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Original Article

High-radiation-exposure work in Korean pressurized water reactors

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ABSTRACT

Owing to strict radiation safety management in Korean nuclear power plants (NPPs), most radiation workers receive very low radiation doses, even lower than the annual dose limit for the general public. However, the occupational dose distribution indicates that some Korean NPP workers receive a relatively higher dose than the average dose. This inequity in radiation exposure could be reduced by providing customized radiation protection measures, such as dose constraints, to workers receiving relatively higher doses. In this study, dose normalization was performed to identify the highest radiation exposure work in Korean pressurized water reactors (PWRs). The results show that most of the occupational exposure in Korean PWRs occurs during the planned maintenance period. Finally, the three highest radiation exposure tasks in Korean PWRs were identified: nozzle dam installation and removal, eddy current testing, and man-way opening and closing.

1. Introduction

The Enforcement Decree of the Nuclear Safety Act sets forth regulations stating that the annual effective dose limit for radiation workers should not exceed 50 mSv, with a five-year cumulative limit of 100 mSv. Additionally, the equivalent dose limits are defined as 150 mSv per year for the lens of the eye and 500 mSv per year for the hands, feet, and skin [1,2]. These regulations are crucial for controlling the radiation exposure of nuclear power plant (NPP) workers and ensuring their radiation safety. Currently, the Republic of Korea operates 25 NPPs, including 22 pressurized water reactors (PWRs) and three pressurized heavy-water reactors (PHWRs). Table 1 provides an overview of the operational status of the Korean NPPs [3]. The Korea Hydro & Nuclear Power (KHNP) is the sole NPP operator in Korea and controls radiation exposure for all NPP workers. An analysis of radiation exposure data for Korean NPP workers over the past decade revealed an overall decreasing trend in radiation exposure levels (see Table 2) [4]. As shown in Table 2, the recent average individual dose in Korean NPPs is approximately 0.5 mSv, which is lower than the annual dose limit (1 mSv) for the general public. Consequently, reducing the radiation dose of NPP workers is significantly challenging, and their doses are expected to remain stable at low levels.

Despite the overall low radiation exposure levels, a small fraction of NPP workers still receive relatively higher radiation doses than the average. Table 3 shows the occupational dose distribution in Korean NPPs over the past decade [5–14]. These findings raise concerns regarding the inequities in radiation exposure among NPP workers engaged in high-radiation-exposure work. In reality, it is difficult to achieve an additional reduction in individual doses because the occupational dose is already maintained at very low levels. Accordingly, it is better to focus on high-radiation-exposure work and implement robust radiation protection measures for such workers, which could lead to not only an overall reduction in radiation dose but also alleviate inequities in radiation exposure among NPP workers. Therefore, identifying high-radiation-exposure work in NPPs is an essential step for maintaining the radiation dose of NPP workers as low as reasonably achievable. This study aimed to investigate occupational doses in Korean PWRs and identify the highest radiation-exposure tasks contributing to inequities in radiation exposure among NPP workers. To achieve these goals, we analyzed the average individual doses, and radiation doses under operational conditions in Korean PWRs. Subsequently, high-radiation-exposure tasks in Korean PWRs were identified by normalizing the radiation doses.

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Table 1
Operation of nuclear power plants in Korea.

NPP	Reactor type	Electric power output (MWe)	Commercial operation date
Kori 1[a]	PWR	608	29-04-1978
Kori 2	PWR	650	25-07-1983
Kori 3	PWR	950	30-09-1985
Kori 4	PWR	950	29-04-1986
Shin Kori 1	PWR	1,000	28-02-2011
Shin Kori 2	PWR	1,000	20-07-2012
Saeul 1	PWR	1,400	20-12-2016
Saeul 2	PWR	1,400	29-08-2019
Shin wolsong 1	PWR	1,000	31-07-2012
Shin wolsong 2	PWR	1,000	24-07-2015
Wolsong 1[b]	PHWR	688	22-04-1983
Wolsong 2	PHWR	700	01-07-1997
Wolsong 3	PHWR	700	01-07-1998
Wolsong 4	PHWR	700	01-10-1999
Hanbit 1	PWR	950	25-08-1986
Hanbit 2	PWR	950	10-06-1987
Hanbit 3	PWR	1,000	31-03-1995
Hanbit 4	PWR	1,000	01-01-1996
Hanbit 5	PWR	1,000	21-05-2002
Hanbit 6	PWR	1,000	24-12-2002
Hanul 1	PWR	950	10-09-1998
Hanul 2	PWR	950	30-09-1989
Hanul 3	PWR	1,000	11-08-1998
Hanul 4	PWR	1,000	31-12-1999
Hanul 5	PWR	1,000	29-07-2004
Hanul 6	PWR	1,000	22-04-2005
Shin Hanul 1	PWR	1,400	07-12-2022
Total	27	25,946	

[a] Permanent Shutdown (18-06-2017).
[b] Permanent Shutdown (24-12-2019).

Table 2
Occupational doses in Korean nuclear power plants over a 10-year period (2012–2021).

Year	Number of reactors	Collective dose (man-mSv)	Collective dose per reactor (man-mSv/reactor)	Number of workers	Average individual dose (mSv)
2012	23	10,471	455	14,715	0.71
2013	23	12,122	527	14,786	0.82
2014	23	8,324	362	14,260	0.58
2015	25	8,861	354	14,926	0.59
2016	25	11,008	440	14,396	0.76
2017	25	7,528	301	14,501	0.52
2018	25	9,025	361	15,877	0.57
2019	26	7,025	270	16,223	0.43
2020	26	8,729	336	16,844	0.52
2021	27	8,911	330	16,796	0.53

2. Materials and methods

KHNP provides an annual report to record and control the radiation exposure of Korean NPP workers. This report includes data on the radiation dose distribution among NPP workers, both internal and external, as well as radiation doses attributed to specific work [5–14]. In this study, the occupational doses in Korean PWRs were analyzed using work-specific data from the annual reports on occupational exposure in Korean NPPs for a ten-year period (2012–2021) since the occupational doses in the annual report are official data that are to be reported to the Korean regulatory body. The reason for using a 10-year dataset was that Korean NPPs typically undergo planned maintenance every 18 months, and one-third of the nuclear fuels are replaced during this maintenance period [15]. Consequently, it takes approximately five years to completely replace nuclear fuels (18 months $\times$ 3 cycles $=$ 54 months). Furthermore, the operating conditions of a reactor may change according to nuclear fuel integrity. Therefore, in this study, these changes are considered and a 10-year dataset was used to comprehensively analyze the radiation doses incurred by each type of work and to identify high-radiation-exposure work in Korean PWRs.

The unit for the radiation dose associated with each task is referred to as the collective dose. The collective dose is the product of the number of workers engaged in a specific task and their average individual dose, representing the total radiation dose incurred during the task. Collective doses can be used as an indicator to assess the rationality of the radiation exposure of NPP workers. For example, consider two teams, Teams A and B, both performing the same tasks. Team A consists of five workers with an average individual dose of 2 mSv, while Team B consists of 20 workers with an average individual dose of 1 mSv. An evaluation based solely on the average individual dose might suggest that Team B had better radiation exposure management because its average individual dose is half that of Team A. However, when we calculated the collective dose, Team A's collective dose was 10 man-mSv (5 workers $\times$ 2 mSv), whereas Team B's collective dose was 20 man-mSv (20 workers $\times$ 1 mSv). Consequently, it becomes apparent that Team A performed better in terms of radiation exposure management for the work, reducing the radiation dose to approximately half that of Team B. Therefore, to identify high-radiation-exposure work, it is imperative to compare the collective doses associated with each task.

To facilitate a quantitative radiation work comparison and identify high-radiation-exposure work, it is necessary to normalize the collective dose. For instance, consider Work A, which requires 100 man-hours and results in a collective dose of 100 man-mSv, and Work B, which requires 10 man-hours and results in a collective dose of 50 mSv. An unnormalized comparison of the collective doses would suggest that Work A results in a higher dose. However, when we normalized the collective dose by dividing it by the working hours, we found that Work A incurred 1 mSv/h, whereas Work B incurred 5 mSv/h. This normalization revealed that Work B resulted in a higher dose per unit of time. Therefore, to compare radiation doses accurately or quantitatively, normalization is essential to determine the radiation dose per working hour. To

Table 3
Occupational dose distribution in Korean nuclear power plants over a 10-year period (2012–2021).

Year	Number of reactors	Number of workers	Number of individuals in specific dose ranges (mSv/y)									Maximum individual dose (mSv/y)	Average individual dose (mSv/y)
			0.1<	[0.1–1)	[1–2)	[2–3)	[3–5)	[5–10)	[10–15)	[15–20)	[20–50)		
2012	23	14,715	9,436	2,715	965	519	524	412	131	12	1	26.64	0.71
2013	23	14,786	9,321	2,892	901	449	465	510	224	24	0	18.17	0.82
2014	23	14,260	9,811	2,382	765	430	415	375	77	5	0	16.51	0.58
2015	25	14,926	10,129	2,615	815	476	433	355	95	8	0	16.29	0.59
2016	25	14,396	9,300	2,644	894	431	510	398	184	35	0	18.13	0.76
2017	25	14,501	10,008	2,584	751	397	382	305	66	8	0	17.64	0.52
2018	25	15,877	10,356	3,198	969	462	466	328	89	9	0	13.71	0.57
2019	26	16,223	11,173	3,165	883	355	353	241	46	5	2	49.67	0.43
2020	26	16,844	11,920	2,796	831	411	421	355	93	17	0	17.56	0.52
2021	27	16,796	11,125	3,406	971	444	415	348	87	0	0	14.09	0.53

Table 4
Occupational doses in Korean pressurized water reactors over a 10-year period (2012–2021).

Year	Number of workers	Number of reactors	Collective dose (man-mSv)	Average individual dose (mSv)
2012	18,100	19	7,920	0.44
2013	18,136	19	10,160	0.56
2014	17,155	19	6,825	0.4
2015	19,214	21	7,135	0.37
2016	19,153	21	9,273	0.48
2017	18,633	21	5,877	0.32
2018	21,299	21	7,436	0.35
2019	21,472	22	5,865	0.27
2020	20,601	22	7,431	0.36
2021	22,019	23	7,578	0.34
Average	19,578	20.8	7,550	0.39

determine high-radiation-exposure work in Korean PWRs, it is necessary to normalize the collective dose from each work because the collective dose depends on the working hours of the radiation work. Normalization calculates the radiation dose per unit time, considering the work duration, and is expressed as follows:

$$\text{Radiation dose per unit time}\left(\frac{\text{mSv}}{\text{h}}\right)=\frac{Collective\ dose\ (man\ mSv)}{Working\ hours\ (man\ h)}.$$

In this study, the total number of PWR workers is overcounted compared to the actual total number of NPP workers due to transient workers. Transient workers are defined as individuals who work at more than one nuclear facility in a year [16]. Each NPP separately reports the occupational doses received by transient workers at each facility. These data appear as separate individual doses, although some data belong to the same worker. To obtain the actual individual dose information, it is necessary to combine the dose records for each individual. However, it is difficult to access an individual's identification information, such as the resident registration number, to combine the occupational dose records for each individual. Therefore, this study used data from the KHNP annual reports to analyze the occupational doses in Korean PWRs without considering transient workers.

3. Results and discussion

3.1. Occupational dose analysis in Korean PWRs

As presented in Table 2, the occupational doses for Korean NPPs have consistently remained below the annual effective dose limit (100 mSv over five years and 50 mSv per year). Despite an overall decreasing trend in these radiation doses, achieving a significant reduction has proven challenging. Over a 10-year period (2012–2021), the number of PWR workers has increased annually from approximately 18,100 in 2012 to 22,000 in 2021. Surprisingly, despite the annual growth in the number of PWR workers, the collective dose remained relatively constant at approximately 7,550 man-mSv over the same period. Additionally, the average individual dose in Korean PWRs over this 10-year period was 0.39 mSv, which is well below the annual effective dose limit for the general public (1 mSv per year). These statistics are summarized in Table 4 [5–14], which shows that the number of Korean PWR workers is overestimated, possibly due to transient workers. Contrary to the occupational dose data shown in Table 4, the actual total number of workers, which excludes multiple counts of transient workers during the year, is used as the number of workers in all Korean NPPs in Tables 2 and 3

In Korean NPPs, operational conditions are categorized into three distinct phases: normal operation, planned maintenance, and intermediate maintenance. The normal operation encompasses routine plant operations, including inspections and safety management, which lead to routine radiation exposure in NPP workers. Planned maintenance, which typically occurs within an 18-month refueling cycle, involves significant facility upgrades, maintenance activities, and equipment replacements. During this phase, NPP workers may experience elevated radiation doses over a short period. In contrast, intermediate maintenance is triggered by abnormal conditions in some NPP components. Radiation exposure during the intermediate maintenance period is irregular and depends on the specific maintenance work. The occupational doses according to operational conditions in Korean PWRs are listed in Table 5 [5–14]. These data reveal that approximately 10 % of the radiation exposure occurs during the normal operation period, approximately 90 % during the planned maintenance period, and approximately 1 % during the intermediate maintenance period. Most occupational radiation exposure in Korean PWRs occurs during the planned maintenance phase [17–19].

It is worth noting that the average individual dose in Korean PWRs is extremely low (0.39 mSv); however, this value represents an average. In other words, some individuals received radiation doses higher than this average. Table 6 shows the dose distribution among Korean PWR workers [5–14]. The majority of PWR workers (approximately 90 %) received doses below 1 mSv, but a minority received doses that, although low in general, were relatively high compared to their peers. This highlights the inequity in radiation exposure among Korean PWR workers, underscoring the need to identify work with high radiation exposure, which was the main goal of this study.

Occupational dose analysis results indicate that the average individual dose in Korean PWRs remains well below the annual effective dose limit. Furthermore, despite the annual increase in the number of PWR workers, the collective dose either remained stable or slightly decreased over time. However, an analysis of the dose distribution revealed that some workers received relatively higher doses than the average. Most occupational exposure in Korean PWRs occurs during the planned maintenance period, with external exposure being the predominant radiation exposure mode.

Table 5
Occupational doses according to the operational conditions in Korean pressurized water reactors over a 10-year period (2012–2021).

Year	Number of PWRs	Collective dose (man-mSv)						
		Normal operation	Ratio (%)	Planned maintenance	Ratio (%)	Intermediate maintenance	Ratio (%)	Total
2012	19	674.99	8.52	7,240.01	91.41	5.15	0.07	7,920.15
2013	19	1,004.44	9.89	8,828.31	86.89	327.78	3.23	10,160.53
2014	19	855.08	12.53	5,969.68	87.46	0.72	0.01	6,825.48
2015	21	748.40	10.49	6,322.90	88.61	64.67	0.91	7,135.97
2016	21	697.18	7.52	8,547.56	92.17	28.75	0.31	9,273.49
2017	21	708.76	12.06	5,168.15	87.94	0.29	0.00	5,877.20
2018	21	611.74	8.23	6,824.22	91.77	0.59	0.01	7,436.55
2019	22	594.53	10.14	5,270.90	89.86	0.00	0.00	5,865.43
2020	22	636.40	8.56	6,785.06	91.30	10.46	0.14	7,431.92
2021	23	800.88	10.57	6,776.75	89.42	1.33	0.02	7,578.96
Average	20.8	733.24	9.85	6,773.35	89.68	43.97	0.47	7,550.57

Table 6
Occupational dose distribution in Korean pressurized water reactors over a 10-year period (2012–2021).

Year	Number of reactors	Number of workers	Number of individuals in specific dose ranges (mSv/y)									Average individual dose (mSv/y)
			0.1<	[0.1–1)	[1–2)	[2–3)	[3–5)	[5–10)	[10–15)	[15–20)	[20–50)	
2012	19	18,100	11,562	4,176	1,163	536	425	217	20	1	0	0.44
2013	19	18,136	11,421	4,157	1,112	508	459	364	106	9	0	0.56
2014	19	17,155	11,643	3,437	1,050	440	372	202	11	0	0	0.40
2015	21	19,214	12,953	4,012	1,205	504	360	176	4	0	0	0.37
2016	21	19,153	12,317	4,049	1,221	527	528	293	36	2	0	0.49
2017	21	18,633	12,948	3,959	916	382	253	163	12	0	0	0.32
2018	21	21,299	13,834	5,219	1,233	524	344	138	12	0	0	0.34
2019	22	21,472	14,945	4,706	1,024	345	253	101	14	1	2	0.27
2020	22	20,601	15,098	3,634	840	396	310	242	66	15	0	0.36
2021	23	22,019	15,023	4,951	1,058	429	314	212	32	0	0	0.34

Table 7
Collective dose normalization from radiation work in Korean pressurized water reactors over a 10-year period (2012–2021).

Category 1 work	Category 2 work	Working hours (man h)	Number of workers	Collective dose (man mSv)				Radiation dose per unit time (mSv/h)
				Normal operation	Planned maintenance	Intermediate maintenance	Total	
A (Refueling)	Nuclear fuel replacement	37,177.23	18,271	18.94	118.44	0.07	137.45	0.00319
B (Reactor vessel or internal)	Disassembly or assembly	17,808.51	8,262	0.48	478.31	2.64	481.43	0.02686
	Inspection	5,775.48	2,767	0.65	78.68	0.04	79.37	0.01362
	Nuclear instrumentation system work	18,115.77	9,352	3.16	497.82	0.15	501.13	0.02748
	Other work	25,464.19	13,033	2.95	630.09	2.76	635.80	0.02474
C (Steam generator primary side)	Man-way work	2,597.84	1,334	0.16	83.03	0.30	83.49	0.03196
	Nozzle dam work	2,452.18	1,632	0.62	165.28	1.08	166.98	0.06740
	Eddy current testing work	12,230.73	5,861	2.08	422.73	0.00	424.81	0.03456
	Tube work	8,347.78	4,020	0.32	178.57	0.00	178.89	0.02139
	Other work	2,312.09	1,243	0.44	106.31	33.62	140.37	0.04598
D (Steam generator secondary side)	Man-way/Hand-hole	1,666.82	954	0.00	51.16	0.00	51.16	0.03069
	Lancing	4,486.23	2,577	0.14	124.44	0.00	124.58	0.02774
	Foreign object search and retrieval	5,336.90	2,714	0.00	164.02	0.00	164.02	0.03073
	Other work	15,962.90	6,590	1.11	86.52	0.00	87.63	0.00542
E (Residual heat removal system & safety injection system)	Residual heat removal & safety injection system	7,263.75	4,213	3.10	93.84	0.04	96.98	0.01292
F (Chemical & volume control system); H (Reactor water clean-up system); J (Primary circuit)	Reactor coolant system	11,271.93	7,012	15.84	134.58	0.17	150.59	0.01194
G (Pressurizer)	Pressurizer	9,335.85	5,272	1.55	119.28	0.24	121.07	0.01278
I (Reactor coolant system pump)	Reactor coolant pump	52,314.63	28,369	109.56	505.15	0.18	614.89	0.00966
K (Valve work)	Valve work	33,968.59	20,750	37.48	294.00	0.42	331.90	0.00866
L (Routine inspections)	Inspection	96,673.43	97,970	30.44	146.43	0.44	177.31	0.00151
M (General work)	Inservice inspection	33,070.53	17,121	1.41	489.38	2.74	493.53	0.01480
	Other inspection	8,757.00	4,237	0.36	14.56	0.00	14.92	0.00166
	Integrated leakage rate test & local leakage rate test	11,178.56	6,918	1.04	37.01	0.02	38.07	0.00331
	System operating	146,891.43	133,918	44.55	159.92	0.57	205.04	0.00109
	Radiation safety & laundry	365,121.00	240,898	77.59	423.76	1.32	502.67	0.00116
	Waste management	144,206.44	95,163	177.29	123.22	0.58	301.09	0.00085
	Vitrification equipment	4,418.80	4,659	2.91	5.00	0.00	7.91	0.00113
	Other work	212,119.04	143,090	148.85	482.98	1.08	632.91	0.00228
N (Scaffolding)	Scaffolding	7,522.31	4,087	1.28	41.72	0.00	43.00	0.00555
O (Insulation)	Insulation work	271.81	103	1.59	2.99	0.00	4.58	0.01100
P (Control rod drive)	Control rod work	6,035.30	3,004	0.35	62.92	0.08	63.35	0.01043
Q (Extra)	Extra	57,378.62	35,611	31.64	167.50	0.24	199.38	0.00292
R (Large task)	Specialized work	5,010.84	2,690	2.06	14.26	0.00	16.32	0.00285
S (Steam generator replacement)	Steam generator replacement	43,068.90	23,618	0.32	238.08	0.00	238.40	0.00553
T (Reactor head replacement)	Reactor head replacement	35,866.25	18,292	0.19	59.05	0.00	59.24	0.00165
Total		1,451,479.66	975,605.00	720.45	6,801.03	48.78	7,570.26	0.51543

3.2. Determining high-radiation-exposure work in Korean PWRs

Currently, radiation work in Korean PWRs is divided into three main categories, with 21, 38, and 214 radiation tasks in Categories 1–3, respectively [20]. Category 1 work is classified according to the area in which the radiation work is performed. Category 2 includes tasks that combine multiple rudimentary tasks from Category 3. Category 3 includes rudimentary work with work codes. In practice, it is difficult to determine the starting and ending points of each Category 3 task because they are conducted consecutively. It is also difficult to calculate the radiation exposure at the Category 3 level. Therefore, radiation exposure during work is typically calculated for Category 2 work.

In this study, we aimed to normalize the radiation dose from Category 2 work and identify the three highest radiation exposure tasks in Korean PWRs. The collective dose from radiation work in Korean PWRs was analyzed for a 10-year period (2012–2021) according to the operational conditions. As shown in Table 7, the normalization results indicate that the three highest radiation exposure tasks in Korean PWRs are nozzle dam installation and removal, eddy current testing (ECT), and man-way opening and closing, in that order. The highest radiation-exposure work is nozzle dam work, with a normalized value of 0.0674 mSv/h, which accounts for 13.07 % of the total radiation dose per unit time. Nozzle dam work is performed at the steam generator nozzle area to block the reactor coolant inlet and outlet during the inspection and maintenance of the steam generator [21]. The second-highest radiation-exposure work is another task performed on the primary side of the steam generator, with a normalized value of 0.04598 mSv/h; however, it was not selected in this study because it is not an individual work but part of the other works performed to prepare the maintenance of the primary side of the steam generator. Thus, in this study, ECT was identified as the second-highest radiation exposure work, with a normalized value of 0.03456 mSv/h, which accounts for 6.71 % of the total radiation dose per unit time. ECT exhibits the second-highest radiation dose per unit time after the other tasks on the primary side of the steam generator. ECT is a nondestructive inspection of equipment such as steam generator tubes and neutron flux detection tubes in Korean NPPs [22]. The third-highest radiation exposure work is man-way work, with a normalized value of 0.03196 mSv/h, which accounts for 6.2 % of the total radiation dose per unit time. Man-way work is the opening and closing of the man-way cover for workers to enter and exit the steam generator water tanks. The results also show that the three highest radiation-exposure tasks in Korean PWRs identified in this study, i.e., nozzle dam installation and removal, ECT, and man-way opening and closing, are maintenance tasks at the steam generator.

4. Conclusion

An analysis of occupational radiation dose data in Korean NPPs revealed that the average individual dose is well below the annual dose limit for radiation workers and even lower than the annual dose limit for the general public. Nevertheless, it is evident that a minority of NPP workers received relatively higher doses than the average, indicating inequities in radiation exposure among workers. Identifying high-radiation-exposure work could help to effectively reduce the occupational dose and resolve inequities in radiation exposure among Korean NPP workers, rather than uniformly reducing the radiation dose for all NPP workers. We conducted the analysis of the occupational dose data for a 10-year period (2012–2021), aiming to identify the three highest radiation-exposure tasks in Korean PWRs.

The occupational dose analysis results showed that most Korean PWR workers receive very low radiation doses, with an average individual dose of 0.39 mSv/y. However, the occupational dose distribution in Korean PWRs indicates that a small fraction of workers receive relatively high doses. Furthermore, approximately 90 % of the total radiation dose occurs during the planned maintenance period. This underscores the fact that most radiation exposure in Korean PWRs is primarily attributed to maintenance work.

The collective radiation dose was normalized to identify high-radiation-exposure work in Korean PWRs. The normalization process yielded the radiation dose per unit time considering the working hours. After normalization, the three highest radiation-exposure tasks in Korean PWRs were identified as nozzle dam installation and removal, ECT, and man-way opening and closing. Finally, inequities in radiation exposure among Korean PWR workers are expected to be alleviated and the overall occupational radiation dose reduced if radiation protection in the field focuses on the high-radiation-exposure work identified in this study.

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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