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Original Article

Organ dose reconstruction for the radiation epidemiological study of Korean radiation workers: The first dose evaluation for the Korean Radiation Worker Study (KRWS)

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ABSTRACT

The Korea Institute of Radiological and Medical Sciences has started a radiation epidemiological study, titled "Korean Radiation Worker Study," to evaluate the health effects of occupational exposure to radiation. As a part of this study, we investigated the methodologies and results of reconstructing organ-specific absorbed doses based on personal dose equivalent, $H_p(10)$, reported from 1984 to 2019 for 20,605 Korean radiation workers. For the organ dose reconstruction, representative exposure scenarios (i.e., radiation energy and exposure geometry) were first determined according to occupational groups, and dose coefficients for converting $H_p(10)$ to organ absorbed doses were then appropriately taken based on the exposure scenarios. Individual annual doses and individual cumulative doses were reconstructed for 27 organs, and the highest values were observed in the thyroid doses (on average 0.77 mGy/y and 10.47 mGy, respectively). Mean values of individual cumulative absorbed doses for the red bone marrow, colon, and lungs were 7.83, 8.78, and 8.43 mSv, respectively. Most of the organ doses were maximum for industrial radiographers, followed by nuclear power plant workers, medical workers, and other facility workers. The organ dose database established in this study will be utilized for organ-specific risk estimation in the Korean Radiation Worker Study.

1. Introduction

Health effects of long-term radiation exposure with low doses below 100 mSv are the most critical and long-debated question in the radiation protection field. To investigate whether the low doses of ionizing radiation can induce cancer, several national and international epidemiological studies on health risks associated with ionizing radiation exposure have been conducted and are presently in progress. However, in numerous epidemiological studies, the radiation health effects were mostly evaluated based on the dose data reported as personal dose equivalent, $H_p(10)$, without evaluating the organ-absorbed dose. To evaluate cancer morbidity and mortality for specific organs, it is first required to assess the organ-specific radiation exposure that might be different depending on the anatomical characteristics (e.g., volume, mass, and location) of the organ. The evaluation of the radiation health effects based on the organ-absorbed dose was adopted in several studies such as the One Million U.S. Radiation Workers and Veterans Study (MWS) [1] and the Japanese Epidemiological Study on Low Dose Radiation Effects (J-EPISODE) [2]. In particular, the 15-Country Collaborative Study [3] conducted by the International Agency for Research on Cancer (IARC) and its follow-up study, the International Nuclear Workers Study (INWORKS) [4], are known as the most comprehensive previous studies that evaluated the organ-absorbed doses based on $H_p(10)$ records.

In South Korea, the Korea Institute of Radiological and Medical Sciences (KIRAMS) has initiated a nationwide radiation epidemiological study, titled the Korean Radiation Worker Study (KRWS) [5], to estimate the health risk of Korean workers arising from occupational radiation exposure. In the KRWS, not only the national

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cancer registry but also a variety of information including demographics, occupational characteristics, and lifestyle factors were collected and linked with dose records in $H_p(10)$ of the workers. To date, the KRWS has investigated 20,605 Korean radiation workers who consented to provide personal information and is planning to expand the study cohort to all such workers. However, as noted above, since the radiation health risk should be analyzed in terms of organ-specific exposure, the cancer information of the cohort should be linked with organ-absorbed dose rather than $H_p(10)$. Thus, to more specifically analyze the radiation health effect for the cohort in the KRWS, it is necessary to reconstruct the organ-absorbed dose of the cohort using the dose records reported as $H_p(10)$.

As a part of the KRWS, the present study developed the methodologies for organ dose reconstruction taking into account exposure conditions of Korean workers and produced the database of organ-absorbed dose for the primary cohort (20,605 workers). Although various empirical and theoretical studies are in progress in the KRWS to obtain dosimetric information associated with exposure conditions, dosimetry technology, calibration practices, and administrative practices, this study focused on establishing a preliminary dose database for the KRWS with currently available information. In context, representative exposure scenarios were first established for the occupation groups, and accordingly, the dose conversion coefficients were considered to determine the organ-absorbed doses. The organ-absorbed doses were evaluated based on $H_p(10)$ (i.e., externally exposed dose), but the doses from internal exposure were considered for nuclear power plant (NPP) workers as well.

The exposure information according to the occupation groups used to develop the exposure scenario was illustrated in Section 2, and the exposure scenario and dose coefficients used in this study were presented in Section 3, along with the results of organ dose reconstruction.

2. Materials and methods

2.1. Study population and dose records

The study population and dose records used in the KRWS are reported elsewhere [6]. The Korean radiation workers who participated in radiation safety education between May 24, 2016 and June 30, 2017 ($n = 42,607$) were initially asked to participate in a self-administered survey, and 35,789 of the workers (84%) responded to this survey. However, subjects with multiple responses, unidentified personal identification numbers, or those who disagreed to participate in the study were excluded. A total of 20,605 workers (male: 17,829, female: 2776) were finally enrolled in the study cohort. The dose records for the cohort were collected from an electronic database maintained by the Central Registry for Radiation Worker Information (CRRWI); the records included external and internal doses reported as personal dose equivalents ($H_p(10)$) and committed effective doses, respectively, from 1984 to 2019. Radiation doses measured or estimated to be below 0.1 mSv were classified as “below recording level” and were regarded as 0 mSv in this study. In the CRRWI database, the workers were categorized into eight occupational types: NPP, industrial radiography, industry (including production and sale), medical institute (except diagnostic radiation technologists), education institute, public institute, research institute, and military facility. However, for simplicity in determining the exposure scenario, these eight occupational types were re-categorized into four groups (see Section 2.3). For individuals registered under multiple occupational types, representative occupational types were selected in accordance with the following order: those with the longest tenure; those with the most recent employment; and those with the highest reported cumulative doses. In terms of external dose (i.e., $H_p(10)$), it is challenging to clarify how much of the $H_p(10)$ resulting from exposure to high-linear energy transfer (LET) radiation (e.g., neutron) is included in the total $H_p(10)$ [5]. However, based on empirical knowledge from regulatory experts and the findings of INWORKS showing that the number of workers exposed to neutron was only 11.8% of the total workers in nuclear power plants and mixed facilities [4], it is expected that the workers exposed to high-LET radiation would account for only a few percent of the total Korean radiation workers. Therefore, in the current study, it was assumed that the reported $H_p(10)$ was accounted for exclusively by photon exposure. Meanwhile, internal dose data were available mainly for workers in NPPs and public institutes because a report on internal dose is mandatory only for workers whose annual dose due to incorporated radionuclides is predicted to be higher than 2 mSv/y. External and internal doses were expected to be reported quarterly and annually, respectively; however, the dose records used in this study were provided as annual doses accumulated according to personal dosimeter types and occupational codes.

2.2. Background on organ dose reconstruction based on $H_p(10)$

Principally, organ doses resulting from external exposure can be estimated by converting measurable quantities to organ-specific absorbed doses that cannot be measured directly. In practice, organ doses are estimated using organ dose conversion coefficients (i.e., organ absorbed dose per physical quantity) generally provided by the International Commission on Radiological Protection (ICRP). However, the conversion coefficients provided by the ICRP are values with respect to fundamental physical quantities such as air kerma free-in-air rather than $H_p(10)$. Therefore, to reconstruct organ doses based on $H_p(10)$ records, the $H_p(10)$ value must be converted first to air kerma using the conversion coefficient for $H_p(10)$ per air kerma. Mathematically, this organ dose reconstruction procedure based on $H_p(10)$ can be expressed by the following equation:

$$D_T = H_p(10) \times \left[\frac{D_T}{K_a} \bigg/ \frac{H_p(10)}{K_a} \right], \tag{1}$$

where D_T is the organ absorbed dose (Gy), $H_p(10)$ is the personal dose equivalent (Gy), and $H_p(10)/K_a$ and D_T/K_a are the dose conversion coefficients for air kerma-to-$H_p(10)$ (Sv/Gy) and air kerma-to-organ dose (Gy/Gy), respectively. Both dose conversion coefficients are dependent on the energy and orientation of the body with respect to the direction from which the radiation originates (i.e., geometry). Therefore, to accurately estimate the organ absorbed doses for radiation workers, it is important to properly use the dose conversion coefficients considering the exposure environments that workers can encounter when working with radioactive substances.

2.3. Information for determining irradiation energy and geometry

The irradiation energies and geometries to which workers are exposed vary widely depending on the type of radiation-related work. Thus, the energy and geometry representing exposure environments for individual workers should be determined based on the work information for an individual. However, since questions seeking specific work information were not involved in the questionnaire sent to the cohort members, we could not determine the irradiation energies and geometries encountered by specific individuals. Instead, we determined the occupation type-dependent irradiation energy and geometry (referred to as representative exposure scenarios) to ensure that dose conversion coefficients could be applied based on occupational types, which were reported together with each personal dose record.

For simplicity, the eight occupational types were re-categorized into four groups (i.e., NPP, industrial radiography, medical institute, and other facilities), considering dosimetric significances and the diversity of radiation-related work among the occupation types. Because the radiation-related work involved in the five “other” occupational types (i.e., industry, educational institutes, public institutes, research institutes, and military facilities) is highly diversified and primarily does not result in significant exposure, these five occupation types were considered as a single group, “other facilities”; therefore, a single exposure scenario was determined and used for these five occupation types. The representative exposure scenario was determined by first analyzing the exposure information for the occupational groups. Here, the exposure information includes not only the type of radiation-related work but also the dose data (i.e., individual dose or collective dose), radiation source type, work protocol, and other factors, for each work type. Based on the exposure information, the representative exposure scenarios were determined as reasonably as possible considering the reliability of the information and its influence on the dose assessment. Most of the information was obtained from the literature, and expert advice was sought where necessary. The irradiation geometries were determined based on six idealized geometries stipulated by the ICRP [7]: antero-posterior (AP), postero-anterior (PA), left lateral (LLAT), right lateral (RLAT), rotational (ROT), and isotropic (ISO). Information on the exposure environments and the methods to determine the representative exposure scenarios for the four occupational groups is provided in the following subsections.

2.3.1. Nuclear power plant (NPP)

Several types of work (or working codes) are performed by NPP workers depending on plant types; for instance, maintenance tasks conducted in Kori unit 3 and 4 are divided into 61 sub-tasks [8]. However, since approximately 90% of the total radiation exposure occurs during an overhaul period (i.e., after reactor shutdown) regardless of the plant type [9], it is reasonable to determine the exposure scenario for NPP workers with a focus on radiation-related tasks performed during an overhaul period. The primary exposure sources following reactor shutdown are radioisotopes produced by neutron activation of metallic wear and corrosion products within the reactor coolant system (RCS). Therefore, The representative photon energy for NPP workers can be determined based on the energies of gamma rays emitted from the predominant activation products such as Co-60, Co-58 and Cs-137 [1]. However, there may be significant differences between the gamma energies emitted from the radionuclides and those that the NPP workers were actually exposed to in their working areas, due to the complex structures present inside the NPP. The structures in the working area may produce considerable scattered photons having various energies and may thus generate heterogeneous radiation fields. Actual measurements of the photon radiation fields in Korean NPPs have been conducted in several studies [10]. Radiation has been measured not only at the energy peaks of activated radionuclides but also at much lower energy ranges (a few hundred kiloelectronvolts) because of Compton scattering (see Figs. 4–6 in Ref. [11]). As shown in Table 1, the average photon energies at various working locations have been reported to be 260–784 keV, which are lower than those emitted directly from the radionuclide sources. Therefore, to determine a representative exposure energy for the NPP workers, scattered photons with low energies should be considered together with gamma rays from radionuclides. As noted earlier, because various types of radiation-related tasks are performed in an NPP, the exposure geometry should be determined with a focus on the tasks involving exposure to high doses. For Korean NPP workers, high doses were mainly observed during activities related to maintenance of the reactor cooling pumps or valves, refueling, and steam generator-related activities [12]. During maintenance activities for the reactor cooling pumps or valves, workers typically perform the task while facing the radiation source. However, in case of the activities resulting in high dose rates, such as refueling and steam generator-related activities, the workers may be irradiated from various directions. For example, workers standing on a reactor cavity for refueling can be exposed to radiations from below. In particular, inside the steam generator, the radiation field is formed primarily downward because of U-tubes located above the head; this causes the workers to be exposed to radiations from the top and behind (due to their bent posture) [13].

Table 1
Average energies of gamma radiations in working areas at Korean NPPs.

Reference	Operation type	Average energy (keV)
[13]	Normal operating	376.04–1041.95
[14]	Overhaul	260–500
[11]	Overhaul	436.78–783.57
	Normal operating	346.68–803.67

2.3.2. Industrial radiography facilities

Industrial radiography is generally performed using sealed radioisotopes, such as Ir-192, Co-60, and Se-75, or X-rays. However, a predominant exposure source for industrial radiographers is Ir-192, which is convenient to shield and transport due to its high specific activity [15]. In Korea, radiography using X-rays is allowed only in radiographic testing (RT) rooms with sufficient shielding installations, and the use of radionuclides in non-approved workplaces without fixed-shielding installations is legally limited to 0.74 TBq of Ir-192. In addition, approximately 78% of industrial radiographers who participated in the survey for this study responded that they use mainly Ir-192. Radiographers are most exposed to radiation when the radionuclide is outside its shielded container. Specifically, the exposure can occur when the radionuclide is being transported to and from a target material, as well as during acquisition of the material's image. However, during acquisition of radiographic images, the radiographer is not likely to be irradiated, because the distance between the source and the radiographer is considerably large. By contrast, when the radionuclide source is traveling outside the shielded container, the radiographer is likely to be irradiated considerably because of the short distance from the source. During this period, the radiographer faces the source. However, from expert advice, we obtained some important information regarding the possibility of lateral exposure. During actual operation, radiographers can wind or release a remote wire with one hand and therefore face the source sideways while the source is moving. In other words, some of the radiographers can be laterally irradiated during handling the radiation source due to the posture facing sideways.

2.3.3. Medical institutes

Under the Korea Nuclear Safety Act, medical radiation workers are limited to personnel who handle unsealed sources or radiation generators for treatment. Personnel operating diagnostic radiation are considered separately as radiation-related workers under the Medical Service Act and were not included in this study cohort. Therefore, herein, radiation workers in medical facilities mainly refer to personnel involved in radiation oncology or nuclear medicine. Since annual doses for workers in nuclear medicine have been reported to be significantly higher than those for other workers [16], it is reasonable to determine the representative exposure scenario for medical workers with a focus on the radiation work performed in nuclear medicine. For workers in radiation oncology, the radiation exposure is not expected to be significant, because the technologists can operate the treatment equipment from an exterior control room. The main radioisotopes used in nuclear medicine include Tc-99 m and Tl-201 in gamma scan or single photon emission CT (SPECT), F-18 in positron emission tomography (PET), and I-131 in thyroid treatment [17]. Table 2 shows the number of times radiopharmaceuticals were used from 1985 to 2011 [18]. Tc-99 m was the most frequently used and is thus expected to be the main contributor to external exposure for workers in nuclear medicine. Although F-18 accounts for only 20% of the total usage of radioisotopes, it could also be a significant contributor due to its high emission energy of 511 keV. Most external exposure for nuclear medicine workers can be regarded as occurring from frontal irradiation. Because the radiopharmaceuticals used in activities such as distribution and injection must be handled very carefully, the personnel usually perform their tasks while looking directly at the radiopharmaceuticals.

2.3.4. Other facilities

Because radiation work in facilities covers several activities using various radioisotopes or radiation generators, it is not feasible to determine a representative exposure scenario based on specific activities. Although dose records for workers in sales and production have been reported to be relatively high [19], the types of radionuclides and activities in sales and production are too diverse to generalize. For the allowable amounts of radioisotopes in sales and production, the main radioisotopes considered are F-18 or Co-60; however, other radioisotopes, such as Ir-192 and Cs-137, also account for significant proportions of dose exposure [20]. Because radioisotopes have been used in various activities in public, research, and military facilities, in addition to sales/production, it is difficult to generalize the exposure scenario. Therefore, for workers in other facilities, the exposure scenario should be determined to represent a typical exposure situation.

2.4. Dose conversion coefficients

As explained previously, two types of dose conversion coefficients are necessary for calculating organ absorbed doses based on $H_p(10)$ values: air kerma-to-$H_p(10)$ conversion coefficients ($H_p(10)/K_a$) and air kerma-to-organ dose conversion coefficients (D_T/K_a). For $H_p(10)/K_a$, we used the values provided in Table A.24 of ICRP 74 [21], which are calculated based on an ICRU slab phantom. In this study, the $H_p(10)/K_a$ values were interpolated and appropriately selected according to the radiation energy and exposure geometry of the representative exposure scenario. The $H_p(10)/K_a$ values for the AP direction were taken directly from the values for 0°. To simulate the LAT geometry, however, the $H_p(10)/K_a$ values calculated for 75° were used; this is because 90° is not appropriate for simulating $H_p(10)$ for laterally incident photons, due to the considerably different shapes of a slab and the human body and since the 10 mm depth for $H_p(10)$ cannot be maintained. Note that the LLAT and RLAT geometries are not distinguishable in a slab phantom. In addition, because 180° corresponds to the angle of posteriorly incident radiation to the slab phantom, in the PA geometry, a photon travels through a bulk of 140 mm, which could be less than a real flight length in the human body to reach the personal dosimeter worn on a chest. Therefore, in the case of the PA geometry, the $H_p(10)/K_a$ values for the AP geometry (0°) were used instead, with corrections for fluence attenuation of the posteriorly incident photon to the anteriorly incident photon. In accordance with the relevant protocol in NCRP 178 [1], the ratios of the fluence-to-male breast conversion coefficients for the AP geometry to those for the PA geometry (e.g., 1.94 for 662 keV) were used. Meanwhile, for the air kerma-to-organ dose conversion coefficients, D_T/K_a, we used the reference values provided in ICRP 116 [7], which were computed based on the ICRP reference voxel-type computational phantom of ICRP 110 [22]. ICRP 116 provides D_T/K_a values for 30 organs considering six idealized geometries (i.e., AP, PA, LLAT, RLAT, ROT, and ISO). To calculate the organ absorbed doses from $H_p(10)$, $H_p(10)/K_a$ and D_T/K_a should be coupled according to the radiation energy and exposure geometry. However, because $H_p(10)/K_a$ values for rotational and isotropic conditions calculated based on the slab phantom do not exist and also involve the problem associated with the PA geometry mentioned earlier, for these geometries, we employed weighted averages of the dose conversion coefficients for aligned exposure geometries. Weighted averages of the dose coefficients for four directions (i.e., AP, PA, LLAT, RLAT) and six directions (i.e., AP, PA, LLAT, RLAT, cranial-caudal, caudal-cranial) were used as surrogate values for the ROT and ISO geometry, respectively. Here, D_T/K_a values for cranial-caudal (head-to-foot) and caudal-cranial (foot-to-head) were acquired from NCRP 178 based on the study of Veinot et al. [23].

Table 2
Radioisotope usage in nuclear medicine from 1985 to 2011 [18].

Radioisotope	Number of times used	Proportion
Tc-99 m	5,859,524	70%
F-18	1,695,889	20%
Tl-201	616,473	7%
I-131	220,588	3%

2.5. Internal exposure

Internal doses from occupational intakes of radionuclides have been annually reported in terms of committed effective doses. However, it is very difficult to derive organ-specific doses from committed effective doses. Because an internal dose is not directly measured but calculated considering the biokinetics of radionuclides, the radionuclide information, physicochemical information (e.g., chemical form and particle size distribution), and intake scenario (e.g., intake route) corresponding to individual effective dose calculations are required to derive organ doses retrospectively. However, it is practically impossible to collect all the information associated with individual effective dose records. Therefore, we considered only the internal doses reported for NPP workers in which internal exposure information could be acceptably generalized. Dose records reported from 2009 to 2013 for Korean NPP workers were analyzed by Lim [9], who found that more than 99% of the reported internal doses were for workers at heavy water reactors, who are predominantly exposed to tritiated water (HTO) [9]. Based on this result, we assumed in this study that the internal doses for NPP workers result exclusively from the inhalation of HTO vapor. Because HTO is chemically equivalent to water and is considered to be homogeneously distributed throughout the body after uptake into blood, all the dose coefficients for organ absorbed doses and committed effective doses for the inhaled HTO vapor are provided as a single value of 1.8E-11 Sv/Bq [24]. Therefore, the organ absorbed doses are numerically equal to the reported effective doses. The effective dose values for NPP workers were thus equally added to all organ absorbed doses derived from $H_p(10)$ (i.e., doses from external exposure).

2.6. Ethics approval

All study participants provided informed written consent prior to study enrollment, and this study has received ethical approval from the institutional review board of the Korea Institute of Radiological and Medical Sciences (IRB No.K-1603-002-034). The investigations were performed following the rules of the Declaration of Helsinki of 1975, revised in 2013.

3. Results and discussion

3.1. Representative exposure scenario

The representative exposure scenarios determined for the occupational groups identified in this study are shown in Table 3. To determine the representative radiation energy, the IARC study considered a combination of two energy ranges (i.e., 100–300 keV and 300–3000 keV). By contrast, in this study, the radiation energy was regarded as a single value, considering the limited accuracy of data on photon radiation field. The exposure geometries were determined as combinations of the idealized geometries.

3.1.1. NPP

Based on a comprehensive understanding of the radiation field measurements in Table 1, the representative exposure energy for an NPP was determined to be a single energy of 662 keV emitted from Cs-137. This value is not only used as a standard gamma source but properly represents a wide range of energies in terms of dose conversion coefficients; for example, the dose conversion coefficient of air kerma to $H_p(10)$ (i.e., $H_p(10)/K_a$) for the AP direction at 662 keV covers dose coefficients for an energy range of 100–1000 keV within a 30% difference. This standardization of irradiation energies as a single value considering the dose coefficients can reasonably prevent any uncertainty arising from overspecifying the radiation field in the calculation of organ absorbed dose. For exposure geometry, the exposure from the AP direction has been suggested as a default exposure geometry by NCRP [1]. However, as noted previously, in case of refueling and steam generator maintenance which generally involve high exposure rates, the exposures under various geometries, such as cranial-to-caudal, caudal-to-cranial, and the PA direction, must also be considered. Therefore, in this study, by comprehensively considering the exposure conditions during various activities, the representative exposure geometry for an NPP was determined as a combination of 50% AP and 50% ISO, which is consistent with that assumed in a previous 15-country study [3].

3.1.2. Industrial radiography

Because Ir-192 can be considered a dominant exposure source resulting in high exposure during the activities of industrial radiography, the representative radiation energy for industrial radiography was simply determined to be 397 keV as an air kerma-weighted average energy of Ir-192 [25]. The representative exposure geometry for industrial radiographers was determined based on exposure from the AP direction, but exposure to laterally incident photon was also considered. Considering that 90–95% of Koreans are right-handed, the RLAT geometry was assumed, and the exposure geometry for industrial radiographers was finally determined to be 75% AP plus 25% RLAT.

Table 3
Representative exposure scenarios (energy/geometry) determined in this study.

Occupational group[a)]	Representative exposure scenario	
	Energy	Geometry[b)]
NPP	662 keV	AP 50%, ISO 50%
Radiography	397 keV	AP 75%, RLAT 25%
Medical	218 keV	AP 100%
Other	662 keV	AP 50%, ROT 50%

[a)] NPP: nuclear power plant; radiography: industrial radiography; Medical: medical institute; Other: other facilities.
[b)] AP: antero-posterior; RLAT: right lateral; ROT: rotational; ISO: (ISO).

3.1.3. Medical institute

The representative radiation energy for medical workers was determined to be 218 keV as a weighted average according to the number of times radioisotopes used in nuclear medicine from 1985 to 2011 (Table 2). Tc-99 m (140 keV) and F-18 (511 keV), accounting for more than 90% of total usage, were the main contributors. The exposure geometry for medical personnel was assumed to be 100% AP.

3.1.4. Other facilities

The value of 662 keV for NPP workers, which represents a wide range of energies in terms of dose coefficient, was selected as the representative radiation energy for workers in other facilities. Considering that the radiation source is typically handled at a height within the reach of the operator, the representative exposure geometry was determined to be a combination of 50% AP plus 50% ROT; normally, radiations from the directions of the head or foot are unlikely.

3.2. Dose conversion coefficients

The conversion coefficients for $H_p(10)$-to-organ absorbed dose (i.e., $D_T/H_p(10)$), in which the two dose conversion coefficients ($H_p(10)/K_a$ and D_T/K_a) are combined, are summarized in Table 4. Dose coefficients for 30 organs/tissues were calculated based on the representative exposure scenarios, but the values for four major organs (red bone marrow (RBM), colon, lungs, and thyroid) and the spleen were given as examples. These combined dose coefficients can be directly multiplied with the $H_p(10)$ for the respective the occupational group. Although in the scenarios considered in this study, most dose coefficients except that of the spleen were maximum for 662 keV and the AP geometry, the weighted dose coefficients except that of the spleen were maximum for the medical institute with a radiation energy of 218 keV (lowest) and an exposure geometry of 100% AP. This is because dose coefficients are not significantly different at energy levels above hundreds of kiloelectronvolts but are influenced primarily by the exposure geometry. The importance of determining the exposure geometry is also reflected in the dose coefficients for the spleen. Because the spleen is anatomically located on the left-side of the body, the weighted dose coefficient for the spleen is the lowest for the industrial radiography group, in which the RLAT geometry is considered. The significance of the exposure geometry in determining the dose coefficient is directly reflected in the organ dose calculation; accordingly, the determination of exposure geometry has a greater effect on the organ dose reconstruction than that of the radiation energy does.

3.3. Analysis of $H_p(10)$ and organ dose

The distribution of individual cumulative dose in $H_p(10)$ is shown in Fig. 1. The cumulative doses were widely distributed with a mean ± standard deviation of 11.72 ± 28.8 mSv and a median of 0.57 mSv. However, most workers were included in a low dose range. The cumulative dose of 15,797 workers, accounting for approximately 77% of the total workers, was lower than 10 mSv. In particular, the number of non-exposed workers—whose doses were below a recorded dose level (0.1 mSv) and were regarded as zero—accounted for 36% (7319). These non-exposed workers included those who did not participate in radiation-related

Table 4
Conversion coefficients for $H_p(10)$-to-organ absorbed dose.

Occupational group[a)]	Energy (keV)	Geometry[b)]	Dose conversion coefficients ($D_T/H_p(10)$) (Gy/Sv)				
			RBM	Colon	Lung	Thyroid	Spleen
NPP	662	AP (50%)	0.723	0.838	0.817	0.999	0.589
		ISO (50%)	0.481	0.504	0.500	0.524	0.453
		Weighted	0.602	0.671	0.659	0.762	0.521
Radiography	397	AP (75%)	0.684	0.810	0.776	0.997	0.528
		RLAT (25%)	0.520	0.585	0.468	0.670	0.186
		Weighted	0.643	0.754	0.699	0.915	0.443
Medical	218	AP (100%)	0.657	0.782	0.737	0.997	0.476
		Weighted	0.657	0.782	0.737	0.997	0.476
Other	662	AP (50%)	0.723	0.838	0.817	0.999	0.589
		ROT (50%)	0.652	0.695	0.652	0.738	0.592
		Weighted	0.688	0.767	0.735	0.869	0.591

a) NPP: nuclear power plant; radiography: industrial radiography; Medical: medical institute; Other: other facilities.
b) AP: antero-posterior; RLAT: right lateral; ROT: rotational; ISO: isotropic.

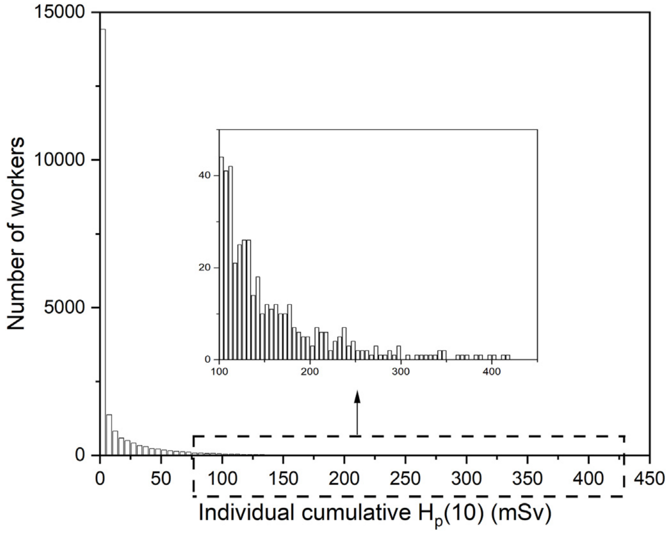

Fig. 1. Distribution of individual cumulative $H_p(10)$. The partial distribution ranging higher than 100 mSv was enlarged in the small box.

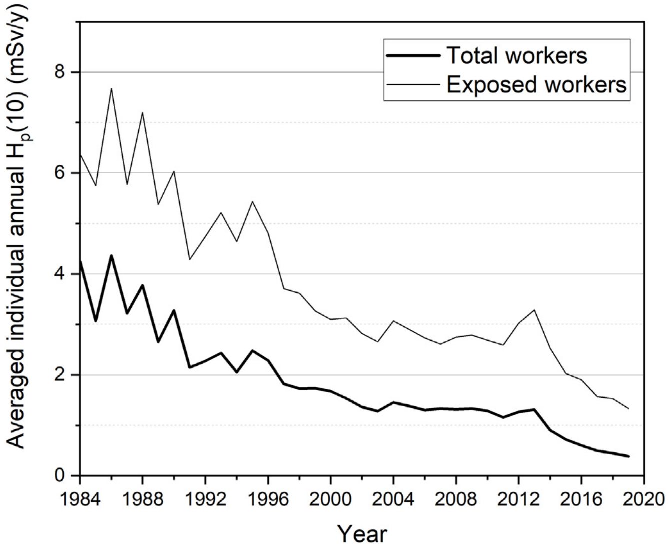

Fig. 2. Averaged individual annual $H_p(10)$ by year (1984–2019). Total workers and exposed workers represent all workers in the cohort and those with at least one dose record above 0.1 mSv, respectively.

activities despite working at a radiation-related facility. The number of workers exponentially decreased as the cumulative $H_p(10)$ increased, and the tail of the distribution stretched out to a maximum cumulative dose of 417 mSv. The averaged values of individual annual $H_p(10)$ by year are shown in Fig. 2. Although significant fluctuations were observed, the average annual dose for the total workers consistently decreased from >4 mSv/y to ~1 mSv/y. This continuous decrease might have resulted from the fact that as radiation is utilized more in Korea, the safety culture has been improved to reduce unnecessary exposure, and safety regulations have been extended and strengthened. As predicted, the annual doses for exposed workers (excluding non-exposed workers) were significantly higher than those for the total workers by a factor of 1.5–3.5. The mean and median of the individual annual doses averaged over 35 years (1984–2019) were 0.85 mSv/y and 0.07 mSv/y, respectively. The median being much lower than the mean again highlights the considerable contribution of the non-exposed workers.

The cumulative doses and average annual doses were also analyzed in consideration of the occupational groups. The mean values of the cumulative dose and average annual dose were maximum for industrial radiographers (26.2 mSv and 2.26 mSv/y, respectively), followed by NPP workers (17.38 mSv and 1.05 mSv/y, respectively) and medical workers (9.04 mSv and 0.69 mSv/y, respectively); the mean values were minimum for workers involved in other facilities (1.70 mSv and 0.13 mSv/y, respectively).

3.4. Reconstructed organ doses

The individual average cumulative organ doses reconstructed for 27 organs are shown in Fig. 3. As can be predicted, most cumulative organ doses except for female organs (i.e., ovaries and uterus) were the highest in industrial radiographers due to the highest cumulative $H_p(10)$, followed by the doses for NPP workers, medical workers, and workers involved in other facilities. However, the magnitudes of the differences in the organ doses are not constant but differ according to the target organs. For example, the average cumulative thyroid dose for industrial radiographers is ~1.5 times that for NPP workers, whereas the doses for the spleen are comparable between the two groups. This difference results from the fact that in this study, the exposure scenarios were considered differently depending on the occupational groups. Although the dose conversion coefficients are the highest for the AP geometry, accounting for 75% of the representative exposure geometry for industrial radiographers, the RLAT geometry for the remaining 25% results in significantly low dose coefficients for several organs, such

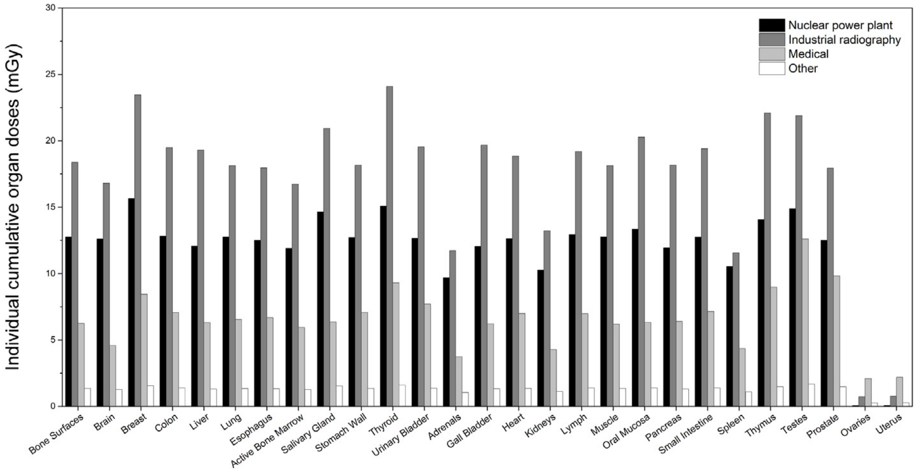

Fig. 3. Individual average cumulative organ absorbed doses according to occupational groups. The last four organs in x-axis represent the sex-specific organs: testes and prostate for male; ovaries and uterus for female.

as the adrenals, kidneys, and spleen. In particular, the dose coefficient for the spleen, located on the left side of the body, is lower for the RLAT than that for the AP geometry by a factor of 3 (see Table 4).

Detailed dose reconstruction results for major organs according to occupational group and gender are shown in Tables 5 and 6. These tables provide a summary of individual annual doses and individual cumulative doses in terms of $H_p(10)$, RBM, the colon, the lungs, and the thyroid, together with the number of workers and the percentage of exposed workers. As noted earlier, the number of non-exposed workers accounts for ~36% of the number of total workers (20,605); thus, the median values of the organ doses are much lower than the mean values. The average individual annual doses and average individual cumulative doses for all workers were maximum for the thyroid (0.77 mGy/y and 10.47 mGy,

Table 5
Distributions of individual annual organ doses for Korean radiation workers.

Occupational category[a)]	Number of workers (% of exposed worker)	Individual annual dose Mean (25 percentile; median; 75 percentile)				
		$H_p(10)$ (mSv/y)	Red bone marrow (mGy/y)	Colon (mGy/y)	Lungs (mGy/y)	Thyroid (mGy/y)
Men						
NPP	6181(76.0)	1.08 (0.01; 0.26; 1.26)	0.74 (0.01; 0.18; 0.87)	0.80 (0.01; 0.19; 0.94)	0.80 (0.01; 0.19; 0.94)	0.92 (0.01; 0.22; 1.08)
Radiography	3346(96.0)	2.34 (0.66; 1.74; 3.33)	1.49 (0.42; 1.11; 2.13)	1.74 (0.49; 1.29; 2.48)	1.62 (0.46; 1.20; 2.30)	2.13 (0.60; 1.58; 3.04)
Medical	1684(80.7)	0.99 (0.03; 0.18; 1.08)	0.65 (0.02; 0.12; 0.71)	0.77 (0.02; 0.14; 0.84)	0.72 (0.02; 0.13; 0.79)	0.99 (0.03; 0.18; 1.08)
Other	6618(42.0)	0.15 (0.00; 0.00; 0.05)	0.11 (0.00; 0.00; 0.04)	0.12 (0.00; 0.00; 0.04)	0.11 (0.00; 0.00; 0.04)	0.14 (0.00; 0.00; 0.05)
Total	17,829(67.6)	0.96 (0.00; 0.11; 1.10)	0.64 (0.00; 0.08; 0.75)	0.72 (0.00; 0.09; 0.84)	0.69 (0.00; 0.09; 0.81)	0.86 (0.00; 0.10; 1.00)
Women						
NPP	185(14.6)	0.01 (0.00; 0.00; 0.00)	0.01 (0.00; 0.00; 0.00)	0.01 (0.00; 0.00; 0.00)	0.01 (0.00; 0.00; 0.00)	0.01 (0.00; 0.00; 0.00)
Radiography	118(58.5)	0.14 (0.00; 0.03; 0.12)	0.10 (0.00; 0.02; 0.08)	0.11 (0.00; 0.03; 0.09)	0.10 (0.00; 0.02; 0.08)	0.13 (0.00; 0.03; 0.10)
Medical	1279(59.9)	0.29 (0.00; 0.04; 0.21)	0.20 (0.00; 0.03; 0.14)	0.25 (0.00; 0.03; 0.17)	0.20 (0.00; 0.03; 0.14)	0.30 (0.00; 0.04; 0.21)
Other	1194(31.8)	0.05 (0.00; 0.00; 0.02)	0.04 (0.00; 0.00; 0.02)	0.04 (0.00; 0.00; 0.02)	0.04 (0.00; 0.00; 0.02)	0.04 (0.00; 0.00; 0.02)
Total	2776(44.7)	0.16 (0.00; 0.00; 0.08)	0.11 (0.00; 0.00; 0.05)	0.14 (0.00; 0.00; 0.06)	0.12 (0.00; 0.00; 0.06)	0.16 (0.00; 0.00; 0.07)
Total						
NPP	6366(74.2)	1.05 (0.00; 0.23; 1.20)	0.72 (0.00; 0.16; 0.83)	0.78 (0.00; 0.17; 0.90)	0.77 (0.00; 0.17; 0.89)	0.90 (0.00; 0.20; 1.04)
Radiography	3464(94.7)	2.26 (0.57; 1.66; 3.27)	1.44 (0.37; 1.06; 2.09)	1.68 (0.43; 1.23; 2.43)	1.57 (0.40; 1.14; 2.26)	2.06 (0.52; 1.51; 2.98)
Medical	2963(71.7)	0.69 (0.00; 0.10; 0.48)	0.46 (0.00; 0.06; 0.32)	0.54 (0.00; 0.08; 0.38)	0.50 (0.00; 0.07; 0.34)	0.69 (0.00; 0.10; 0.47)
Other	7812(40.4)	0.13 (0.00; 0.00; 0.04)	0.10 (0.00; 0.00; 0.03)	0.11 (0.00; 0.00; 0.04)	0.10 (0.00; 0.00; 0.03)	0.12 (0.00; 0.00; 0.04)
Total	20,605(64.5)	0.85 (0.00; 0.07; 0.84)	0.57 (0.00; 0.05; 0.59)	0.64 (0.00; 0.06; 0.65)	0.61 (0.00; 0.06; 0.63)	1.77 0.00; 0.07; 0.77)

[a)] NPP: nuclear power plant; radiography: industrial radiography; Medical: medical institute; Other: other facilities.

Table 6
Distributions of individual cumulative organ doses for Korean radiation workers.

Occupational category[a]	Number of workers (% of exposed worker)	Individual cumulative dose Mean (25 percentile; median; 75 percentile)				
		$H_p(10)$ (mSv)	Red bone marrow (mGy)	Colon (mGy)	Lungs (mGy)	Thyroid (mGy)
Men						
NPP	6181(76.0)	17.9 (0.12; 2.10; 14.0)	12.3 (0.09; 1.48; 9.84)	13.2 (0.09; 1.59; 10.6)	13.1 (0.09; 1.58; 10.5)	15.2 (0.11; 1.83; 12.2)
Radiography	3346(96.0)	27.1 (4.53; 17.5; 38.6)	17.3 (2.90; 11.1; 24.7)	20.2 (3.37; 13.0; 28.8)	18.7 (3.14; 12.1; 26.7)	24.6 (4.12; 15.9; 35.2)
Medical	1684(80.7)	13.6 (0.21; 1.99; 12.2)	8.89 (0.14; 1.30; 7.95)	10.5 (0.16; 1.54; 9.39)	9.90 (0.15; 1.45; 8.85)	13.6 (0.21; 1.98; 12.2)
Other	6618(42.0)	1.94 (0.00; 0.00; 0.46)	1.45 (0.00; 0.00; 0.36)	1.58 (0.00; 0.00; 0.38)	1.53 (0.00; 0.00; 0.37)	1.81 (0.00; 0.00; 0.43)
Total	17,829(67.6)	13.3 (0.00; 0.94; 11.4)	8.87 (0.00; 0.66; 7.75)	9.94 (0.00; 0.73; 8.63)	9.57 (0.00; 0.71; 8.34)	11.9 (0.00; 0.86; 10.3)
Women						
NPP	185(14.6)	0.08 (0.00; 0.00; 0.00)	0.06 (0.00; 0.00; 0.00)	0.06 (0.00; 0.00; 0.00)	0.06 (0.00; 0.00; 0.00)	0.07 (0.00; 0.00; 0.00)
Radiography	118(58.5)	1.12 (0.00; 0.15; 0.68)	0.75 (0.00; 0.11; 0.45)	0.89 (0.00; 0.13; 0.54)	0.77 (0.00; 0.12; 0.46)	1.00 (0.00; 0.14; 0.60)
Medical	1279(59.9)	3.01 (0.00; 0.20; 1.77)	2.07 (0.00; 0.14; 1.21)	2.54 (0.00; 0.17; 1.49)	2.10 (0.00; 0.14; 1.23)	3.03 (0.00; 0.20; 1.78)
Other	1194(31.8)	0.35 (0.00; 0.00; 0.13)	0.27 (0.00; 0.00; 0.10)	0.30 (0.00; 0.00; 0.11)	0.28 (0.00; 0.00; 0.11)	0.32 (0.00; 0.00; 0.12)
Total	2776(44.7)	1.59 (0.00; 0.00; 0.47)	1.11(0.00; 0.00; 0.34)	1.34 (0.00; 0.00; 0.39)	1.13 (0.00; 0.00; 0.35)	1.58 (0.00; 0.00; 0.44)
Total						
NPP	6366(74.2)	17.4 (0.00; 1.90; 13.2)	11.9 (0.01; 1.33; 9.30)	12.8 (0.01; 1.43; 10.0)	12.8 (0.01; 1.42; 9.96)	14.8 (0.01; 1.65; 11.6)
Radiography	3464(94.7)	26.2 (3.78; 16.1; 37.5)	16.7 (2.41; 10.3; 24.0)	19.5 (2.82; 12.0; 28.0)	18.1 (2.61; 11.2; 26.0)	23.8 (3.45; 14.7; 34.2)
Medical	2963(71.7)	9.04 (0.00; 0.79; 5.80)	5.95 (0.00; 0.53; 3.93)	7.06 (0.00; 0.63; 4.69)	6.53 (0.00; 0.56; 4.19)	9.04 (0.00; 0.79; 5.84)
Other	7812(40.4)	1.70 (0.00; 0.00; 0.37)	1.27 (0.00; 0.00; 0.29)	1.38(0.00; 0.00; 0.31)	1.34 (0.00; 0.00; 0.30)	1.58 (0.00; 0.00; 0.35)
Total	20,605(64.5)	11.7 (0.00; 0.57; 8.42)	7.83 (0.00; 0.42; 5.75)	8.78 (0.00; 0.46; 6.41)	8.43 0.00; 0.44; 6.18)	10.5 (0.00; 0.53; 7.61)

[a] NPP: nuclear power plant; radiography: industrial radiography; Medical: medical institute; Other: other facilities.

respectively), followed by the colon (0.64 mGy/y and 8.78 mGy, respectively), lungs (0.61 mGy/y and 8.43 mGy, respectively), and RBM (0.57 mGy/y and 7.38 mGy, respectively). In particular, for industrial radiographers, the organ doses were observed to be noticeably high (e.g., the average cumulative organ doses were higher than 15 mGy) due to the high $H_p(10)$.

Since more than 86% of all workers were males, the order of doses for male workers by occupational group was identical to that of the doses for all workers; that is, the organ dose was the highest for industrial radiographers, followed by NPP workers, medical workers, and workers at other facilities. However, for female workers, the highest dose was observed in medical workers, not industrial radiographers. Surprisingly, the doses for NPP workers were the lowest; for example, the individual cumulative thyroid dose for female NPP workers was only 0.07 mGy, while that for female medical workers was 3.03 mGy. This difference with the male workers is due to the contribution of non-exposed workers. In case of the female workers, the ratio of the exposed workers to the total workers was the highest in the medical institute among the four occupational groups and the lowest in the NPP (only 14.6%).

As noted earlier, internal exposure was considered only for NPP workers. Thus, the annual and cumulative organ doses for NPP workers are the total doses, including internal doses and external doses derived from $H_p(10)$. The committed effective doses for internal exposure were reported for 6890 NPP workers (98% of the total NPP workers), and the individual cumulative internal dose was 0.49 mSv.

3.5. Limitations of this study

This study, as the initial step of a long-term follow-up epidemiological study, includes several limitations that warrant further investigation. The primary limitation comes from the uncertainty in determining the exposure scenario. The representative exposure scenarios determined based on literature and expert judgement still involve significant uncertainties. The exposure scenario should be more specifically established based on scientific and empirical data; for example, the exposure energy and geometry can be determined based on statistical analysis of a survey or actual measurement of a radiation field. For the workers exposed to high levels of doses (e.g., NPP workers performing refueling or steam generator maintenance), it is particularly necessary to apply individual task-based exposure scenarios. For this, an investigation on the radiation task information for individual workers is first required. Regarding handling of the dose records, the angular dependency of personal dosimeter response should also be investigated via simulations and experiments. In addition, we are aware of the imperfection of the dose conversion coefficients calculated based on the idealized geometries and the ICRP reference phantoms. Although ICRP has stated that the impacts of the differences in radiation fields between the idealized geometries and the actual exposure are not extreme [26], it is still necessary to consider more realistic radiation fields, particularly when the body is in close proximity to a point source producing a diverging radiation field. Also, the physical differences between the Korean workers and the

ICRP reference phantoms constructed based on the reference anatomical and physiological data can cause significant biases in the use of dose coefficients. Although the dose conversion coefficients calculated using Korean computational phantoms [27] were not employed in the current study due to an absence of values for cranial-caudal and caudal-cranial geometries, the use of dose coefficients based on Korean reference phantoms (e.g., Mesh-type reference Korean phantoms, MRKPs [28]) can improve the accuracy of dose reconstruction for Korean radiation workers. Regarding the internal exposure, we only considered the inhalation of HTO for NPP workers due to the lack of information associated with the dose calculation (e.g., chemical type and particle size distribution) but are aware that inhalation of uranium is one of the main sources for internal exposure for workers in nuclear fuel production facilities. The organ absorbed doses caused by the uranium inhalation should be investigated and added in future works. Lastly, in the current study, shielding effects by using protective equipment such as a lead apron were not considered due to a lack of relevant information for individual workers. The shielding effects are particularly important for interventional radiologists or cardiologist. In order to obtain doses actually delivered to the body of the workers, the reported $H_p(10)$ should be corrected considering the use of protective equipment in future works.

4. Conclusion

This paper described the first nationwide study on organ dose reconstruction for Korean radiation workers based on extensive personal dose records. Considerable efforts were made to establish exposure scenarios that can represent the characteristics of radiation-related work and to derive exposure scenario-based dose conversion coefficients. The individual cumulative doses reconstructed in the current study will be widely utilized in epidemiology studies to interpret the radiation health effects according to dose levels. Although the majority in the cohort had low levels of doses, this study still provides scientific fundamental data to statistically investigate whether such low doses can cause health effects. Subsequent studies for the organ dose reconstruction will extend the cohort to all Korean radiation workers including retired and radiation-related workers in the medical field (more than 190,000) and accordingly update the organ dose database for the cohort. In addition, to avoid a misinterpretation of the dose reconstruction results and to utilize the results appropriately in epidemiological studies, uncertainty analysis in the organ dose reconstructions will be also conducted.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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