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Development of Korean CARcinogen EXposure: IARC Group 2A Carcinogens

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Backgrounds: Reliable exposure data are critical for occupational cancer prevention and epidemiological studies. We developed the Korean CARcinogen EXposure (K-CAREX) to provide exposure prevalence and intensity for 20 carcinogens classified as Group 1 by the International Agency for Research on Cancer (IARC). This study extends K-CAREX to include IARC Group 2A agents.

Methods: National data sources, including the Work Environment Measurement Database (WEMD), Special Health Examination Database (SHED), and Work Environment Condition Survey (WECS), provided basic exposure data. A stepwise estimation approach was employed to refine exposure prevalence estimates by industry, derived from the WEMD, SHED, and WECS. WEMD was used to estimate exposure intensity by industry, whereas SHED was used to assess exposure prevalence by occupation. Matched data, representing workers who wore samplers and underwent health examinations for the same carcinogen in the same year, were used to estimate exposure intensity by occupation.

Results: A total of 18 IARC Group 2A agents were included. Exposure prevalence was estimated for all 18 carcinogens by industry, and exposure intensity was estimated for 16. The number of exposed workers was estimated, with 162,153 workers exposed to lead, for example. Exposure prevalence and intensity were also assessed for 18 and 16 carcinogens, respectively, by occupation.

Conclusion: The K-CAREX database was developed to estimate exposure prevalence and intensity by industry and occupation for 18 IARC Group 2A agents. These findings provide valuable data for cancer prevention and epidemiological studies. Future work may expand K-CAREX to include IARC Group 2B agents and other carcinogenic agents.

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1. Introduction

Many workers are exposed to a variety of chemicals, gases, and dusts during their work. As the workforce ages, these exposures are increasingly linked to chronic diseases such as cancer [1] and neurodegenerative disorders [2]. Occupational cancer has long been a major concern in occupational health, and more recently, neurodegenerative diseases like Parkinson's disease and amyotrophic lateral sclerosis have been suspected of being associated with occupational exposures to chemicals and metal fumes [3].

Aging workers are submitting more claims for work-related diseases, a trend observed in many aging populations [4]. However, determining the work-relatedness of these diseases is often challenging, as only a small proportion of chemicals have been tested for carcinogenicity or other health effects, with most agents remaining untested [5]. Additionally, past exposures are often difficult to trace due to the lack of historical exposure data.

For the effective prevention of occupational diseases, including cancer, it is essential to identify hazardous chemicals and their distribution. Basic epidemiological data, such as the industries and occupations where exposure occurs, are critical for addressing these issues [6]. Furthermore, well-designed epidemiological studies are needed to assess the health effects of exposures. While precise measurements of exposure are ideal, they are often impractical given the vast number of chemicals, jobs, and industries involved. To address this, job-exposure matrices (JEMs) have been developed to estimate exposure probability, frequency, and intensity by occupation [7,8].

The CARcinogen EXposure (CAREX) project provides an industry-based exposure matrix, estimating the number of exposed workers and the exposure prevalence [9]. However, as exposure circumstances become more complex, comprehensive matrices, including both industry-based and occupation-based components, are needed for population-based studies [10].

To develop the Korean CARcinogen EXposure (K-CAREX), we initiated the project in 2014 by reviewing existing matrices such as EU CAREX [9] and Finnish Job-Exposure Matrix (FINJEM) [11] and identifying relevant data sources for the Republic of Korea. We first developed a methodology to estimate exposure prevalence by industry, combining objective data with expert judgment [12]. This methodology was applied to International Agency for Research on Cancer (IARC) Group 1 agents, resulting in estimates of the number of exposed workers and exposure prevalence by industry [13]. We then developed a methodology [14] using workplace measurement data to estimate exposure intensity across different industries, ultimately determining exposure intensity for 22 carcinogens [15]. In addition, we conducted a pilot study to explore the feasibility of developing an occupation-based exposure matrix [16]. As a result, we generated data on exposure prevalence for 20 IARC Group 1 agents and exposure intensity for 22 IARC Group 1 agents by occupation [17].

In this study, we extended the K-CAREX framework to include selected IARC Group 2A agents. We describe the process of estimating exposure prevalence and intensity for these carcinogens and discuss the methodologies used to develop the K-CAREX for IARC Group 2A agents.

2. Methods

2.1. Data sources

In the Republic of Korea, workplaces exposed to any of the 192 chemical and physical agents designated by the Ministry of Employment and Labor (MOEL) are required to undergo annual monitoring for these hazardous agents [18]. Monitoring typically involves airborne measurements taken for at least six hours during the work period. The results are submitted to the Republic of Korea Occupational Safety and Health Agency (KOSHA), which has compiled this data since 2002 into the Work Environment Measurement Database (WEMD) [19]. The WEMD includes industry codes, measurement levels, sampling times, measurement locations, and occupational exposure limits (OELs); however, it does not include information on occupations and the limits of detection. A detailed description of the WEMD is available elsewhere [14,15].

Workers exposed to 181 physical and chemical agents, including night shiftwork, as designated by the MOEL, must undergo annual special health examinations [13]. The results of these examinations are submitted to KOSHA and electronically compiled into the Special Health Examination Database (SHED), which has been in operation since 2000. The SHED contains data on industry codes, occupation codes, and various clinical tests, including biological monitoring. Further details on the SHED can be found elsewhere [12].

The KOSHA conducts a nationwide occupational exposure survey every five years, known as the Work Environment Condition Survey (WECS) [13]. The WECS investigates the types of chemicals and physical agents used in workplaces, as well as the number of workers exposed to these agents. This survey includes all manufacturing workplaces with five or more employees and used sampling methods for other sectors, as well as for manufacturing workplaces with fewer than five employees. The 6th WECS survey, conducted in 2019, was used in this study. The WECS includes data on industry codes and the number of exposed workers.

Additionally, the 2020 National Census data, which surveyed industry and occupation for 20% of the population, was used as baseline data to estimate the number of exposed workers.

2.2. Selection of target carcinogens

In 2023, we reviewed the list of carcinogens published by the IARC and identified 93 agents classified as probable human carcinogens (Group 2A). We then cross-referenced these with agents designated for workplace exposure monitoring and special health examinations in the Republic of Korea. As a result, we identified 17 IARC Group 2A agents listed in both the WEMD and SHED, which were subsequently selected as target carcinogens. These agents included acrylamide, aniline, antimony, benzotrichloride, 2-bromopropane, cobalt, dichloromethane, dimethyl sulfate, dimethylformamide, epichlorohydrin, hydrazine, indium, methyl chloroform, lead, perchloroethylene, styrene, and 1,2,3-trichloropropane.

In addition, night shiftwork was selected as a target carcinogen due to the large number of exposed workers and its inclusion in the special health examination, despite not being subject to workplace exposure monitoring. Accordingly, a total of 18 IARC Group 2A agents were selected as target carcinogens.

2.3. Classification of industry and occupation

For the standard industrial classification (SIC), we used the Republic of Korea Standard Industrial Classification (KSIC, 10th revision), which is based on the International Standard Industrial Classification (ISIC, 4th revision). For the standard occupation classification (SOC), we used the Republic of Korea Standard Classification of Occupations (KSCO, 7th revision), which follows the International Standard Classification of Occupations (ISCO-08). The databases used in this study—WEMD, SHED, WECS, and the Census—are all coded according to the KSIC, while SHED and the Census are also coded according to the KSCO. We applied the 3-digit SIC and SOC codes in the current analysis.

2.4. Estimation process of the industry-based exposure matrix

The industry-based exposure matrix includes estimates of exposure prevalence and intensity by industry [13,15]. For estimating exposure prevalence and number of exposed workers by industry, we utilized the WEMD, SHED, WECS, and Census databases.

In the first step, we calculated three reference estimates of exposure prevalence, derived from the WEMD, SHED, and WECS. Workplace environmental monitoring is conducted on a sampling basis. For a unit workplace with ten or fewer employees, a minimum of two measurements is required—except in cases with only one worker, where a single measurement is sufficient. In larger unit workplaces, one measurement is required for every five employees. To account for this sampling scheme, the number of measurements in the WEMD was multiplied by a factor of four and then divided by the total number of employees in the industry, resulting in the exposure prevalence derived from the WEMD [12]. For the SHED, the number of health examinees in each industry was divided by the total number of employees in that industry. A detailed description of the reference estimate calculation process is provided elsewhere [12]. For the WECS, the estimates were directly calculated from the survey data, accounting for survey weights such as company size and the manufacturing/non-manufacturing sector classification.

In the second step, using the three reference prevalence estimates, we developed three rules to estimate exposure prevalence transparently and reasonably. The first rule involved assigning the average of the WEMD and SHED estimates as the base estimate when both were available. If only the WEMD estimate was available, it was used as the base estimate. If only the SHED and WECS estimates were available, the SHED estimate was assigned as the base estimate. In all other cases, a zero estimate was assigned.

The second rule applied a weighting factor to adjust the base estimates for potential overestimation in non-manufacturing sectors (SIC: 011–032, 423–990), which can occur, for example, when an industry comprises many workplaces, but exposure is present and measured in only one of them. The weighting factor was calculated as the average of two components: the monitoring rate and the health examination rate. The monitoring rate was defined as the number of employees in companies that conducted environmental monitoring for any of the 192 designated hazardous agents—within a given industry in the WEMD, averaged over the years 2020 to 2022—divided by the total number of individuals in the same industry, based on the 2020 Census. Similarly, the health examination rate was defined as the number of employees in companies that conducted special health examinations for any of the 179 designated hazardous agents (excluding two related to night shiftwork)—within a given industry in SHED, averaged from 2020 to 2022—divided by the corresponding industry population in the 2020 Census. The final weight factor, calculated as the average of these two rates, was applied to non-manufacturing sectors.

The third rule involved a review by industrial hygiene experts (DUP, SC, and DHK), who refined the preliminary estimates—calculated as the base estimate multiplied by a weighting factor—into final estimates. Prior to reviewing the preliminary estimates, the experts examined relevant articles and documents identified through literature searches, including IARC monographs and the American Conference of Governmental and Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) documents, to ensure the estimates were reasonable. The final exposure prevalence estimates were derived from this expert review process. The number of exposed workers was then calculated by multiplying the final exposure prevalence estimates by the number of individuals in each industry, based on the 2020 Census data.

For exposure intensity by industry, we used data from the WEMD between 2020 and 2022. The semi-quantitative exposure rating method used for IARC Group 1 agents was also applied to Group 2A agents [14]. The 95th percentile (X95) value was calculated for each 3-digit industry code across these years. Measurements with less than 30 minutes of sampling time, missing sampling time information, or values more than ten times the OEL were excluded. Industries with fewer than 20 measurements, or no measurements, were assigned an exposure rating of zero. This threshold of 20 measurements was implemented to minimize the potential influence of coding errors in industries with sparse data. Exposure ratings (1–5) were then assigned based on the X95 level relative to the OEL, using the following thresholds: less than 1% of the OEL (rating 1), less than 10% of the OEL (rating 2), between 10% and 50% of the OEL (rating 3), between 50% and 100% of the OEL (rating 4), and greater than the OEL (rating 5). The Korean OELs used in this study were based on the TLVs set by the ACGIH, with the 2020 Korean OELs applied in the analysis [20].

2.5. Estimation process of the occupation-based exposure matrix

For estimating exposure prevalence by occupation, the number of health examinees (averaged between 2020 and 2022) in each occupation within the SHED was divided by the total number of individuals in the corresponding occupation in the 2020 Census [17].

The WEMD data includes information on exposure levels but lacks occupation information, whereas the SHED provides information on occupation. To estimate exposure intensity, data from the WEMD (2020–2022) were linked with the SHED (2020–2022) using a unique identifier (year + company + worker), resulting in a matched dataset. For example, if a worker wore samplers for airborne lead monitoring and simultaneously underwent a special health examination, including a blood lead level test in the same year, that worker was included in the matched dataset [16,17].

For exposure intensity by occupation, the matched data were used to compute the X95 for each 3-digit occupation code across 2020 and 2022 [17]. Measurements greater than ten times the OELs were excluded from the estimation process. Following the same method used for estimating exposure ratings by industry, occupations with no measurements or fewer than 20 measurements were assigned an exposure rating of "0". Exposure ratings (1, 2, 3, 4, or 5) were then assigned based on the X95 relative to the OEL. Statistical analyses were performed using R version 4.3 (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

A total of 18 carcinogens were assessed in this study (Table 1). Exposure prevalence by industry and occupation was available for all 18 carcinogens, while exposure intensity by industry and occupation was available for 16 carcinogens, with the exception of benzotrichloride and night shift work (Table 1). Insufficient measurements were available to assess exposure intensity for benzotrichloride, and there is no measurement for night shift work.

The number of workplace measurements and special health examinees conducted between 2020 and 2022, categorized by carcinogen and based on both industry- and occupation-based matrices, are presented in Table 2. For example, for lead, 98,763 measurements were taken between 2020 and 2022, and 225,274 workers underwent special health examinations during the same period. Table 2 also presents the estimated number of exposed workers by carcinogen, as well as the Korean OELs. In 2020, an estimated 162,153 workers were exposed to lead.

Table 1
IARC Group 2A agents assessed and availability of corresponding exposure matrices

No	Agent	Industry-based matrix		Occupation-based matrix	
		Prevalence	Intensity	Prevalence	Intensity
1	Acrylamide	Yes	Yes	Yes	Yes
2	Aniline	Yes	Yes	Yes	Yes
3	Antimony	Yes	Yes	Yes	Yes
4	Benzotrichloride	Yes	No	Yes	No
5	2-Bromopropane	Yes	Yes	Yes	Yes
6	Cobalt	Yes	Yes	Yes	Yes
7	Dichloromethane	Yes	Yes	Yes	Yes
8	Dimethyl sulfate	Yes	Yes	Yes	Yes
9	Dimethylformamide	Yes	Yes	Yes	Yes
10	Epichlorohydrin	Yes	Yes	Yes	Yes
11	Hydrazine	Yes	Yes	Yes	Yes
12	Indium	Yes	Yes	Yes	Yes
13	Methyl chloroform	Yes	Yes	Yes	Yes
14	Lead	Yes	Yes	Yes	Yes
15	Perchloroethylene	Yes	Yes	Yes	Yes
16	Night shiftwork	Yes	No	Yes	No
17	Styrene	Yes	Yes	Yes	Yes
18	1,2,3-Trichloropropane	Yes	Yes	Yes	Yes

IARC, the International Agency for Research on Cancer.

The top 10 3-digit minor industrial groups by lead exposure prevalence are shown in Table 3 as an example. The “manufacture of basic precious and non-ferrous metals” industry showed the highest exposure prevalence at 17.08%. Exposure prevalence data for 18 carcinogens across 232 industrial groups are available online (https://k-carex-2a.shinyapps.io/sic_prevalence).

Regarding exposure intensity by industry, the “manufacture of batteries and accumulators” industry had the highest exposure rating of 4 (Table 4). Exposure intensity data for 16 carcinogens across 232 industrial groups are available online (https://k-carex-2a.shinyapps.io/sic_intensity).

The top 10 3-digit occupational groups by lead exposure prevalence are shown in Table 5. “Other construction, electricity, and production-related managers” had the highest exposure prevalence at 21.03%. Exposure prevalence data for 18 carcinogens across 156 occupational groups are available online (https://k-carex-2a.shinyapps.io/soc_prevalence).

For exposure intensity by occupation, “production-related elementary workers” had the highest exposure rating of 4 (Table 6). Exposure intensity data for 16 carcinogens across 156 occupational groups are available online (https://k-carex-2a.shinyapps.io/soc_intensity).

4. Discussion

Occupational cancer remains a significant issue in occupational health. However, not all workers are aware that exposure to chemicals and dusts in the workplace can lead to certain types of cancer. As a result, the number of workers recognized for occupational cancer in the Republic of Korea is lower than expected, largely due to low claim rates for occupational cancers [21,22]. Even when workers do submit claims, a significant proportion are rejected for various reasons, such as the strength of the exposure-cancer relationship, duration of exposure, latency periods, and confounding factors [23,24]. In some cases, determining work-relatedness is challenging, even for occupational health professionals with expertise in occupational cancers.

Establishing the association and causal relationship between carcinogen exposure and cancer requires extensive biomedical and epidemiological evidence. This process is often hindered by the rarity of some cancers and limited exposure measurements and records available for study subjects. While population-based studies, such as case-control and cohort studies, can be used, assessing exposure in the general population remains challenging [25]. To address this, expert judgment for the reconstruction of retrospective exposure or JEMs are commonly employed [7]. While expert judgment can provide useful exposure estimates, it is often not transferable to other studies and is subject to the assessors’

Table 2
Number of measurements and number of health examinees in exposure matrices

IARC Group 2A	Industry-based matrix			Occupation-based matrix		OEL
Agent	WEMD	SHED	Exposed	Matched	SHED	
	Measurement	Examinees		Measurement	Examinees	
Acrylamide	8,558	30,073	12,869	4,694	32,258	0.03 mg/m^3
Aniline	2,022	15,542	5,478	904	18,627	2 ppm
Antimony	27,450	129,848	58,688	12,369	140,034	0.5 mg/m^3
Benzotrichloride	10	298	17	NA	363	C 0.1 ppm
2-Bromopropane	296	1,978	652	181	2,231	1 ppm
Cobalt	32,887	164,043	71,540	14,441	174,021	0.02 mg/m^3
Dichloromethane	31,375	137,733	56,807	23,065	226,764	50 ppm
Dimethyl sulfate	50,368	215,892	96,423	417	5,880	0.1 ppm
Dimethylformamide	784	4,643	1,564	18,562	157,712	10 ppm
Epichlorohydrin	3,227	15,550	5,851	1,471	19,524	0.5 ppm
Hydrazine	2,018	14,538	4,952	979	15,986	0.05 ppm
Indium	3,299	13,815	6,242	1,063	19,886	0.01 mg/m^3
Methyl chloroform	3,997	21,594	8,333	1,802	23,153	350 ppm
Lead	98,763	225,274	162,153	34,803	249,854	0.05 mg/m^3
Perchloroethylene	5,056	24,221	10,060	2,086	30,770	25 ppm
Night shiftwork	NA	3,166,436	2,861,673	NA	3,502,918	NA
Styrene	63,597	165,487	86,928	27,099	190,431	20 ppm
1,2,3-Trichloropropane	171	1,514	420	65	2,304	10 ppm

IARC, the International Agency for Research on Cancer; OEL, occupational exposure limit; WEMD, work environment measurement database; SHED, special health examination database; NA, not applicable.

Table 3
Top 10 industrial groups according to exposure prevalence of lead

Industry		WEMD	SHED	WECS	Prevalence	Exposed
Code	Description	%	%	%	%	N
242	Manufacture of basic precious and non-ferrous metals	23.17	10.98	1.19	17.08	9,777
282	Manufacture of batteries and accumulators	13.78	18.96	2.46	16.37	5,517
274	Manufacture of watches, clocks and its parts	11.21	21.41	0	16.31	425
351	Electric power generation, transmission and distribution	21.35	10.13	0	15.74	11,934
241	Manufacture of basic iron and steel	17.07	9.91	0.32	13.49	14,242
243	Casting of metals	18.65	4.56	1.51	11.6	2,046
289	Manufacture of other electrical equipment	9.68	11.49	1.06	10.59	1,591
311	Building of ships and boats	19.67	0.6	1.08	10.14	12,326
340	Maintenance and repair services of industrial machinery and equipment	8.56	8.97	0.16	8.77	4,073
062	Mining of non-ferrous metal ores	11.88	5.44	1.11	8.66	23

WEMD, work environment measurement database; SHED, special health examination database; WECS, work environment condition survey; N, estimated number of exposed workers.

subjective biases [26]. JEMs, such as FINJEM, have proven valuable [8]; however, large, systematic JEMs covering a broad range of substances remain rare.

The K-CAREX was initially developed to estimate the number of exposed workers by industry [13]. Over time, the framework has evolved to include exposure intensity by industry [15] and an occupation-based exposure matrix, resulting in a comprehensive system covering both exposure prevalence and intensity by industry and occupation [17]. The industry-based exposure matrix of K-CAREX is comparable to the EU CAREX [9] and Canadian CAREX [27], allowing estimation of the number of exposed workers by industry. This information supports surveillance of occupational carcinogen exposure, prioritization of occupational cancer prevention efforts, and estimation of occupational cancer burden [28]. The occupation-based exposure matrix is comparable to JEMs such as FINJEM [11] and CANJEM [29] providing exposure data for population-based epidemiological studies. By providing detailed data on exposure prevalence and intensity by industry and occupation, K-CAREX serves as a multi-purpose framework for occupational cancer prevention and epidemiological research. Furthermore, K-CAREX is publicly available online or, upon request, from the corresponding author to researchers, policymakers, and workers. In this study, we expanded the K-CAREX framework to include IARC Group 2A agents.

The process for estimating exposure prevalence by industry in this study differs that used in our previous approach [13]. For IARC Group 1 agents, we used a panel of 37 industrial hygiene experts to provide estimates, with the median estimate serving as the final exposure prevalence estimate and first and third quartiles representing a range akin to confidence intervals [13]. However, for IARC Group 2A agents, we adopted a more efficient method. This change was driven by several factors. First, the multiple expert-based process is both time- and resource-intensive, despite the rapid accumulation of annual data. Second, many IARC Group 2A agents have limited measurement data, making it more efficient to involve a smaller number of experts. For example, 2-bromopropane, a degreasing agent, was associated with an incident of reproductive toxicity among workers in an electronics company in the Republic of Korea [30]. This incident led the government to strictly regulate its use, resulting in only 296 measurements being recorded between 2020 and 2022 (Table 2). Third, the K-CAREX framework may eventually expand to include IARC Group 2B agents and non-carcinogenic agents, necessitating the need for a more streamlined estimation process. In our previous approach, which combined expert judgment with objective sources to estimate lead exposure prevalence, the expected number of lead-exposed workers in 2010 was 129,250 (based on the median) [12]. In the current study, the expected number of lead-exposed workers in 2020 was 162,153, aligning with the results of the previous study. These findings suggest that our new methodology for estimating exposure prevalence by industry is both transparent and robust.

For occupation-based estimates, we were unable to obtain a stable denominator for estimating exposure prevalence, which precluded the use of exposure prevalence by occupation to estimate the number of exposed workers in those occupations [17]. Therefore, the exposure prevalence by occupation should not be considered a reliable estimate of exposure prevalence and should

Table 4
Top 10 industrial groups according to exposure intensity of lead

Industry		N	Rating
Code	Description		
282	Manufacture of batteries and accumulators	2,306	4
259	Manufacture of other fabricated metal products; metalworking service activities	4,685	3
242	Manufacture of basic precious and non-ferrous metals	4,095	3
291	Manufacture of general purpose machinery	3,535	3
243	Casting of metals	2,457	3
251	Manufacture of structural metal products, tanks, reservoirs and steam generators	1,362	3
222	Manufacture of plastics products	1,322	3
852	Secondary education	455	3
221	Manufacture of rubber products	447	3
492	Passenger land transport, except transport via railways	329	3

N, number of measurements between 2020 and 2022 from work environment measurement database.

Table 5
Top 10 occupational groups according to exposure prevalence of lead

Occupation Code	Description	Examinee	Census	Prevalence %
149	Other Construction, Electricity and Production Related Managers	1,683	2,667	21.03
872	Freight Train Related Workers	1,936	4,674	13.81
799	Other Technical Workers	17,560	46,113	12.69
153	Environmental, Cleaning, and Protective Service Related Managers	404	1,374	9.80
141	Construction, Electricity and Production Related Managers	13,403	47,739	9.36
861	Power Generation and Distribution Equipment Operators	7,751	28,277	9.14
899	Other Machine Operators	14,906	63,673	7.80
135	Information and Communications Related Managers	672	2,933	7.64
752	Transport Equipment Mechanics	7,568	52,803	4.78
232	Chemical Engineers and Technicians	5,053	44,698	3.77

Examinee, number of special health examinees between 2020 and 2022; Census, number of individuals in national census 2020.

not be used to estimate the number of exposed workers by occupation. Nonetheless, we believe that information on exposure prevalence by occupation may provide valuable insights into whether exposure occurs, which can be useful for epidemiological analyses.

There are differences in the number of health examinees in the industry- and occupation-based matrices (Table 2). While the exact causes of these differences have not been fully identified, several factors likely contribute. First, industry data were extracted in 2023, while occupation data were extracted in 2024. The different years of data extraction may potentially lead to variations in the number of health examinees. Second, the industry data underwent a more detailed cleaning process, removing duplicates and correcting errors in the industry code, while no such detailed cleaning was done for the occupation data. Future studies should harmonize the health examinee data to improve the consistency between industry- and occupation-based exposure matrices.

The databases used in this study have several limitations, which are explained in detail elsewhere [13,31]. Briefly, workplace monitoring is conducted in accordance with government guidelines; however, companies often aim to avoid violating OELs, which can result in monitoring outcomes that are typically lower than the established OELs. Additionally, some companies fail to conduct required monitoring due to oversight or the cost of monitoring [32], and the extent of non-participation is not well documented. Monitoring and health examination rates (Supplemental Table 1) may reflect this, but the true proportion of non-participating workplaces or workers is unclear. Furthermore, workplace monitoring and health examinations are more commonly conducted in the manufacturing sector, which may lead to underrepresentation of non-manufacturing sectors and potential bias in exposure estimates. Some public officers, such as firefighters and police officers, as well as self-employed individuals like farmers and fishermen, are excluded from occupational surveillance systems, meaning their exposure is not monitored. Finally, occupational information in the SHED is often nonspecific. When not provided by companies, special health examination institutions with limited knowledge of work processes assign occupation codes, leading to a large proportion of nonspecific occupations. For example, the “other construction, electricity, and production-related managers” group in Table 5 showed the highest exposure prevalence for lead, even though managers are less likely to be exposed to lead than manual workers. This high exposure prevalence may result from errors in occupation coding, issues with Census data, or a combination of these factors. However, the underlying cause remains unclear and requires further investigation.

In conclusion, we have developed the K-CAREX for IARC Group 2A agents, which includes both industry- and occupation-based exposure matrices. The industry-based matrix covers exposure prevalence for 18 carcinogens and exposure intensity for 16 carcinogens across 232 industrial groups, while the occupation-based matrix covers exposure prevalence for 18 carcinogens and exposure intensity for 16 carcinogens across 156 occupational groups. The updated K-CAREX framework for IARC Group 2A agents may aid efforts in occupational cancer prevention and provide valuable exposure data for epidemiological studies. Future studies may expand the K-CAREX framework to include IARC Group 2B agents and other non-carcinogenic agents.

Table 6
Top 10 occupational groups according to exposure intensity of lead

Occupation Code	Description	N	Rating
930	Production Related Elementary Workers	11,675	3
899	Other Machine Operators	2,820	3
841	Metal Casting and Metal Processing Related Operators	2,252	3
799	Other Technical Workers	2,084	3
842	Painting and Coating Machine Operators	1,078	3
832	Chemical, Rubber and Plastic Production Machine Operators	779	3
851	Metal Work Machinery Operators	468	3
741	Die and Mold Makers, Metal Casting Workers and Forge Hammersmiths	108	3
782	Construction Related Technical Workers	32	3
141	Construction, Electricity and Production Related Managers	1,108	2

N, number of measurements between 2020 and 2022 from matched data.

CRediT authorship contribution statement

Dong-Hee Koh: Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Sangjun Choi:** Writing – review & editing, Validation, Methodology, Investigation. **Ju-Hyun Park:** Writing – review & editing, Validation, Software, Formal analysis. **Sang-Gil Lee:** Writing – review & editing, Validation, Investigation. **Hwan-Cheol Kim:** Writing – review & editing, Validation, Investigation. **Inah Kim:** Writing – review & editing, Validation, Investigation. **Jeehee Min:** Writing – review & editing, Validation, Investigation. **Yujin Kim:** Writing – review & editing, Project administration, Data curation. **Jihye Lee:** Writing – review & editing, Resources, Project administration, Data curation. **Dong-Uk Park:** Writing – review & editing, Supervision, Methodology, Investigation.

Ethical statement

The study protocol was approved by the Institutional Review Board of the Catholic Kwandong University, International St. Mary's Hospital, Incheon, the Republic of Korea (IS24QIMI0030).

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Conflicts of interest

The authors declare that they have no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2025.05.007.

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