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ESTIMATION OF ORGAN DOSES AMONG DIAGNOSTIC MEDICAL RADIATION WORKERS IN SOUTH KOREA

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This study aimed to estimate the radiation organ doses from occupational exposure in 94 396 Korean medical radiation workers. Data on badge doses (i.e. personal dose equivalent at 10 mm) between 1996 and 2011 obtained from a national dosimetry registry, survey data from 2012 to 2013, and organ dose conversion coefficients provided by the International Commission on Radiological Protection (ICRP) were used for the estimation. The highest mean cumulative badge doses (26.87 mSv) were observed in radiologists, followed by radiologic technologists (15.96 mSv). Male workers exhibited higher mean cumulative badge doses, across occupational groups. The estimated organ doses showed similar trends with those of badge doses. Organs located outside the apron's coverage such as the thyroid showed higher mean organ doses than those protected by the apron. Our findings could contribute to future radiation epidemiologic studies to investigate health effects from occupational radiation exposure in Korea.

INTRODUCTION

Epidemiologic studies on occupational exposures to ionizing radiations are important, as they could provide a more realistic understanding of the shape of the dose–response relationship of low-dose (<100 mGy) and low-dose rate (<5 mGy/h) radiation exposure. Medical radiation workers, as a study population, constitute the largest part of exposed radiation workers[(1)]. A series of cohort-based epidemiologic studies for medical workers, conducted in several countries[(2, 3)], have contributed to the understanding of risks from chronic low-dose radiation exposure. Multiple organ doses, however, have only been estimated in the US radiologic technologists study[(4, 5)], while a study on Chinese x-ray workers[(6)] estimated colon dose. Studies on radiologic technologists in Japan[(7)] and medical radiation workers in Canada[(8)] were based only on badge dose data.

Organ dose estimation is a promising resource in assessing the site-specific health risks associated with exposure to ionizing radiations[(9)]. Previously conducted studies on occupational radiation exposure incorporated the estimation of organ-specific doses as an elementary part of the investigation[(10–13)]; however, these studies mainly focused on workers from the nuclear field. Studies on organ dose estimations in medical radiation workers are rare due to lack of personal dose data.

There has been a rapid growth in the number of medical radiation workers, in South Korea—from 33 000 in 2004 to 76 493 in 2015[(14, 15)]. The numbers of radiologic practices and equipment have also expanded over the past 2 decades. The number of computed tomography, e.g. tripled between 1995 and 2015[(16)]. A cohort was launched in 2012, comprising 11 265 certified radiologic technologists—the largest group of medical radiation workers in South Korea—who were enrolled in the National Dosimetry Registry (NDR)[(17)]. Since some of these cohort members were exposed to radiation before the start of the NDR in 1996, we conducted a historical dose reconstruction procedure for these technologists in 2016, to obtain a comprehensive exposure history, for the purpose of epidemiological research[(18)].

The purpose of the present study was to estimate the organ-specific radiation doses for the medical radiation workers enrolled in the NDR of South Korea. Estimating organ doses at the individual level can provide useful scientific evidence and serve as a fundamental step forward in the assessment of the organ-specific risks of occupational radiation exposure.

MATERIALS AND METHODS

Study population

The study population included all the diagnostic medical radiation workers who were enrolled in the NDR between 1996 and 2011 (n = 94 396). The NDR is a government-operated centralized dosimetry data registry for all diagnostic radiation workers, including radiologic technologists, radiologists, doctors, dentists, dental hygienists, nurses and others.

Since its introduction, the registry has mandated that all medical workers who are exposed to radiation wear badge dosemeters. In addition, employers are required, by the law, to report their workers' personal dosimetry data to the Korea Center for Disease Control and Prevention, every quarter. Recently, we constructed a registry-based cohort for these diagnostic medical workers, by merging NDR badge dose data, from 1996 to 2011, with the datasets obtained from the Korean National Cancer Registry and death certificates. This cohort dataset could provide the opportunities to evaluate the association between radiation doses and overall health effects.

The NDR contains demographic and occupational information including dose measurements, year and age at the time of exposure, job title, type of facility, sex and birth year. The study population was stratified into 42 strata, by sex, job title and type of facility (Table 1), for the purpose of dose reconstruction. As for the type of facility, tertiary and secondary hospitals were categorized as 'Hospital' and doctors' clinics as 'Clinic'. The 'Others' category included community health centers, dental facilities, military organizations and educational institutes. These stratifying parameters were identified as important predictive variables for the evaluation of medical occupational radiation exposure and used as stratification factors in a previously conducted badge dose reconstruction study on radiologic technologists[18]. The present study was reviewed and approved by the Institutional Review Board of Korea University (1040 548-KU-IRB-16-203-A-1).

Reconstruction of badge doses before 1996

The annual and cumulative individual badge doses were calculated by combining the quarterly badge readings for the workers enrolled in the NDR. Quarterly doses below 0.01 mSv, which is the lowest detectable level of NDR, were substituted with 0.005 mSv—the midpoint between 0.01 mSv and 0. To examine how relevant this value (0.005 mSv) was, we fitted a Tobit regression model to log quarterly doses, presuming that the doses below 0.01 mSv were censored observations. The fitted expected dose below 0.01 mSv was 0.00465 mSv—which was nearly identical to our assumed value of 0.005 mSv.

For those who started working in the field of radiation before 1996 (n = 13 178; 14.0% of the total enrollees in the NDR), historical badge doses were reconstructed using a model in which yearly doses were taken as a log linear function of time and age (Equation 1)[18].

$$\log D = \beta_0 + \beta_1(y2000) + \beta_2(a35) \qquad (1)$$

where D is the annual dose, $y2000$ is the year at exposure centered at 2000, a35 is the age at exposure centered at 35 years. The year and age variables were centered to make the models' intercepts more interpretable. The three parameters in each stratum—β_0, β_1 and β_2—were fitted for each of the 42 strata. The ages at the time of the first exposure were estimated for each sex and occupational group, using our previous survey findings[19], to determine the first year of reconstruction for individual workers. The reconstructed doses were then combined with the NDR badge doses to yield individual cumulative doses. To avoid the overestimation of doses in the remote past, when applying the model, the doses prior to 1980 were assumed to have not exceeded those in 1980 or later, based on the literature which reported that high-dose exposures were less common before 1980, in Korea[20, 21]. The proportion of workers affected

Table 1. Number of diagnostic medical radiation workers by job title, sex, and type of facility.

Job title	Male						Female						Overall
	Hospital		Clinic		Others		Hospital		Clinic		Others		
	N	%[a]	N	%[a]	N	%[a]	N	%[a]	N	%[a]	N	%[a]	
Radiologic technologist	10 529	(39.9)	5970	(22.7)	779	(3.0)	4043	(15.3)	4529	(17.2)	506	(1.9)	26 356
Radiologist	798	(52.5)	241	(15.9)	18	(1.2)	371	(24.4)	87	(5.7)	5	(0.3)	1520
Doctor	3779	(20.2)	11 708	(62.7)	499	(2.7)	1326	(7.1)	1263	(6.7)	109	(0.6)	18 684
Dentist	221	(1.4)	13	(0.1)	12 045	(76.7)[b]	176	(1.1)	8	(0.1)	3242	(20.6)[b]	15 705
Dental hygienist	15	(0.1)	1	(0.0)	54	(0.4)[b]	824	(6.1)	16	(0.1)	12 578	(93.3)[b]	13 488
Nurse	341	(4.5)	62	(0.8)	21	(0.3)	4371	(57.8)	656	(8.7)	2110	(27.9)	7561
Others	3221	(29.1)	1220	(11.0)	2335	(21.1)	1784	(16.1)	512	(4.6)	2010	(18.1)	11 082
Sum	18 904		19 215		15 751		12 895		7071		20 560		94 396

[a]Row percentage.
[b]The majority of dentists (96.2%) and dental hygienists (90.4%) in the 'Others' facility category worked at dental clinics.

by this assumption was 1.9% (n = 1765). The combined number of measured and reconstructed annual doses for the 94 396 cohort members is 653 717, among which 532 067 (81.4%) are measured and the remaining 121 650 (18.6%) are reconstructed; the first year of reconstruction was extended to 1945.

Organ dose estimation

The organs and tissues in which the doses were estimated included the brain, breasts, colon, lungs, red bone marrow, stomach and the thyroid. The estimation of the organ doses involved the use of measured TLD badge readings and two conversion coefficients, provided by the International Commission on Radiological Protection (ICRP): the organ absorbed dose per unit of air kerma free-in-air (Gy per Gy)[22] and the personal dose equivalent per unit of air kerma free-in air (Sv per Gy)[23] (Equation 2). We assumed an antero-posterior irradiation geometry, which is the most common in occupational exposure scenarios among medical workers. The dominant energy of the diagnostic radiation fields was assumed to be between 30 and 40 keV[5].

$$D_T = H_p(d)\left[\frac{D_T}{K_a}\Big/\frac{H_p(d)}{K_a}\right] \tag{2}$$

where D_T is the organ dose; $H_p(d)$ is the personal dose equivalent; $\frac{D_T}{K_a}$ is the air kerma-to-organ dose conversion coefficient; and $\frac{H_p(d)}{K_a}$ is the air kerma-to-personal dose equivalent conversion coefficient. The organ dose estimation method was adopted from Simon *et al.*[5], to adjust for the probability of three different circumstances with regards to apron use and the placement of the badge, relative to the apron: probability of 'no apron use (P_{NoA})', probability of 'wearing an apron with a badge outside (P_{AO})', and probability of 'wearing an apron with a badge underneath (P_{AU})'. These probabilities were derived from a survey result for Korean radiation technologists, conducted in 2012–2013[17]. To reflect the shielding effect, an attenuation rate of 0.8 was assumed for the use of a lead apron[5, 24]. A Korean study also supports the rate based on 0.5 mm Pb apron use[25] although determining attenuation rate is a complicated task affected by a wide range of factors including lead equivalent, apron type, and distance from the source. The attenuation factor refers to the reduced proportion of radiation exposure from apron use, and is calculated using the mean probability of wearing aprons and the attenuation rate[5]. Incorporating the personal badge doses, conversion coefficients, probabilities of wearing an apron, and badge locations, the formulae for the organs under the apron and for those above the apron are shown in Equations 3 and 4, respectively, which were also adopted from the same study[5].

$$D_o = D_c * R_{coef} * (P_{NoA} + AA * P_{AO} + P_{AU}) \tag{3}$$

$$D_o = D_c * R_{coef} * (P_{NoA} + P_{AO} + P_{AU}/AA) \tag{4}$$

where D_o is the organ dose; D_c is the personal cumulative badge dose; R_{coef} is the averaged conversion coefficient ratios at 30 and 40 keV in the antero-posterior direction of exposure; P_{NoA} is the probability of not wearing aprons at work; P_{AO} is the probability of wearing aprons with the badge outside; P_{AU} is the probability of wearing aprons with the badge inside; and AA is the apron attenuation factor.

RESULTS

Of the 94 396 NDR cohort members, 53 870 (57.1%) were males and 40 526 (42.9%) were females. 'Radiologic technologist' was the most common profession (27.9%) followed by 'Doctor' (19.8%) and 'Dentist' (16.6%). With respect to the type of facility, 'Hospital,' 'Clinic' and 'Others' constituted 33.7, 27.8 and 38.5% of the cohort, respectively (Table 1). The reconstruction models (Supplementary Table S1) indicated that the calendar year was inversely related to the badge doses in all the strata. The age at the time of exposure was also inversely related to the badge dose in radiologic technologists, while these associations were either inconsistent or negligible in the other job titles.

Table 2 summarizes the cumulative badge doses (mSv), by sex, job title and year at the first exposure. There were considerable variations in the cumulative doses between job titles. The highest mean cumulative doses were observed in radiologists (26.87 mSv) and radiologic technologists (15.96 mSv), while the lowest levels were observed in nurses (1.93 mSv) and dental hygienists (0.61 mSv). There was a substantial difference in the mean cumulative doses between male (21.16 mSv) and female (6.07 mSv) radiologic technologists, while there was a marginal-to-moderate gap, in terms of sex, in the other job titles. Downward temporal trends in the cumulative badge doses were noticed in both sexes, and all the job titles.

The cumulative doses (mGy) received by the selected organs, by sex and job title, are shown in Table 3. Like in the case of cumulative equivalent doses, the highest site-specific doses for all the organs were observed in radiologists and radiologic technologists. The mean doses received by the organs located outside the apron or close to the body surface, such as the thyroid gland (10.23 mGy) and the breasts (5.03 mGy), were estimated to be greater than those received by the more deeply seated organs,

Table 2. Cumulative badge doses (mSv) by sex, job title and year at first exposure, among diagnostic medical radiation workers in South Korea, until 2011.

Year at the first exposure	Male					Female					Overall				
	N	Median	Mean	1Q	3Q	*N*	Median	Mean	1Q	3Q	*N*	Median	Mean	1Q	3Q
Radiologic technologist															
Before 1980	366	77.84	81.20	67.85	91.12	33	23.81	23.87	19.00	26.96	399	76.63	76.46	64.29	88.78
1980s	1825	40.51	44.67	28.28	54.71	314	13.82	17.04	9.67	18.82	2139	36.68	40.62	22.52	52.15
1990s	5289	18.75	25.93	9.48	33.30	1512	5.47	8.93	2.79	10.35	6801	14.90	22.15	6.63	28.36
2000s	9798	5.87	11.96	1.51	16.21	7219	1.94	4.91	0.58	5.62	17 017	3.56	8.97	0.95	10.99
Whole period	17 278	12.73	21.16	3.73	29.49	9078	2.67	6.07	0.82	7.36	26 356	7.33	15.96	1.83	21.27
Radiologist															
Before 1980	147	89.69	100.39	70.08	118.39	26	122.79	126.07	84.77	143.28	173	91.71	104.25	71.64	124.50
1980s	282	30.36	37.40	18.47	46.32	96	24.95	33.17	16.71	45.29	378	28.26	36.33	17.74	46.32
1990s	467	7.56	11.94	4.00	12.09	261	7.94	9.39	5.02	11.57	728	7.69	11.02	4.49	11.89
2000s	161	1.38	5.16	0.31	4.75	80	1.27	2.72	0.40	2.95	241	1.32	4.35	0.31	3.45
Whole period	1057	12.71	30.00	4.80	38.78	463	9.20	19.72	4.44	17.88	1520	11.33	26.87	4.70	32.00
Doctor															
Before 1980	274	25.72	32.62	19.18	34.74	13	17.23	35.40	14.96	36.75	287	25.52	32.75	18.83	34.83
1980s	609	9.59	15.46	6.57	16.63	73	8.31	13.21	5.43	15.70	682	9.49	15.22	6.43	16.59
1990s	2870	3.40	8.55	1.64	7.34	357	4.52	6.67	2.13	7.95	3227	3.49	8.34	1.69	7.48
2000s	12 233	0.48	2.35	0.13	1.55	2255	0.47	1.61	0.13	1.42	14 488	0.48	2.24	0.13	1.52
Whole period	15 986	0.84	4.48	0.21	3.49	2698	0.68	2.76	0.16	2.45	18 684	0.81	4.23	0.20	3.29
Dentist															
Before 1980	188	7.74	9.18	6.06	10.33	4	7.55	8.16	4.92	10.79	192	7.74	9.16	6.05	10.33
1980s	628	3.95	5.18	2.79	5.74	68	2.84	3.57	2.18	4.22	696	3.86	5.02	2.68	5.61
1990s	552	1.89	3.03	1.12	3.58	226	1.72	2.53	0.93	2.96	778	1.87	2.89	1.07	3.30
2000s	10 911	0.53	1.25	0.19	1.20	3128	0.40	0.89	0.14	0.91	14 039	0.50	1.17	0.18	1.13
Whole period	12 279	0.64	1.66	0.23	1.57	3426	0.46	1.06	0.16	1.09	15 705	0.59	1.53	0.21	1.47
Dental hygienist															
Before 1980	1	—	—	—	—	—	—	—	—	—	1	—	—	—	—
1980s	—	—	—	—	—	21	4.17	6.22	3.51	8.98	21	4.17	6.22	3.51	8.98
1990s	4	1.99	2.94	1.73	3.20	415	1.24	2.13	0.58	2.61	419	1.25	2.13	0.58	2.61
2000s	65	0.18	0.55	0.06	0.60	12 982	0.20	0.55	0.06	0.55	13 047	0.20	0.55	0.06	0.55
Whole period	70	0.22	0.72	0.07	0.80	13 418	0.22	0.61	0.06	0.59	13 488	0.22	0.61	0.06	0.59
Nurse															
Before 1980	4	46.72	73.27	32.51	87.48	6	90.77	84.96	79.60	98.41	10	82.74	80.29	42.28	98.41
1980s	7	15.40	25.92	11.64	37.90	76	19.83	26.41	14.19	30.71	83	19.81	26.37	13.56	31.19
1990s	16	11.11	15.53	2.61	19.81	269	4.02	7.55	1.48	8.12	285	4.10	8.00	1.57	8.83

(*Continued*)

Table 2. (Continued)

Year at the first exposure	Male					Female					Overall				
	N	Median	Mean	1Q	3Q	*N*	Median	Mean	1Q	3Q	*N*	Median	Mean	1Q	3Q
2000s	397	0.25	1.85	0.05	1.36	6786	0.25	1.27	0.06	0.79	7183	0.25	1.30	0.06	0.81
Whole period	424	0.31	3.44	0.07	1.64	7137	0.28	1.84	0.07	0.97	7561	0.28	1.93	0.07	1.00
Others															
Before 1980	613	34.06	69.15	22.23	77.94	90	15.21	25.73	8.86	34.07	703	32.01	63.59	20.80	70.61
1980s	797	9.80	16.25	6.00	17.92	425	5.19	7.35	2.67	9.88	1222	8.02	13.16	4.71	15.59
1990s	1897	1.60	8.52	0.46	4.60	2284	0.76	1.55	0.27	1.79	4181	1.00	4.71	0.34	2.75
2000s	3469	0.27	1.39	0.07	0.70	1507	0.19	0.81	0.05	0.55	4976	0.24	1.21	0.06	0.67
Whole period	6776	0.82	11.26	0.19	6.14	4306	0.62	2.37	0.16	2.01	11 082	0.71	7.81	0.18	3.74

including the bone marrow (2.21 mGy) and stomach (2.95 mGy). Greater estimates were observed in the male workers, for all the organs.

DISCUSSION

This study presents information on the radiation doses in a population of 94 396 Korean medical radiation workers. Radiologists received the highest cumulative organ doses, followed by radiologic technologists. The thyroid and breast organ sites showed higher doses than the other sites. The differences in the organ doses, between the sexes, was the most pronounced among radiologic technologists. Both the badge and organ doses showed downward temporal trends. The estimates of this study could be used as exposure data for future epidemiologic studies on the health risks of medical occupational radiation exposures in South Korea.

The cumulative doses for radiologists were higher than those for radiologic technologists, in both sexes. The differences in cumulative doses between radiologists and radiologic technologists can be attributed to distinctions between professional roles, and related practice environments such as different work practices, their frequency, badge wearing, separation from patients, wearing protective devices[19]. This could also be attributed to the distinct distributions of the year and age at the time of exposure, between the two job titles. Among the study population, 21.2% of the radiologic technologists started their careers before 1996, while the corresponding value was 61.1% among radiologists: i.e. the radiologists in the NDR, between 1996 and 2011, were older than the radiologic technologists and, subsequently, would have been exposed to radiations for longer periods. Except in the earliest period, lower cumulative doses were estimated in the radiologists than the radiologic technologists (Table 2); further evaluation may be required, in the radiologist group, to find out if this was a reflection of improved exposure management or poor cooperation in terms of wearing the badge.

The superficial organs and tissues received higher doses than the more deeply seated organs, which is consistent with other reports which focused on medical workers[4, 5]. The site-specific doses varied not only by organs but also by different job titles for the same organs. In particular, the occupational differences were more significant in the organs close to the surface, such as the thyroid gland and the breasts, mainly due to their higher conversion coefficients. The differences between the radiologists and dental hygienists were as high as 37.75 and 18.45 mGy, in terms of the mean thyroid gland and breast doses. The corresponding values for the red bone marrow and the brain were 8.19 and 4.31 mGy, respectively. Considering that breast and thyroid cancers are

Table 3. Cumulative organ doses (mGy) for selected sites, by sex and job title, among diagnostic medical radiation workers in Korea, until 2011.

Job title	Male (n = 53 870)				Female (n = 40 526)				Overall (n = 94 396)			
	Median	Mean	1Q	3Q	Median	Mean	1Q	3Q	Median	Mean	1Q	3Q
Brain												
Radiologic technologist	2.05	3.40	0.60	4.74	0.47	1.08	0.15	1.31	1.22	2.60	0.31	3.48
Radiologist	2.04	4.82	0.77	6.23	1.63	3.50	0.79	3.17	1.88	4.42	0.77	5.20
Doctor	0.14	0.72	0.03	0.56	0.12	0.49	0.03	0.43	0.13	0.69	0.03	0.54
Dentist	0.10	0.27	0.04	0.25	0.08	0.19	0.03	0.19	0.10	0.25	0.03	0.24
Dental hygienist	0.03	0.12	0.01	0.13	0.04	0.11	0.01	0.11	0.04	0.11	0.01	0.11
Nurse	0.05	0.55	0.01	0.26	0.05	0.33	0.01	0.17	0.05	0.34	0.01	0.18
Others	0.13	1.81	0.03	0.99	0.11	0.42	0.03	0.36	0.12	1.27	0.03	0.63
All	0.28	1.69	0.06	1.64	0.09	0.47	0.02	0.33	0.16	1.17	0.04	0.89
Breast												
Radiologic technologist	9.03	15.01	2.64	20.91	1.81	4.11	0.55	4.98	5.12	11.25	1.26	14.96
Radiologist	9.02	21.28	3.41	27.51	6.22	13.34	3.00	12.10	7.84	18.86	3.23	22.53
Doctor	0.60	3.18	0.15	2.48	0.46	1.87	0.11	1.66	0.57	2.99	0.14	2.32
Dentist	0.45	1.17	0.16	1.12	0.31	0.72	0.11	0.74	0.41	1.08	0.15	1.03
Dental hygienist	0.15	0.51	0.05	0.57	0.15	0.41	0.04	0.40	0.15	0.41	0.04	0.40
Nurse	0.22	2.44	0.05	1.17	0.19	1.25	0.05	0.66	0.19	1.31	0.05	0.68
Others	0.58	7.99	0.13	4.36	0.42	1.60	0.11	1.36	0.49	5.51	0.12	2.60
All	1.22	7.47	0.26	7.23	0.33	1.78	0.08	1.25	0.65	5.03	0.15	3.71
Colon												
Radiologic technologist	5.26	8.74	1.54	12.18	1.40	3.19	0.43	3.87	3.31	6.83	0.86	9.20
Radiologist	5.25	12.39	1.99	16.02	4.83	10.36	2.33	9.39	5.12	11.77	2.07	13.85
Doctor	0.35	1.85	0.08	1.44	0.36	1.45	0.08	1.29	0.35	1.79	0.08	1.42
Dentist	0.26	0.68	0.09	0.65	0.24	0.56	0.08	0.57	0.26	0.66	0.09	0.63
Dental hygienist	0.09	0.30	0.03	0.33	0.11	0.32	0.03	0.31	0.11	0.32	0.03	0.31
Nurse	0.13	1.42	0.03	0.68	0.15	0.97	0.04	0.51	0.15	0.99	0.03	0.52
Others	0.34	4.65	0.08	2.54	0.33	1.24	0.08	1.05	0.33	3.33	0.08	1.73
All	0.71	4.35	0.15	4.21	0.25	1.39	0.06	0.97	0.43	3.08	0.10	2.40
Lung												
Radiologic technologist	4.49	7.46	1.31	10.40	0.93	2.10	0.28	2.55	2.57	5.62	0.64	7.48
Radiologist	4.48	10.58	1.69	13.68	3.19	6.83	1.54	6.20	3.99	9.44	1.65	11.23
Doctor	0.30	1.58	0.07	1.23	0.24	0.96	0.06	0.85	0.29	1.49	0.07	1.16
Dentist	0.23	0.58	0.08	0.56	0.16	0.37	0.06	0.38	0.21	0.54	0.07	0.52
Dental hygienist	0.08	0.25	0.03	0.28	0.07	0.21	0.02	0.21	0.07	0.21	0.02	0.21
Nurse	0.11	1.21	0.02	0.58	0.10	0.64	0.02	0.34	0.10	0.67	0.02	0.35
Others	0.29	3.97	0.07	2.17	0.21	0.82	0.06	0.70	0.25	2.75	0.06	1.31
All	0.60	3.71	0.13	3.60	0.17	0.91	0.04	0.64	0.32	2.51	0.07	1.86
Red bone marrow												
Radiologic technologist	3.85	6.40	1.13	8.92	0.93	2.11	0.28	2.56	2.33	4.92	0.60	6.60
Radiologist	3.85	9.08	1.45	11.74	3.20	6.85	1.54	6.21	3.58	8.40	1.46	9.81
Doctor	0.26	1.36	0.06	1.06	0.24	0.96	0.06	0.85	0.25	1.30	0.06	1.02
Dentist	0.19	0.50	0.07	0.48	0.16	0.37	0.06	0.38	0.18	0.47	0.07	0.45
Dental hygienist	0.07	0.22	0.02	0.24	0.07	0.21	0.02	0.21	0.07	0.21	0.02	0.21
Nurse	0.09	1.04	0.02	0.50	0.10	0.64	0.02	0.34	0.10	0.66	0.02	0.34
Others	0.25	3.41	0.06	1.86	0.22	0.82	0.06	0.70	0.23	2.40	0.06	1.20
All	0.52	3.19	0.11	3.09	0.17	0.92	0.04	0.64	0.30	2.21	0.07	1.70
Stomach												
Radiologic technologist	5.12	8.51	1.50	11.86	1.27	2.88	0.39	3.49	3.13	6.57	0.80	8.81
Radiologist	5.11	12.06	1.93	15.59	4.36	9.36	2.11	8.48	4.85	11.24	1.96	13.25
Doctor	0.34	1.80	0.08	1.40	0.32	1.31	0.08	1.16	0.34	1.73	0.08	1.36
Dentist	0.26	0.67	0.09	0.63	0.22	0.50	0.08	0.52	0.25	0.63	0.09	0.61
Dental hygienist	0.09	0.29	0.03	0.32	0.10	0.29	0.03	0.28	0.10	0.29	0.03	0.28
Nurse	0.12	1.38	0.03	0.66	0.13	0.87	0.03	0.46	0.13	0.90	0.03	0.47
Others	0.33	4.53	0.08	2.47	0.29	1.12	0.08	0.95	0.31	3.21	0.08	1.62
All	0.69	4.23	0.15	4.10	0.23	1.25	0.06	0.88	0.40	2.95	0.09	2.28

(*Continued*)

Table 3. (Continued)

Job title	Male (n = 53 870)				Female (n = 40 526)				Overall (n = 94 396)			
	Median	Mean	1Q	3Q	Median	Mean	1Q	3Q	Median	Mean	1Q	3Q
Thyroid												
Radiologic technologist	18.02	29.96	5.28	41.74	4.06	9.24	1.25	11.21	10.63	22.82	2.69	30.44
Radiologist	18.00	42.47	6.80	54.90	14.00	30.02	6.76	27.22	16.34	38.68	6.76	45.82
Doctor	1.20	6.34	0.29	4.94	1.03	4.20	0.24	3.73	1.16	6.03	0.28	4.70
Dentist	0.91	2.35	0.32	2.23	0.70	1.61	0.24	1.66	0.85	2.19	0.30	2.10
Dental hygienist	0.31	1.01	0.10	1.14	0.33	0.93	0.09	0.91	0.33	0.93	0.09	0.91
Nurse	0.44	4.86	0.09	2.33	0.43	2.80	0.11	1.48	0.43	2.92	0.11	1.51
Others	1.16	15.94	0.27	8.70	0.94	3.61	0.24	3.05	1.04	11.15	0.26	5.46
All	2.43	14.90	0.52	14.43	0.73	4.01	0.18	2.82	1.36	10.23	0.31	7.74

among the most prevalent cancers in Korean women, the considerably high organ doses, in these organs, call for the careful inspection of the additional risks for female workers, in this occupational category.

The estimated organ doses were generally greater in the male workers than in the female workers. It is suggested, therefore, that there could be a clear sex divide in terms of the practice types or workload, between male and female workers. A previously conducted Korean study[17, 26] also showed differences in the types of practices between male and female radiologic technologists: CT scanning, portable chest radiography and C-arm radiography were more likely to be performed by male workers while mammography was almost exclusively performed by female workers. Other studies also reported similar differences between the sexes, in the frequency of radiologic practice, among all Korean medical radiation worker groups[27], dentists[28] and Japanese radiologic technologists[29]. In addition, male radiologic technologists were older than female radiologic technologists which implies longer duration of exposure and higher cumulative doses. These findings support that sex is an important determinant of occupational exposure, especially among radiologic technologists.

In our study, the estimated site-specific doses for radiologic medical workers were lower compared with those estimated in the United States Radiologic Technologists (USRT) study[4]. Although the total person-years in the USRT study was nearly 10 times as high as that in this study, the mean cumulative badge doses calculated in the USRT study were five times higher than those of the present study (76 versus 15.96 mSv). Considering that the USRT study incorporated earlier calendar years than this study, in which higher exposure levels are likelier, Korean radiologic technologists may be more exposed to higher radiation doses than their counterparts in the USA. This difference could be attributed to the actual differences in the technological features or workloads of radiologic practices between the two healthcare settings. Variations in the radiation reconstruction methods may also be behind this difference. For example, the reconstruction methods in the USRT study incorporated both published literature and badge measurements as references, while this study mainly relied on models that were fitted to data from more recent calendar years.

A major strength of this study is that the enrollees in the NDR represent virtually all diagnostic medical radiation workers in South Korea. This breadth of the NDR allowed reduction of uncertainty regarding personal badge measurement. All the participants in the NDR have personal dosemeters, and the organ doses for the majority of the participants (86.0%) were estimated based exclusively on these actual measurements. Another advantage of using NDR data is that the NDR is a government-run, single registry system, and any potential variations in the measurement quality and interpretation algorithms between the different monitoring companies, have been controlled by the regulatory authority. The detailed information collected from another survey[19], for a large fraction of eligible cohort members, provided an additional advantage. This survey supplied information on the safety practices and career history of workers, and this information was reported as reliable enough to use in epidemiologic studies[30].

The authors acknowledge the following limitations. No reliable records or publications, pertaining to past occupational exposure, were available to which the reconstruction process could have been referenced. Assumptions made in the conversion of the cumulative dose equivalents to organ-specific doses predominantly included energy from X-ray machines, irradiation geometry and attenuation by the use of a lead apron, which could lead to uncertainty. In addition, these assumptions could not be separately assigned to different job titles, sexes and types of facilities. Application of monochromatic energy due to lack of period-specific machine specifications could also lead to underestimation of energy deposition and subsequently organ doses.

CONCLUSIONS

In summary, this study estimated the organ-specific cumulative effective doses from occupational exposure to radiation, among Korean medical radiation workers. Considering the limited number of studies that focused on the dose–response evaluation associated with low-to-moderate fractionated exposures to ionizing radiation, among medical radiation workers, the organ-specific dose information obtained from this study could contribute to future radiation epidemiologic studies based on this population. The scope of dosimetry can also be further refined, as more information on occupational details and sophisticated methodology are available.

SUPPLEMENTARY MATERIAL

Supplementary material can be found at *Radiation Protection Dosimetry* online.

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CONFLICT OF INTEREST

The authors have no competing interests or conflicts of interest to declare.

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