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Occupational radiation monitoring at a large medical center in Japan

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Abstract Occupational radiation dose monitoring is a method of ensuring that radiation levels are within the regulatory limits. Our objective in this study was to evaluate the radiation doses experienced by personnel at a radiology facility between 2001 and 2010. Overall, 2418 annual dose records for workers who were categorized into four occupational groups were analyzed. The groups included: (1) radiologists, (2) radiologic technologists, (3) nurses, and (4) other workers, who belong to other hospital departments, but who participate partially in some radiologic procedures. The dose distribution was found to be skewed, with 76 % of personnel having received no measurable doses and almost 2 % having received doses of more than 2 mSv. The weighted-average annual doses ranged from 0.13 to 0.57, 0.9 to 2.12, 0.01 to 0.19, and 0.01 to 0.09 mSv for the radiologists, radiologic technologists, nurses, and the other workers, respectively. The radiologic technologists received the highest radiation exposure among the four groups. It was found that the average annual doses were decreasing over time for the radiologists, radiologic technologists, and others, whereas they were increasing for the nurses. Nurses play an important role in assisting radiologists and patients during various radiologic procedures, which might have increased their average annual dose. During the 10-year period of this study, there was no incidence of a dose exceeding the annual dose limit of 20 mSv. Furthermore, there was no detectable neutron exposure.

Keywords Personnel · Monitoring · Occupational · Radiation dose

1 Introduction

Radiation can be highly dangerous when protective and preventive techniques are not applied and when safe practices are not taken into consideration. The International Commission on Radiological Protection (ICRP) [1] recommends a concise system of radiologic protection, including dose limits for radiation workers. This system has formed the basis for safety standards of international organizations such as the International Atomic Energy Agency (IAEA). The ICRP, in a publication [103] [1], recommends taking into consideration societal and socioeconomic factors in keeping the radiation exposure and the number of exposed individuals as low as reasonably achievable (ALARA). This was one of the fundamental principles in radiation protection. The importance of this study stems from its being the first to investigate the personnel radiation levels in the Radiology Department of the University of the Ryukyus hospital. No previous analysis has been done that checked for any trends or changes in the levels of radiation doses received by various monitored groups.

2 Materials and methods

2.1 Research facility and occupational groups

Our study was carried out at a large medical center in Okinawa, Japan. Ionizing radiation is widely used in the Radiology Department, which consists of three divisions,

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diagnostic radiology, radiotherapy, and nuclear medicine. The radiotherapy division encompasses external-beam therapy and brachytherapy. The common practice in Japan and in our hospital is that radiologists, radiologic technologists, and nurses work in a rotation-shift system. This means that workers rotate among these three divisions. In Japan, the three major divisions are staffed by the same group of physicians, technologists, and nurses, who rotate based on a weekly or monthly schedule.

It is difficult to specify a group of workers for each of the major divisions. Therefore, in our study, data are presented according to occupational specialties, i.e., radiologists, radiologic technologists (RTs), nurses, and "others". An attempt to recognize personnel specialties based on the dosimeter used was made. However, it had a limited outcome, because only those wearing ring (finger) dosimeters were identifiable. They belonged to the nuclear medicine section. For other dosimeters used by the majority of workers at the chest level, it was not possible to identify the sub-specialties.

The "others" group included many workers who did not originally belong to the radiology department, but who took part in some of the radiologic procedures. They were monitored for radiation exposure while participating. The "others" group included workers from the following: internal medicine, surgery, neurosurgery, orthopedics, urology, pediatrics, obstetrics and gynecology, anesthesiology, dentistry, emergency department, nursing department, and resident physicians. It is difficult to subdivide workers according to similar tasks, such as radiology, interventional radiology, nuclear medicine, and radiotherapy. Personnel exposure to radiation in the radiology department was routinely measured for the years 2001–2010.

2.2 Characteristics of the utilized glass badges

The dosimetric system used in this study was manufactured, operated, and calibrated at the Chiyoda Technol Corporation in Japan. The glass badge is a type of solid-state dosimeter composed of silver-activated phosphate glass [2, 3]. It has the ability to become radiophotoluminescent (RPL) after being exposed to ionizing radiation. RPL glass emits fluorescent light upon irradiation with ultraviolet light. The glass badge is equipped with three metal filters of Al, Cu, and Sn, and with plastic filters of different thicknesses, to enable a wide-energy-range detection of X- and γ-rays and β-particles. When neutron detection is required, a CR-39 plastic [4] solid-state nuclear track named wide-energy-range NeuPit is added to the glass badge along with four types of filters. This design makes a glass dosimeter capable of measuring X- and γ-rays, β-particles, and neutrons.

Table 1 Parameters of the glass badges used, with the mounting site

Dosimeter code (wearing site)	Detected radiation (detection range)	Energy range
FS (neck, chest, and abdomen)	X and γ (0.1 mSv–10 Sv)	X and γ (10 keV–10 MeV)
	β (0.1 mSv–10 Sv)	β (300 keV–3 MeV)
NS (chest and abdomen)	X and γ (0.1 mSv–10 Sv)	X and γ (10 keV–10 MeV)
	β (0.1 mSv-10 Sv)	β (300 keV–3 MeV)
	Neutron (0.1 mSv–60 mSv)	Neutron (0.025 eV–15 MeV)
JP (ring–finger)	X and γ (0.1 mSv–1 Sv)	25 keV–3 MeV

The glass badges utilized have a lower detection limit of 0.1 mSv. The definition and specifications for each type of glass badge used are given in Table 1. The detector codes given by the manufacturer in Table 1 pertain to either the type of radiation detected or to the part of the human body being monitored.

The NS dosimeter is designed to detect X- and γ-rays, β-particles, and also neutrons; hence the letter N (NS). The FS dosimeter is worn on the neck, chest, and abdomen to monitor X- and γ-rays, β-particles, but not neutrons, whereas the JP dosimeter is used only for monitoring of the finger dose for X- and γ-rays.

In Japan, a personnel dosimeter is designed to be worn on specific body parts for monitoring of personal radiation dose equivalents. Dosimeters which are worn on the chest (for males) or abdomen (for females) were considered primary, and they were used by all personnel of the Radiology Department. For determination of the personal dose equivalent at 10 mm depth below a specified point on the body, $H_p(10)$, glass badges were worn at the primary locations, i.e., the chest or abdomen. Secondary dosimeters worn on the neck or finger in conjunction with the primary dosimeters were used by a few personnel based on the nature of their work, e.g., interventional radiology and nuclear medicine, which causes a direct radiation exposure to the skin/extremities. They were used for assessment of the skin and extremity doses at 0.07 mm depth [$H_p(0.07)$] [1]. Personnel dosimeters worn at the neck were used for assessment of $H_p(10)$ and $H_p(0.07)$, whereas ring dosimeters were used only on a finger for assessment of $H_p(0.07)$.

The NS dosimeter was used by the radiotherapy workers, who had little risk of neutron exposure, and who constituted ~4 % of the total personnel. The JP dosimeter was used by a few radiologists and nuclear medicine workers (~1 %) who had a risk of skin/extremity exposure. The remaining workers, who comprised 95 % of the personnel, used one glass badge, either on the chest or on the abdomen, i.e., FS. Because of their duties, nurses have very little risk of skin/extremity exposure. Therefore, they wore no secondary dosimeters.

2.3 Dose assessment

The calculation of the effective dose E from a non-uniform exposure to the whole body was carried out by the Chiyoda Technol Corporation based on the technical guide provided by the Japanese Radiation Council [5] as follows:

$$E = 0.11H_a + 0.44H_b + 0.45H_c, \quad (1)$$

where E is the effective dose for the whole body, H_a is the equivalent dose for the external exposure of the head and neck at 1 cm depth in skin, H_b is the equivalent dose for the external exposure of the chest at 1 cm depth, and H_c is the equivalent dose for the external exposure of the abdomen at 1 cm depth. The coefficient factors of 0.11, 0.44, and 0.45 pertain to tissue-weighting factors provided in the 2007 Recommendations of the ICRP [1].

In practice, most of the workers wore primary dosimeters with the assumption of uniform exposure, whereas some other workers wore a pair of primary and secondary dosimeters when a non-uniform exposure was assumed.

$H_p(10)$ measurement was used for assessment of the equivalent dose at the primary positions, i.e., the chest and abdomen. Therefore, in Eq. (1), the quantities H_b and H_c represent the equivalent dose [$H_{p(chest)}(10)$ or ($H_{p(abdomen)}(10)$]. The $H_p(0.07)$ measured at the secondary positions (neck and finger) was used for assessment of the skin/extremity doses [1]. For workers who wear only a primary dosimeter, FS or NS, Chiyoda Technol Corporation assumes a uniform exposure and only reports their equivalent dose, $H_p(10)$. For those wearing two dosimeters, primary and secondary, their doses are reported as two separate quantities, i.e., $H_p(10)$ and $H_{p(skin/extremity)}(0.07)$. According to the ICRP [1], the recommended annual dose limit for skin and extremity exposure is 500 mSv. The data for $H_p(0.07)$ were analyzed separately.

According to the manufacturer [6], if a dose is undetectable, i.e., if it is less than the lower detection limit, it is denoted with an "X". For the numerical analysis, "X" notations were given a zero value. A majority of the monitored personnel received 12 radiation reports annually from the manufacturer regarding their monthly doses (i.e., 12 radiation measurement records for 12 months). However, some workers, such as those belonging to other hospital departments and part-time workers, had lower than 12 annual records. Therefore, an average weighting method was applied for calculation of the participation of the <12-records personnel in the annual average. Furthermore, doses were estimated in the case of faulty badge readings, and mechanically or radiation-damaged badges, by consideration of a worker's dose record over a year. Then, the average dose can be estimated. The weighted average refers to the arithmetic average, in which data points possess various weights and contribute differently to the final average. The weighted-average $\bar{X}$ can be expressed as

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i W_i}{\sum_{i=1}^{n} W_i}, \quad (2)$$

where X_i is the total annual dose measured in the unit of mSv/person for the i-th worker, and W_i is the number of monthly dose measurements for the same worker in the corresponding period.

3 Results

3.1 Annual [$H_p(10)$] dose distribution

The number of workers in the groups of radiologists and nurses showed a small decrease, with a range between 24–19 and 23–20 for radiologists and nurses, respectively, between the years 2001 and 2010. RTs showed a slight increase from 19 to 27, whereas the "others" showed a marked decrease from 250 to 89. A total of 2418 annual dose records of workers categorized into the four occupational groups were analyzed. The percentage of workers occupational

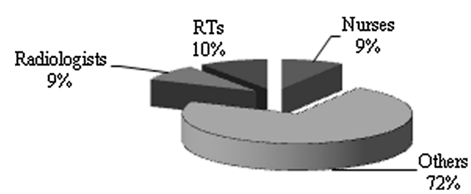

Fig. 1 Percentages of workers constituting the four occupational groups for the 10 years of study were 9, 10, 9, and 72 % for the radiologists, radiologic technologists, nurses, and "others", respectively

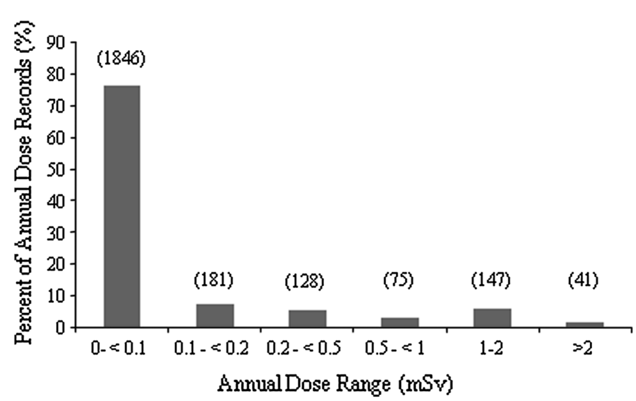

Fig. 2 Dose distribution of the annual dose records from 2001 to 2010. *Numbers* in *parentheses* correspond to the number of dose records

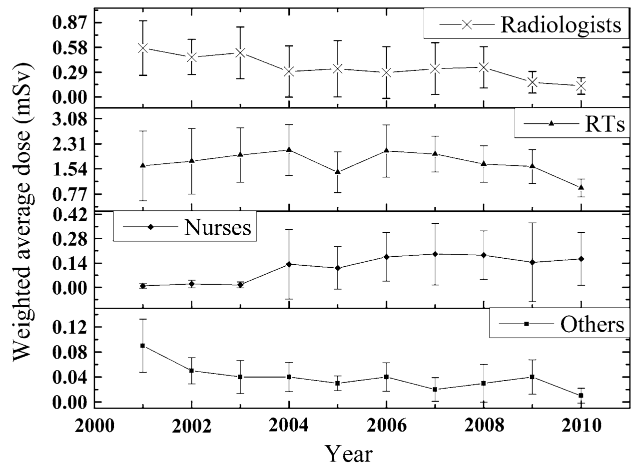

Fig. 3 Weighted-average annual $H_p(10)$ doses for radiologists, radiologic technologists, nurses, and "others". *Error bars* around the mean values indicate the uncertainty for annual measurements

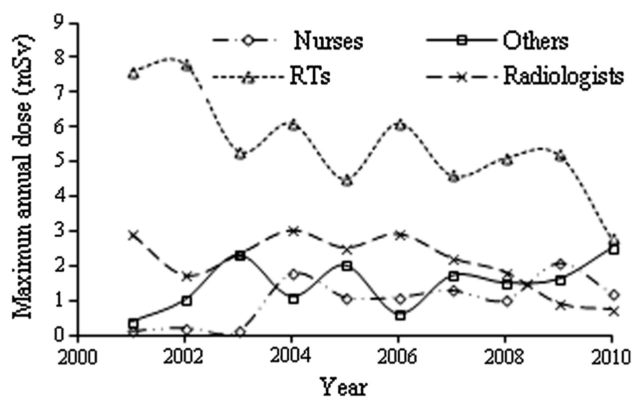

Fig. 4 Maximum detected doses for radiologists, radiologic technologists, nurses, and "others" were 2.9, 7.8, 2.1 and 2.5 mSv, respectively, over the investigation period

classification is shown in Fig. 1. It shows that the "others" group constituted ~72 % of all monitored workers. The dose distribution of the 2418 records is noticeably skewed, as presented in Fig. 2. Approximately 76 % of the personnel did not receive any measurable doses, whereas almost 2 % received doses of more than 2 mSv.

The distributions of the weighted-average and the maximum effective doses for each group in the period from 2001 to 2010 are illustrated in Figs. 3 and 4. The weighted-average annual effective doses ranged from 0.13 to 0.57, 0.96 to 2.12, 0.01 to 0.19, and 0.01 to 0.09 mSv for the radiologists, RTs, nurses, and "others", respectively.

Figure 3 shows that the RTs received the highest average annual effective dose among the monitored groups. The error bars indicate one standard deviation (SD) around the average values for annual measurements. The SD was calculated for every working group based on the number of workers and their measured annual doses. The remaining

Table 2 Collective doses for all monitored groups in units of man-mSv

Year	Collective dose (man-mSv)				
	Radiologists (%)	RTs (%)	Nurses (%)	Others (%)	Total (%)
2001	13.7 (21)	31.1 (49)	0.2 (<1)	19.0 (30)	64.0 (100)
2002	12.6 (22)	32.0 (57)	0.4 (1)	11.1 (20)	56.1 (100)
2003	12.4 (23)	35.4 (66)	0.3 (1)	5.5 (10)	53.5 (100)
2004	6.8 (11)	46.6 (72)	2.5 (4)	8.5 (13)	64.5 (100)
2005	5.6 (13)	30.3 (70)	2.1 (5)	5.3 (12)	43.3 (100)
2006	6.3 (11)	39.8 (68)	3.5 (6)	8.5 (15)	58.1 (100)
2007	6.6 (12)	41.9 (74)	4.2 (7)	4.2 (7)	56.9 (100)
2008	6.6 (12)	40.6 (72)	3.9 (7)	5.7 (10)	56.7 (100)
2009	3.6 (7)	42.0 (79)	2.9 (5)	4.5 (8)	52.9 (100)
2010	2.5 (8)	25.9 (79)	3.3 (10)	1.0 (3)	32.6 (100)

occupational groups received average doses below 1 mSv during the 10-year period.

The RT group shows a drop in 2005. A detailed monthly analysis was done to reveal any possible cause for this drop, but we could not find any special reason. Furthermore, it can be concluded from Fig. 3 that the average annual radiation doses for the radiologists, RTs, and "others" have been decreasing over the 10-year period. Only the nurses showed a slightly increasing dose trend. Figure 4 shows the maximum dose received by each of the four occupational groups. Again, the RTs received the highest radiation exposure among the groups investigated. An analysis revealed that there were no neutron components of the doses recorded during the 10-year period.

3.2 Skin/extremity [$H_p(0.07)$] dose

The workers from the nuclear medicine division could be easily identified among the remaining workers because they alone wore JP (finger) dosimeters. They received the highest average skin/extremity dose among the investigated groups. The weighted-average annual skin and extremity doses ranged from 0 to 2.9, 0.2 to 31.5, and 0 to 4.4 mSv for the radiologists, RTs, and "others", respectively.

3.3 Total collective dose

The total collective dose calculated for the four groups is tabulated in Table 2 and illustrated in Fig. 5 along with the change of the number of workers over time. The collective dose decreased by approximately a factor of two between 2001 and 2010. The total number of monitored workers decreased considerably between 2008 and 2010, from 228 to 155 workers.

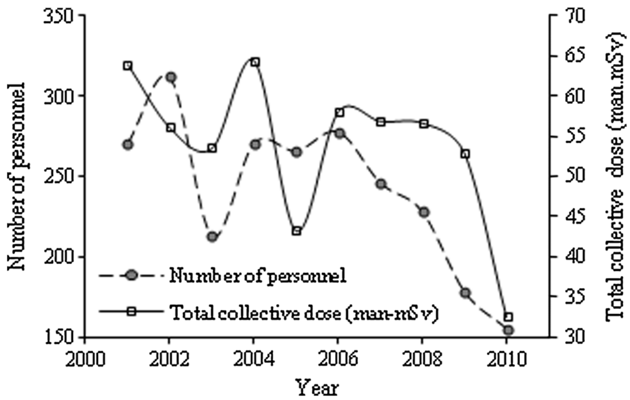

Fig. 5 Total collective doses and number of personnel showing a decreasing trend by a factor of 2 over the investigation period

Table 2 shows the collective dose for each group and the percentage contribution of that dose to the total annual collective dose in the Radiology Department from 2001 to 2010. The exposure received by the RTs was the main contributor to the total collective dose, with a range of 49–79 %. It is clear that the collective dose for the radiologists and "others" decreased, whereas that for RTs and nurses increased. The percentage contribution to the total collective dose was 7–23, 1–10, and 3–30 % by the radiologists, nurses, and "others", respectively.

4 Discussion

Personnel radiation dose monitoring for 10 years showed variation in the number of monitored workers for all groups. The number of workers in the groups of radiologists and nurses decreased by only a small percentage. RTs showed a slight increase in the number of workers over the years, whereas the "others" showed a marked decrease in the number of workers. The number of RTs increased because of an increase in the number of machines and an expansion of the Radiology Department. However, the number of workers in the "others" group decreased drastically. Until 2008, those in the "others" group were monitored with glass badges. After that, different groups of workers were categorized based on the nature of their work. Those who had a risk of high radiation exposure by primary or scattered beams continued to wear glass badges, whereas workers who were less likely to be in the beam path, like those assisting in operating rooms and in orthognathic surgery were monitored by different instantaneous pocket dosimeters, which give an instant reading. Therefore, in our facility, the number of "others" who were monitored with a glass badge decreased considerably from 164 in 2008 to 89 in 2010.

The weighted-average annual effective doses for the various groups of personnel were investigated. A decade of radiation dose trends was explored and analyzed through personnel dose monitoring. A portion of the monitored workers, constituting ~28 % of the total, belonged only to the Radiology Department. This included radiologists, RTs, and nurses. The remaining workers (72 %) composed of the "others" group who belong to other hospital departments. The "others" were engaged in a portion of the radiologic procedures and thus were monitored for radiation exposure.

During the 10-year period, the occupational radiation doses did not exceed the ICRP dose limit of 20 mSv/year [1]. Excluding the nurses, the weighted-average annual doses for each group showed a decreasing tendency. This was due to continuous innovation and the development of new technology, which provided new ways of protecting both patients and workers from radiation. The number of RTs has increased gradually from 19 workers in 2001 to 27 in 2010, which resulted in radiation exposure being distributed among more workers. In addition, in 2005, the nuclear medicine division replaced the extraction (milking) of ^{99m}Tc with direct outsourcing. RTs working in nuclear medicine stopped milking radioisotopes from generators. All of this helped partially to reduce the RTs' average dose trend.

The introduction of new image intensifiers with higher sensitivity of fluoroscopy machines helped greatly to reduce not only the patient doses, but also radiologists' annual doses. In addition, the radiology department gives educational lectures for the hospital staff regarding radiation safety. This has been introduced in the last few years and takes place annually, which helped in raising radiation awareness among radiation workers about the correct radiation protection practices. The trend of the dose to "others" decreased because they were slowly withdrawing from participation in radiologic procedures. Physicians, dentists, and assistants usually receive doses <0.1 mSv, i.e., they receive no measurable dose.

The increasing trend of radiation doses for nurses can be explained by the fact that, in the last few years, they have started to assist radiologists during many routine and interventional radiologic procedures. They have gotten into closer proximity to patients, and hence received a higher radiation exposure. A change in the nature of their work and the duties assigned to them has increased their annual average doses, an outcome that can be compared to that in a similar study [7].

The results of this work are comparable to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report. UNSCEAR world values for average annual effective doses are 0.5 and 0.79 mSv [8] for radiologists and nuclear medicine workers, respectively. Moreover, a recent study by Mora and Acuna [9] showed that the average annual effective dose was

0.37 mSv for radiologists and 1.55 mSv for nuclear medicine workers. These results are in agreement with the analyzed weighted-average annual effective doses that range from 0.13 to 0.57 and 0.96 to 2.12 for the radiologists and RTs, respectively, in the present study. In our study, the majority of the nuclear medicine workers belonged to the RTs group.

The annual average doses of workers wearing NS dosimeters, i.e., in radiotherapy, were very low compared to those of the other occupational groups because their exposure results from external-beam irradiation from linear accelerators that are remotely controlled from separate rooms.

The highest average annual effective dose levels were measured for the RTs, followed by the radiologists due to the nature of their work. Some RTs and radiologists participate in interventional procedures, which subject them to high levels of radiation. Generally, radiologists' trend should be for higher radiation dose levels [7, 9]. However, of an average of 20 radiologists working within the department every year, only four to five carry out interventional procedures. A few numbers of radiologists participating in radiologic procedures, in addition to not following the rule of wearing a glass badge for monitoring, explain why the radiologist group had such low levels of radiation doses.

The radiologists and RTs working in the nuclear medicine division are frequently exposed to continuous radiation fields during the preparation and injection of radioisotopes. Therefore, nuclear medicine workers receive the highest radiation doses among those in the RT group itself, as was also concluded in other studies [7, 8, 10–13].

The primary contribution to the total annual collective dose comes from the RTs and nuclear medicine workers, whose exposure accounts for 69 % of the total annual collective dose. The majority of workers in our study (~95 %) wore only one glass badge, either on the chest or on the abdomen. It is important to provide educational training programs and lectures for all monitored workers to keep their radiation exposure at a minimum.

5 Conclusion

During the 10-year period of personnel dose monitoring, there was no evidence that radiation doses exceeded the annual limit of 20 mSv. The dose distribution was found to be skewed toward the low-dose range, with ~76 % of workers receiving an annual dose of <0.1 mSv, which is below the lower limit of detection. There was some variation in the average annual doses among the four investigated groups. These variations result from differences in the nature of the work and adherence to radiation protection rules and regulations among the different groups of workers. We can also conclude that the RTs received the highest average annual doses among the four groups because they work in areas containing high levels of radiation. It is, therefore, essential to increase these monitoring efforts, provide continuous education, and improve the protection of all personnel.

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Conflict of interest The authors declare that they have no conflict of interest.

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