be used to identify high-risk groups and to prioritize preventive efforts as part of comprehensive carcinogen exposure surveillance and health impact assessment systems for Korean 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; Cogliano *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 benzo[*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 examinees 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,

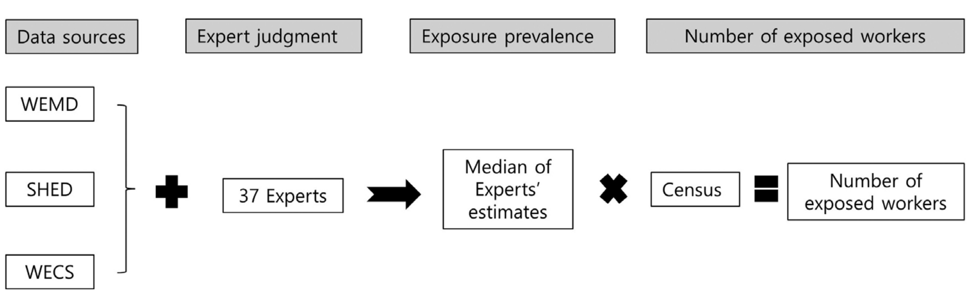

Figure 1. Schematic of the overall estimation process. SHED, Special Health Examination Database; WECS, Work Environment Condition Survey; WEMD, Work Environment Measurement Database.

Table 1. Characteristics of reference data sources by carcinogen.

Carcinogen	WEMD	SHED	WECS
	No. of measurement (2010–2012)	No. of health examinees (2009–2011)	No. of companies (2009, 2014)
Arsenic	1914	15 900	89
Asbestos	550	30 879	6
Benzene	11 996	59 011	1293
Beryllium	169	256	21
1,3-Butadiene	2622	15 081	76
Cadmium	6062	7025	143
Chromium, hexavalent	15 551	22 057	3346
Ethylene oxide	7380	8857	291
Formaldehyde	28 459	50 848	1077
Mineral oil mist	91 622	154 554	28 949
Nickel	89 023	150 444	3399
Polycyclic aromatic hydrocarbons	1027	6698	643
Radiation, ionizing	NA	56 216	NA
Silica, crystalline	30 643	1122	2277
Sulphuric acid	44 617	120 874	5709
Trichloroethylene	19 780	26 375	2133
Ultraviolet, artificially occurring	NA	177 147	NA
Vinyl chloride monomer	2418	8838	156
Welding fumes	141 968	315 906	NA
Wood dust	18 871	25 283	NA

NA, not applicable; SHED, Special Health Examination Database; WECS, Work Environment Condition Survey; WEMD, Work Environment Measurement Database.

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 in this industry. 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%.

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.

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

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	0.03	0	Experts' median	0

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.

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 judgement, 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

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	0.05	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 Buildings	1.15	2.55	0	0	0.36	1.00	0.36	Experts' median	480
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 (fourthrevision); 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.

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