Methodology for Simultaneous Relative-calibration of Multiple Personal Dosimeters in a $^{226}$Ra Irradiation Field

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The reopening of the research reactor at Kyoto University required regular calibration of many personal dosimeters. However, it is not practical to subscribe to a calibration service for all the dosimeters. Traceability to the Japanese National Standard is transferred to a representative dosimeter with $^{137}$Cs and $^{60}$Co radioactive sources by the service. Here, we show a method to simultaneously confirm the accuracy of 100 dosimeters by using the transfer dosimeter in an irradiation field of a $^{226}$Ra radioactive source. The background in the 2.9-m $\times$ 4.0-m $\times$ 3.3-m chamber was 0.001 mSv day$^{-1}$, and thus had no effect on calibrations. The position dependence of dose equivalents from the source at the centre of the chamber was an inverse square of distances for the primary rays and was inconsequential for scattered rays. The angular dependence around a 44-cm-radius from the source was isotropic. After an irradiation time of 48 minutes, the average difference in readings between the transfer dosimeters and others arranged in the circle was 1.3%, and each difference was within the $\pm$ 10% error range stipulated by the manufacturer. These results demonstrate that this irradiation field is ideal for the metrological confirmations of multiple personal dosimeters.

KEY WORDS: personal dosimeter, personal dose equivalent, metrological confirmation, irradiation field, gamma ray, $^{226}$Ra radioactive source.

1 INTRODUCTION

Kyoto University has a research reactor on the Kumatori campus that is shared internationally.1 However, since the accident at the Fukushima Daiichi nuclear power plant in March 2011, operations at the reactor had been suspended to reinforce all safety precautions. In August 2017, the Nuclear Regulation Authority decided that the reactor met all the regulations for nuclear power plants. The reactor was reopened, and many long-term and single-day users have already visited. Therefore, many personal dose equivalents for users, in addition to those for reactor workers, must be individually monitored.

At the reactor, there are about 300 silicon-diode-based personal dosimeters for gamma rays or neutrons.2, 3 Personal dose equivalents displayed by the dosimeters must be traced to the Japanese National Standard and be regularly checked for accuracy.4 Laboratories accredited by the Japan Calibration Service System (JCSS), based on the Measurement Law and the ISO/IEC 17025 accreditation, can perform dosimeter calibrations with standard secondary instruments and irradiation equipment.5 The latter emit gamma rays from $^{137}$Cs or $^{60}$Co radioactive sources at personal dose equivalent rates in the range 1 $\mu$Sv h$^{-1}$–1 Sv h$^{-1}$, or neutrons from $^{241}$Am-Be or $^{252}$Cf radioactive sources at personal dose equivalent rates in the range 10 $\mu$Sv h$^{-1}$–10 mSv h$^{-1}$. However, it is not practical to subscribe to JCSS for all the dosimeters possessed at the reactor. It is also difficult to control their radioactive sources in a university, because periodic replacement and/or substantial half-life corrections are needed.

Here, the fundamental characteristics are characterised for an irradiation field constructed with a $^{226}$Ra radioactive source that emits multi-energy gamma rays. A methodology is described that confirms the accuracy of multiple dosimeters by their orientations in the characterised field. The half-life correction for the 1,600-y half-life reduces the uncertainty for personal dosimeters.6 The convoluted energy for the gamma rays weighted with emission rates was approximately 0.73 MeV, which was between those emitted from the $^{137}$Cs and $^{60}$Co radioactive sources. Thus, a representative “transfer” dosimeter was traceable by JCSS to the Japanese National Standard with $^{137}$Cs and $^{60}$Co radioactive sources, and all other
dosimeter readings were compared with the dose equivalent of the transfer dosimeter with a 226Ra radioactive source. These two procedures simultaneously allow the metrological confirmations of many dosimeters.

II MATERIALS AND METHODS

The gamma-ray dosimeters (MYDOSE mini; Hitachi, Ltd.) were based on the Japanese Industrial Standards (JIS) Z4308:1991 and could monitor personal dose equivalents in real time.7, 8 They displayed a personal dose equivalent for gamma rays according to ICRP Report 74.9 The minimum reading was 0,001 mSv.

A representative dosimeter was calibrated with 137Cs and 60Co radioactive sources by the Chiyoda Technol Corporation, which is an accredited calibration laboratory (i.e., a secondary standard). In the calibrations, based on JIS Z4511:2005, the dosimeter was irradiated three times by 1-mSv dose equivalents from each source. From the averages, two absolute calibration factors were determined. Hence, this transfer dosimeter was traceable to the Japanese National Standard.

A 226Ra radioactive source (Amersham, Plc.) was prepared to calibrate all the other dosimeters. It ensured that the dosimeter readings exceeded a certain value, because the certification issued in 1963 stated that the 226Ra content was 10.34 mg. The active area was shielded by a platinum-iridium alloy.

An irradiation field was constructed in an empty 2.9-m × 4.0-m × 3.3-m room, as depicted in Fig. 1. Three walls, excluding the entrance door, were covered with 1.4 m of reinforced concrete. A rotating platform attached to a 50-cm-radius acrylic disk with a 3-cm thickness was set in the centre of the chamber.

In Fig. 2, the experimental arrangement is shown that used the transfer dosimeter to acquire the fundamental characteristics of the irradiation field. An acrylic support unit held the dosimeters at precise distances from the radioactive source. It can accommodate two dosimeters at the upper and lower levels. The support unit was placed at the centre of the top face of the acrylic disk. The transfer dosimeter was placed on the upper level, and the field background was accumulated for 24 hours.

After the background measurement, the radioactive source was placed in an acrylic holder at the centre of the platform. It was above 104 cm from the floor. The location dependence in the irradiation field was estimated by translating the support unit to various points in the chamber. The incidence plane of the transfer dosimeter was consistently interfaced with the source. Effects of scattered rays generated by adjacent dosimeters were evaluated by closely arranging many support units that mounted two dosimeters each around the radioactive source.

The personal dose equivalents were obtained three times for each condition. Averages and standard deviations (± σ) were then calculated. Each irradiation time was 15 minutes. The 226Ra radioactive source was removed with long tongs from the acrylic holder at end of each measurement and placed outside of the irradiation chamber. This procedure required less than 10 sec.

Fig. 1 Schematic of the irradiation chamber. The floor was 2.9 m × 4.0 m. The height from the floor to the ceiling was 3.3 m. In the centre, there was a 50-cm-radius, 3-cm-thick acrylic disk attached at the top of a platform.

Fig. 2 Schematic of the experimental arrangement. A 226Ra radioactive source was located at the top of an acrylic holder, 104 cm above the floor. The upper and lower levels of the acrylic support each accommodated two personal dosimeters. Shadow dosimeters indicate the measurement points.
III RESULTS AND DISCUSSION

The absolute calibration factors of the transfer dosimeter for the $^{137}$Cs and $^{60}$Co radioactive sources were 0.97 and 1.10, respectively. Thus, the calibration factor for the $^{226}$Ra radioactive source was expected to be one. In the absence of the $^{226}$Ra radioactive source, the background accumulation rate was 0.001 mSv day$^{-1}$ at the centre of the irradiation chamber. Thus, the field background was negligible.

Personal dose equivalents as a function of the distance $d$ from the radioactive source are plotted in Fig. 3. The data were fitted to $C_1/d^2 + C_2$, where the constant $C_1$ refers to the primary rays, and the constant $C_2$ refers to scattered rays. The second term was less than the minimum reading of the dosimeter. Thus, the first term dominates and the dosimeter position dependence was an inverse square of the distance for the primary rays and was inconsequential for the scattered rays. The data justified the use of the platform attached to the acrylic disk in the irradiation field.

Personal dose equivalents around a 44-cm-radius circle centred at the radioactive source are shown in Fig. 4. The mean value was $0.093 \pm 0.002$ mSv. The personal dose equivalent was $0.093 \pm 0.001$ mSv when the platform was rotating at a rate of 360 deg-min$^{-1}$. These results were consistent within the errors, and indicated that rotation of the platform was not consequential. Thus, there was an isotropic angular dependence around the radioactive source. In addition, the personal dose equivalent for the lower level in the support unit was $0.096 \pm 0.003$ mSv, which was within the error limits of that for the upper level. Hence both levels in the support unit could be used for the dosimeters.

Effects from adjacent dosimeters were estimated by using 25 support units closely apposed on the 44-cm-radius semicircle centred at the radioactive source. Each support unit...
had two dosimeters, and the transfer dosimeter was mounted in the upper level on the thirteenth support unit. The personal dose equivalent was 0.093 ± 0.002 mSv when the platform was rotating at a rate of 360 deg-min⁻¹, which was consistent within the error of the above results. Thus, contributions from gamma rays scattered from other dosimeters were negligible.

The orientation of the irradiation field was determined by those fundamental characteristics, as shown in Fig. 5. The field consisted of 50 support units closely arranged in a 44-cm-radius circle on top of the acrylic disk. 100 dosimeters were exposed for 48 minutes while rotating the platform at a rate of 360 deg-min⁻¹. The average difference in readings between the transfer dosimeters and the others was 1.3 ± 1.3%, and each difference was within the ± 10% error range stipulated by the manufacturer. Consequently, the uncertainty of this irradiation field was 2.6% (k = 2).

These fundamental characteristics of this irradiation field simultaneously ensure the qualities and metrological confirmations of multiple dosimeters by using a transfer dosimeter traced by JCSS to the Japanese National Standard with 137Cs and 60Co radioactive source. The high accuracy of the field enables the use of many calibrated dosimeters for radiation protection. This knowledge will reduce radiation exposure for users, and provide a safer environment for workers at reactors or radiation facilities.

IV CONCLUSION

We have constructed a 226Ra irradiation field for personal dosimeters and have examined its fundamental characteristics. The field can simultaneously provide metrological confirmations of multiple dosimeters by using a transfer dosimeter traced by JCSS to the Japanese National Standard with 137Cs and 60Co radioactive source. The high accuracy of the field enables the use of many calibrated dosimeters for radiation protection. This knowledge will reduce radiation exposure for users, and provide a safer environment for workers at reactors or radiation facilities.

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